DESIGN, PROCUREMENT AND CONSTRUCTION STRATEGIES FOR MINIMIZING WASTE IN CONSTRUCTION PROJECTS

By

SAHEED O. AJAYI

BSc (Hons.), MSc, ACIAT, MCIOB

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Declaration

I declare that this thesis represents my own work carried out by me, except where due acknowledgement has been made in the text, and that it has not been submitted either in part or full for any other award than the degree of Doctor of Philosophy of the University of the West of England. Materials from other sources have been duly acknowledged and referenced in line with ethical standards, and the list of publications made from the thesis has been provided.

Signed: SAHEED O. AJAYI

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Abstract

The construction industry contributes the largest portion of waste to landfill, and it consumes a significant proportion of mineral resources excavated from nature. Due to adverse environmental impacts of waste generation, as well as financial gains associated with its minimisation, waste intensiveness of the industry has remained a major concern across nations. This study investigates the design, procurement and construction strategies for waste minimisation, using a dynamic approach. Apart from an investigation of the key and underlying measures for construction waste mitigation, the study considers the interrelationship between stages of projects' lifecycle. This is as activities carried out at an earlier stage are capable of engendering occurrences at later stages of the dynamic project delivery processes.

Following the tenets of critical realism philosophy and exploratory sequential mixed method, the study combined qualitative and quantitative approaches at intensive and extensive stages respectively. At the early stage of the study, data were collected through literature review and focus group discussions with industry experts. Results of the qualitative study were used to develop a questionnaire, which was analysed using statistical approach and structural equation modelling. As a means of investigating the key drivers of waste minimisation at a holistic level, a system dynamic model was developed to simulate the interplay and effects of different strategies that were confirmed through the previous process.

The study suggests that design stage has the most decisive impacts on construction waste minimisation. At this stage, the key dimensions for designing out waste include design for modern methods of construction, collaborative design process, design for standardisation and waste-efficient design documentation. Error-free design and involvement of contractors at early design stage are part of the critical success factors for designing out waste. With design being much important for waste minimisation, competencies of designers in terms of waste behavioural competency, design task proficiency, construction-related knowledge and inter-professional collaborative competency are essential for designing out waste. Materials procurement process could enhance waste minimisation by considering its key dimensions for driving waste-efficient projects, which includes waste-efficient materials purchase management, suppliers' alliance and waste-efficient bill of quantity. Efficient materials take-off and take back scheme are confirmed as critical success factors for driving waste minimisation through materials procurement processes. During construction activities, waste could be reduced through prefabrication and offsite technology, contractual requirements, maximisation of materials reuse and improved collaboration, among others. Prefabrication, supply chain alliance and collaborative procurement routes are confirmed as the critical success factors for reducing waste during construction process. Dynamic interplay among these sets of strategies suggests that notwithstanding the significance of the different measures during design, procurement and construction processes, prefabrication technology and collaborative procurement route are the holistic drivers of construction waste minimisation.

The study implies that designers could effectively drive waste minimisation through dimensional coordination and standardisation of design in line with standard materials supplies. In addition to the need for prefabrication and offsite technologies, increasing collaboration among project team is requisite to reducing waste generated by construction activities. By implementing the strategies suggested in the study, substantial proportion of construction waste would be diverted from landfill.

Dedication

To my wife, Nurat
For her prayers,
encouragement and
unwavering
supports

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List of Publications from the Thesis

1. Oyedele, L.O., **Ajayi, S.O**. and Kadiri, K.O., 2014. Use of recycled products in UK construction industry: An empirical investigation into critical impediments and strategies for improvement. *Resources, Conservation and Recycling*, 93, pp. 23-31.

2. **Ajayi, S.O**., Oyedele, L.O., Bilal, M., Akinade, O.O., Alaka, H.A., Owolabi, H.A. and Kadiri, K.O., 2015. Waste effectiveness of the construction industry: Understanding the impediments and requisites for improvements. *Resources, Conservation and Recycling*, 102, pp.101-112.

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5. **Ajayi, S.O.,** Oyedele, L.O., Bilal, M., Akinade, O.O., Alaka, H.A. and Owolabi, H.A., 2017. Critical management practices influencing on-site waste minimization in construction projects. *Waste management*, 59, pp.330-339.

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List of Abbreviations

ACE:	Architecture, Construction and Engineering
AGFI:	Adjusted Good of Fit Index
AMOS:	Analysis of a Moment Structures
SPSS:	Statistical Package for the Social Sciences
APM:	Association of Project Managers
AVE:	Average Variance Extracted
BIM:	Building Information Modelling
BRE:	Building Research Establishment
BREEAM:	Building Research Establishment Environmental Assessment Method
CDEW:	Construction, Demolition and Excavation Wastes
CF:	Construction Factors
CFA:	Confirmatory Factor Analysis
CFI:	Comparative Fit Indices
CfSH:	Codes for Sustainable Homes
CIAT:	Chartered Institute of Architectural Technologists
CIOB:	Chartered Institute of Buildings
CIWM:	Chartered Institute of Waste Managers
CR:	Composite Reliability
CSF:	Critical Success Factor
DC:	Design Competency
DF:	Design Factors
DOWTB:	Designing out Waste Tool for Buildings
DPC:	Design. Procurement and Construction
DQI:	Design Quality Indicators
DST:	Dynamic System Theory
GDP:	Gross Domestic Product
GFA:	Gross Floor Area
GFI:	Global Fit Index
HM:	Her Majesty
ICE:	Institute of Chartered Engineers
IPD:	Integrated Project Delivery
IStructE:	Institution of Structural Engineers

KPI:	Key Performance Indicators
LEED:	Leadership in Energy and Environmental Design
MAR:	Missing at Random
MCAR:	Missing Completely at Random
ML:	Maximum Likelihood
MMC:	Modern Methods of Construction
MSV:	Maximum Squared Variance
NFI:	Normed-Fit Index
NMAR:	Not Missing at Random
NNFI:	Tucker-Lewis Index
OCM:	Occupational Competency Models
PAYT:	Pay as You Throw
PF:	Procurement Factors
PGFI:	Parsimony Goodness of Fit Index
PNFI:	Parsimonious Normed Fit Index
RIBA:	Royal Institute of British Architects
RICS:	Royal Institute of Chartered Surveyors
RMR:	Root Mean Square Residual
RMSEA:	Root Mean Square Error of Approximation
SDM:	System Dynamic Modelling
SEM:	Structural Equation Modelling
SRMR:	Standardized Root Mean Square Residual
SWMP:	Site Waste Management Plan
WRAP:	Waste and Resource Action Plan

CHAPTER 1: INTRODUCTION

1.1 Background to the Study

The construction industry accounts for the largest portion of global waste and pollution (Faniran and Caban, 1998; Ibrahim *et al.*, 2010), as it generates up to 30% of total material waste (Begum *et al.*, 2009). For instance, the UK Construction and Demolition Waste (CDEW) amounts to about 110 million tonnes, which is over 60% of national waste generated (Paine and Dhir, 2010). Figures from other large economies also suggests that construction-related waste is up to 40% in Brazil (Saraiva *et al.*, 2012), 35% in Canada (Kofoworola and Gheewala, 2009), 44% in Australia (Shen and Tam, 2002), 65% in Hong Kong (Esin and Cosgun, 2007), and up to a third of the US waste to landfill (Kibert, 2000). While these figures suggest that a holistic approach to reducing construction-related waste is indispensable to the global sustainability agenda, it is tragic that existing industrial practice lack comprehensive benchmark for managing waste throughout project lifecycle, i.e. design, procurement, and construction stages. Worst still, current waste tools such as WRAPNet, SmartWaste, SmartAudit, etc. mainly proffer opportunities for managing waste after its occurrence, thus making it a belated intervention.

Apart from environmental sustainability, reduced resource excavation and prevention of several environmental hazards as likely results of material waste reduction (Yuan, 2013; Anderson *et al.*, 2004), apropos waste minimisation techniques have considerable economic benefits (WRAP, 2007). This would result in savings in forms of the cost of wasted materials, cost of storage, landfill tax, and cost of disposal (Coventry and Guthrie, 1998), which are usually shifted to the clients (Guthrie *et al.*, 1999). Due to these significant benefits of waste minimisation, there has been a large body of knowledge on construction waste (e.g. Faniran and Caban, 1998; Poon *et al.*, 2004; Formoso *et al.*, 2002; Dainty and Brooke, 2004; Treolar *et al.*, 2003; Osmani *et al.*, 2008; WRAP, 2007/2009b; Wang *et al.*, 2014, etc.). However, these series of studies lacked vigour by failing to produce a holistic approach that covers all stages of project delivery process. As such, there is a need for a dynamic approach in looking into the relationship between main waste-efficient indicators at design, procurement and construction stages. This would not only establish impacts of one waste mitigation strategy on other, but it is also expected to provide practitioners with an optimum approach to prevent waste causative factors from design to completion.

Usually referred to as “something that the producer or holder discards or intends to or is required to discard” (Guthrie *et al.,* 1999), waste is caused by various activities occurring from design to completion. While it is usually argued by designers that waste occurs on site during construction activities (Osmani *et al*., 2008), design related flaws and complexities as well as procurement activities, among others, contribute to total waste generation (Faniran and Caban, 1998; Osmani, 2012). This suggests that a holistic approach to minimise project waste is a collective effort among all stakeholders, and it is expected to consider every phase of project delivery processes.

In trying to identify its sources in projects, waste has been categorised using various yardsticks. Coventry *et al.* (2001) classified waste into bricks, blocks and mortar, packaging, timber, metal, special waste, dry lining and others. Spivey (1974 in Faniran and Caban, 1998) used similar classification with an addition of garbage and sanitary waste, while Faniran and Caban (1998) noted that Gavilan and Bernold (1994) classified waste based on their causes: design, procurement, handling, operation, residual, and others. Irrespective of identification models, waste is usually estimated per unit volume of total materials purchased or as a percentage of total cost of materials (Ekanayake and Ofori, 2004).

Because its clear economic and environmental impacts, governments across many nations, especially the UK, have come with various fiscal and legislative measures aiming at reducing the total amount of waste that finally goes to landfill. Among these are an imposition of landfill tax per quantity of waste disposed in the landfill and the use of aggregate tax to encourage use and re-use of reclaimed materials (HM Government, 2008; WRAP, 2009b). Further efforts include funding of Waste Resource Action Plan (WRAP) and other bodies to investigate and enlighten individuals and businesses on better ways of managing waste and strategies for enhancing recycling.

Efforts to manage waste has been categorised into four hierarchical orders, known as the waste hierarchy. This involves reduce, re-use, recycle/recover and disposal (Guthrie *et al*., 1999), with “reduce” and “re-use” offering better environmental and economic benefits. The former seeks to decrease waste generated while the latter deals with reabsorption of the waste generated (Faniran and Caban, 1998). Alternatively, when “reduce and re-use” become impracticable, processing of waste materials to produce a derivative product, known as recycling, becomes the best option. Despite the criticism that it also consumes a substantial amount of energy that results in environmental pollution (Chong and Hermreck, 2011; Benjamin, 2010), waste recycling reduces the need for extracting raw materials (WRAP, 2009b) and prevents pollution due to mining and production processes (Halliday, 2008). These options are usually expected to be explored before the decision to landfill waste, especially as it results in total economic loss and comes with series of negative environmental impacts, asides nations running out of landfill sites (Oyedele *et al.*, 2013; Poon, 2007).

However, rather than adopting any of the strategies depicted by the waste hierarchy, it has been argued that there is a possibility of preventing waste by using some set of tactics during design stages (Faniran and Caban, 1998; WRAP, 2007,2009a; Yuan, 2013). Government funded WRAP identified five waste spectrums that are capable of reducing the waste burden of construction projects. These according to WRAP involve design for reuse and recovery, off-site construction, deconstruction and flexibility, materials optimisation, and waste-efficient procurement (WRAP, 2009a). In buttressing their importance, Jaillon et al. (2009) and Tam *et al*. (2007b) argue that wastage reduction level in a prefabricated building is up to 52% and 84.7% respectively. Anink *et al.* (1996) also recognised that design for de-constructability ensures building materials are re-used at the end of building lifecycle. As such, reducing waste at source, by implementing waste minimisation strategies before actual waste generation, is undoubtedly preferable as it seeks to prevent waste generation.

Accordingly, there is increasing awareness that rather than concentrating on site effort to reduce and manage waste during construction activities as usually entrenched in Site Waste Management Plan, waste minimisation should be considered throughout all stages of building process – design to completion (Ekanayake and Ofori, 2004). This becomes imperative if waste and its associated negative economic and environmental impacts are to be prevented, or in a worst-case scenario, minimised.

1.2 Problem Statement

Construction industry consumes over 50% of mineral resources and generates largest portion of waste in landfill (Anink et al., 1996; Paine and Dhir, 2010). In the UK, a 2013 figure suggests that out of 100% of waste generated, 44%, 14%, 13%, 13%, 9% and 7% are due to construction, commercial, industrial, household, mining and agricultural activities respectively (DEFRA, 2013). As this means that the industry contributes the largest proportion of UK waste to landfill, similar patterns exist in other large economies (Oyedele et al., 2014). Construction activities in the US generates about 29% of landfill waste (Yu et al., 2013), while the industry landfills about 40%, 44%, 27% and 25% in Brazil, Australia, Canada and Hong Kong respectively (Yeheyis et al., 2013; Lu and Tam, 2013; Oyedele et al., 2014). Evidence suggests that the construction industry generates about 35% of waste to landfill across the globe (Solís-Guzmán et al., 2009). It has been argued that continuous sustainability of the industry depends on how well it manages waste generation (Udawatta et al., 2015); particularly since waste minimisation is requisite to preventing materials depletion

In addition to the negative environmental impacts of waste, reducing construction waste could result in substantial financial gains. Research by the UK's Building Research Establishment (BRE) suggests that up to £130million is accruable to the UK economy by reducing just 5% of its construction waste (BRE, 2003). These savings are in forms of the cost of acquiring the wasted materials, the cost of storage, cost of transportation and disposal as well as the landfill tax payable for waste disposal (Coventry and Guthrie, 1998). Thus, construction waste minimisation has significant economic and environmental benefits.

1.3 Gap in Knowledge and Justification for the Study

Research into nature, causes, environmental and economic impacts of waste is not new in the construction industry. However, many of the studies have narrowly focussed on causes and impacts of waste (Esin and Cosgun, 2007; Bossink and Brouwers, 1996; Kofoworola and Gheewala, 2009). Others proffer solution to waste after it is generated (Treolar *et al.*, 2003; WRAP, 2009b, 2010; Guthrie and Mallet, 2005; Sassi and Thompson, 2008).), thus providing an avenue for reducing waste to landfill rather than preventing waste generation. Other sets of studies have also investigated waste minimisation from a unitary perspective, while the causes of waste are dynamic throughout all stages of building delivery process (Yuan *et al*., 2012), thereby calling for a dynamic approach to the study.

For instance, Faniran and Caban (2008), Esin and Cosgun (2007), Bossink and Brouwers (1996) and Kofoworola and Gheewala (2009), among others, investigated causes and impacts of construction waste. These studies did not only unfold some inscrutability; they identified design stage as a significant point for waste prevention. However, apart from over-reliance on subjective opinions of their respondents, identifying causes of waste, as carried out by the studies, does not necessarily prevent waste occurrence. On the other hand, Al-Hajj and Hamani (2011), Gamage *et al*. (2009) and Formoso *et al.* (2002) carried out a study of different construction and procurement processes to determine case-based causes of waste. Again, despite the fact that these set of studies have successfully contributed to waste management, they have failed to provide strategic directions for minimising waste while they almost leave out design stages, which is crucial to waste prevention (Faniran and Caban, 1998).

Furthermore, previous studies focussing on waste management (e.g. Treolar *et al.,* 2003; WRAP, 2009b, 2010; Guthrie and Mallet, 2005; Sassi and Thompson, 2008) successfully advocated and provided guidelines for waste re-use and recycling as a means of waste management. However, they have concentrated on strategies for managing waste after it has been generated.

The third category of waste management studies suggested different strategies for reducing construction waste. These studies have robustly furnished practitioners with a set of tactics that could be adopted to prevent waste generation (e.g. Osmani *et al*., 2008; WRAP, 2007, 2009a; Wang *et al.,* 2014; Begum *et al.,* 2007; Dainty and Brooke, 2004; Poon *et al.,* 2004). Notwithstanding the fact that decision made at one stage of delivery process (e.g. design stage) have impacts on other stages (Sterman, 1992), the studies have been carried out at unitary basis, while causes and effects of waste are complex, dynamic and interconnected (Love *et al*., 2000; Kollikkathara, 2010). Thus, the studies failed to identify the dynamic interplay between different factors required for waste minimisation throughout all stages of project delivery process. It is, therefore, imperative to channel appropriate methodology towards unravelling dynamism of waste and preventive measures (Yuan *et al.*, 2012; Sudhir *et al.,* 1997).

Based on the need to study construction waste at a dynamic level, few studies have adopted dynamic system methodology in studying the phenomenon. For instance, Tam *et al.* (2014) and Ye *et al.* (2012) developed System Dynamic Models (SDM) to investigate effects of different policies on waste management strategies, such as landfilling, prevention, reuse and recycling. *Li et al.* (2014) also adopt SDM in measuring impacts of prefabrication on waste reduction. Yuan and Wang (2014) proposed a dynamic model suitable for determining cost of waste disposal in China, by integrating various waste predictive factors. Yuan *et al*. (2011) used SDM to carry out cost-benefit analysis of different waste management approaches. Similarly, Hao *et al*. (2008) developed a simulation model that established interconnection between various onsite activities, towards determining ultimate waste management strategy. Love *et al.* (2000) and Han *et al*. (2013) also applied SDM to design management. Reworks caused by design errors was modelled and simulated to unravel complex problems and interrelated factors that lead to design errors, cost overrun and time overrun.

Despite an excellent demonstration of the suitability of SDM in explaining dynamism of factors contributing to waste occurrence and strategies for its management, the set of studies failed to channel the dynamic approach in a comprehensive manner by incorporating design, procurement and construction stages. Also, its capacity to identify interconnections between waste causative factors as well as management strategies is yet to be adequately explored. Hence, to proffer a holistic construction waste management approach, there is a need for understanding dynamic relationship between all waste preventive measures at design, procurement and construction stage. This would help in proposing the design, procurement and construction strategies for waste minimisation.

Further categories of study produced toolkits and frameworks for predicting and managing project waste. These include Building Waste Assessment Score-BWAS by Ekanayake and Ofori (2004), which ranks the significance of different causes of waste. Others include NetWaste, SmartAudit, DOWTB and BREMap. These sets of tools either predict the quantity of waste or suggest strategies for managing waste after it has occurred. This means that these toolkits either provide a belated intervention or lack the strategic framework for real waste prevention. Although SmartWaste for SWMP is widely adopted in the UK construction industry, it only provides an avenue for site waste managers to plan for ways of managing their waste (Shiers *et al*., 2014); and it is based on their instinct, without any objective guides of their decision.

Thus, it is based on these gaps in knowledge and the need to provide frameworks and guide for waste-efficient projects that this study emerges. The study seeks to build on existing knowledge to integrate and develop a holistic strategy for minimising construction waste throughout project lifecycle stages. Using dynamic system approach, the study focuses on design, procurement and construction strategies for waste minimisation as well as dynamic relationship between measures taken at different stages of project delivery process.

1.4 Aim and Objectives

The overall aim of this study is to develop the design, procurement and construction strategies for minimising waste in construction projects. Apart from an investigation of the key and underlying measures for construction waste mitigation, the study examines the interrelationship between stages of projects' lifecycle, as activities carried out at an earlier stage is capable of engendering occurrences at later stages. In a bid to accomplish this aim, the following research objectives would be fulfilled.

a) To investigate Critical Success Factors (CSF) and underlying measures for engendering waste minimisation through design, materials procurement and construction processes.

b) To determine critical competencies for designing out waste from construction projects.

c) To develop an integrated and dynamic model of key strategies for preventing waste through activities at design, procurement and construction stages of project delivery process.

d) To understand the dynamic relationship and interplay among key waste preventive measures at design, procurement and construction stages.

1.5 Research Questions

In order to achieve the aim and objectives of this study, the following set of research questions would be answered:

a) Considering the whole stages of construction project delivery lifecycle, what are the key and underlying strategies for driving waste minimisation?

b) What are the competencies required for designing out waste in construction projects?

c) How do waste preventive measures at design, procurement and construction stages of project lifecycle interplay with one another?

d) What are the optimal ways of preventing and managing waste through design, procurement and construction processes?

1.6 Summary of Research Methodology

Several techniques and approaches were adopted in collecting and analysing data to fulfil the aim and objectives of this study. The study involved the use of literature review, focus group discussions and questionnaire survey for its data collection. Its data analysis involves textual interpretivism using Atlas-ti, statistical analysis with the aid of SPSS, Structural Equation Modelling through IBM AMOS and dynamic relationship evaluation using a Dynamic Modelling (SDM) tool called VENSIM. Figure 1.1 shows a methodological flow chart for the study. A sample of the questionnaire used is available in Appendix 1. Methodological approaches used in achieving each of the study's objectives are briefly explained in the following sub-sections.

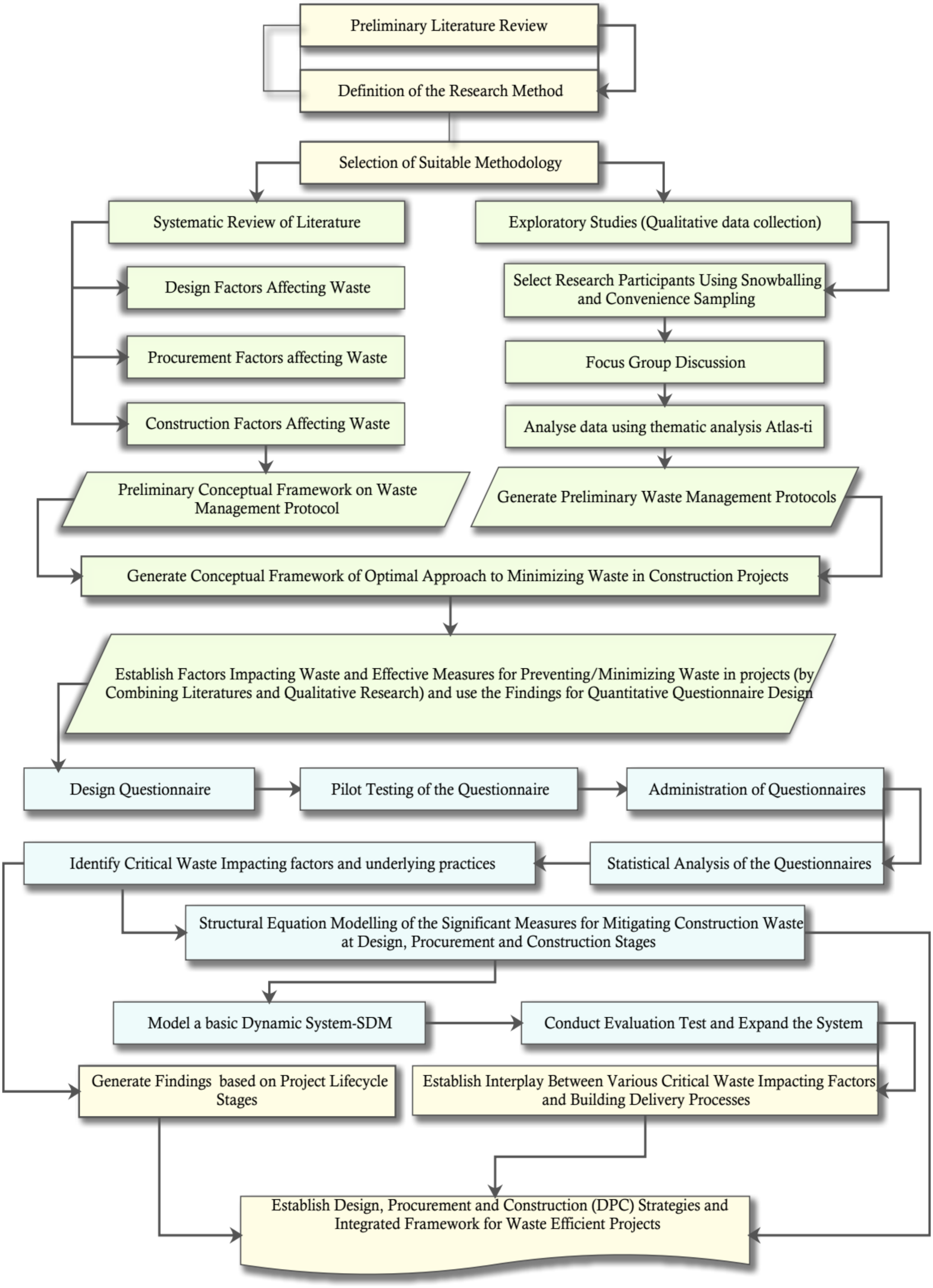


Figure 1.1: Methodological Flow for the Study

1.6.1 Methodology: Objective 1

Objective: *To investigate Critical Success Factors (CSF) and underlying measures for engendering waste minimisation through design, materials procurement and construction processes.*

To explore the design, procurement and construction measures for minimising waste generated by construction activities, two key methods were used. These include:

1) Systematic review of extant literature to determine the factors, measures and strategies that are capable of contributing to, or reducing, waste generated by construction activities
2) Due to the desire for comprehensiveness of the identified measure, focus group discussions were carried out with designers, contractors, materials suppliers, and other experts within the Architecture, Construction and Engineering (ACE) industry.
3) Using outputs of literature review and interview, a questionnaire was design, pilot-tested and administered.
4) For each of design, procurement and construction measures, descriptive statistics, reliability and multivariate analyses were carried out for the purpose of data validation and identification of CSF.
5) In order to determine the underlying measures for engendering low waste construction projects, confirmatory factor analyses were carried out with the aid of AMOS Structural Equation Modelling tools

1.6.2 Methodology: Objective 2

Objective: *To determine critical competencies for designing out waste from construction projects.*

Extant literature was thoroughly reviewed about competency frameworks and competencies required for driving low waste construction projects throughout all stages of projects lifecycle. Further exploration of the competencies was carried out through series of focus group discussions used for achieving objective one. Other methods used in achieving this specific objective are as follows:

1) Distribution of robust questionnaire designed from outputs of literature review and focus group discussions.

2) The questionnaire was then analysed with the aid of Statistical Packages for Social Scientists (SPSS) using various data screening techniques, reliability analysis and descriptive statistics.
3) Structural Equation Modelling (SEM) was used to confirm factor structure underlying the competencies for mitigating waste.

1.6.3 Methodology: Objective 3

***Objective**: To develop an integrated and dynamic model of key strategies for preventing waste through activities at design, procurement and construction stages of project delivery process.*

In order to fulfil the focus of this objectives, the identified factors were grouped into three key group based on their stage of implementation. This resulted in design, procurement and construction factors with each group having sub-groups as determined by confirmatory factor analysis. In order to understand the interplay of waste preventive measures, other steps and analyses involved are as follow:

1) Structural Equation Modelling (SEM) was carried out with AMOS. It allowed rigorous analysis to ensure that only significant factors were retained for further analysis. The SEM supplied factor weight that served as an input for flow rate in the System Dynamic Modelling (SEM) tool, VENSIM.
2) Based on the confirmatory factor analysis, dynamic relationship between all the key measures was modelled with VENSIM Structural Equation Modelling tool. This provided a graphical cause and effect diagrams, representing the interplay of various waste preventive measures.
3) Impacts and interplay of design, procurement and construction measures were simulated on one another to determine the optimal measures for mitigating construction waste.

1.6.4 Methodology: Objective 4

***Objective:** To understand the dynamic relationship and interplay among the key waste preventive measures at design, procurement and construction stages.*

As an overarching objective, this was achieved by building on previous objectives. The following steps were involved:

1. The causal loop diagram developed was converted to allow simulation and quantitative analysis of the System Dynamic Model.
2. A case study of a completed construction project was used to obtain data on the adoption rate of various construction waste management strategies and overall project waste efficiency.
3. Relationships between various elements of the model were represented through mathematical modelling, which enhances simulation of the dynamic impacts of one strategy on the other.
4. Various strategies included on the model were isolated to simulate their causal influences on the whole system. The simulation provides avenue to determine overall significant of different strategies and stages on other strategies, as well as their impacts on the overall waste efficiency of construction projects.

1.7 Unit of Study

Unit of study refers to the major entity that would be explored or analysed in a study (Hopkins, 1982). It is summarily what is examined to draw a conclusion from the study. Depending on the focus of research, the unit of analysis could be individuals, groups, organisations, projects, artefacts, geographical units, social interactions, etc. To avoid ecological fallacy which occurs when a conclusion is made on individuals based on analysis of group, or exception fallacy that occurs when group conclusion is based on exceptional individual cases, it is important that the unit of analysis is appropriately designed (Trochim, 2006).

As the purpose of this study is to investigate and develop design, procurement and construction measures for waste-efficient construction projects, the unit of study is the project that the study is aimed at improving. Although the study also seeks to investigate the designers and contractors' competencies for achieving waste efficiency, the ultimate goal of establishing the competencies is to improve projects performance with regards to waste efficiency. As such, the unit of study for this research is the projects, and all conclusions and recommendations are meant to improve projects towards reducing waste generated from projects.

1.8 Scope and Limitation

The overall goal of this study is to investigate the optimal design, procurement and construction strategies for waste-efficient projects with respect to construction industry. As such, data was collected from such stakeholders as designers, suppliers, contractors and waste management experts, among others. Meanwhile, activities of the construction industry are diverse, and it is divided into two, which are building construction and infrastructural facilities. The scope of the project is limited to building construction projects.

Within the context of LEAN, waste is studied both in terms of materials and non-materials waste such as time loss. The materials aspect of waste has been the focus of this study, and no attempt has been made to look into process waste within its context, especially as the physical waste constitutes increasing environmental impacts (Faniran and Caban, 1998). Similarly, Skoyles (1976) categorised waste as direct waste which involves complete loss of materials due to damages or other physical activities, and indirect waste which may be as a result of over thickness of building elements resulting in excessive use of materials. In this study, waste has been approached from the concept of physical waste, which has more tendency of increasing waste to landfill (Oyedele *et al*., 2013).

1.9 Significance of the Study

The UK construction activities contributes about 60% of total waste generated (Paine and Dhir, 2010), US landfill site consists of about one-third waste of construction origin (Yu *et al*., 2013), while a typical Australian landfill site has up to 44% waste from Construction Demolition and Excavation (Shen and Tam, 2002). The figures are similarly alarming in other countries. The impending problems of continuous waste landfilling are clear. While building related activities consumes about 50% of materials taken from nature, wastage of the materials results in continuous extraction, with tendency of materials depletion (Anink *et al*., 1996). Also, it is commonly known that resource excavation and waste landfilling contribute to environmental pollution (Manfredi *et al*., 2009; Huanga *et al*., 2013). Equally, waste reduction and reduced resource excavation have significant economic benefits (Coventry and Guthrie, 1998). Evidence shows that reducing construction waste by 5% could save up to £130million in the UK construction industry (BRE, 2003). It is, therefore, imperative that studies are carried out not only to find solution to managing waste after it occurred but to provide construction professionals with relevant knowledge and guidelines for preventing and minimising waste. In such case, there would be opportunity to adopt optimum technique for low waste project delivery.

The influence of this study is in two-folds, contributing to the field of practice as well as the body of literature and knowledge base of construction research. In design and construction management, the study would enhance professional practices by providing practitioners with a toolkit for understanding measures for improving waste efficiency of design, procurement and construction processes. The study provides designers, suppliers and contractor with strategies for mitigating waste; thereby enhancing waste-efficient project delivery. It would as such help in preventing economic loss and negative environmental impacts associated with construction waste.

Previous studies on waste minimisation have been carried out at unitary level while causes of waste are dynamic and multiplicity in nature (Hao et al., 2008). This study contributes to existing body of knowledge by building on existing studies, using Structural Equation and System Dynamic Modelling, to determine interplay between various waste preventive and minimisation measures.

1.10 Structure of the Thesis

This thesis consists of eleven chapters, ranging from introduction to conclusion. Chapter one sets background and justifies the needs for the study. Review of literature on both theoretical and methodological approaches to the study is presented in chapter two, three and four. In chapter five, methodological approach to the study, covering philosophy, epistemology, strategies and approaches are presented. Data collection and analytical techniques for each of Qualitative and quantitative studies are presented in Chapter six and seven respectively. Chapters eight and nine cover Structural Equation Modelling

(SEM) and System Dynamic Modelling (SDM) respectively. Findings of the study are discussed in chapter ten, while Chapter 11 provides a concluding section for the study. Figure 2 illustrates the contents of the thesis.

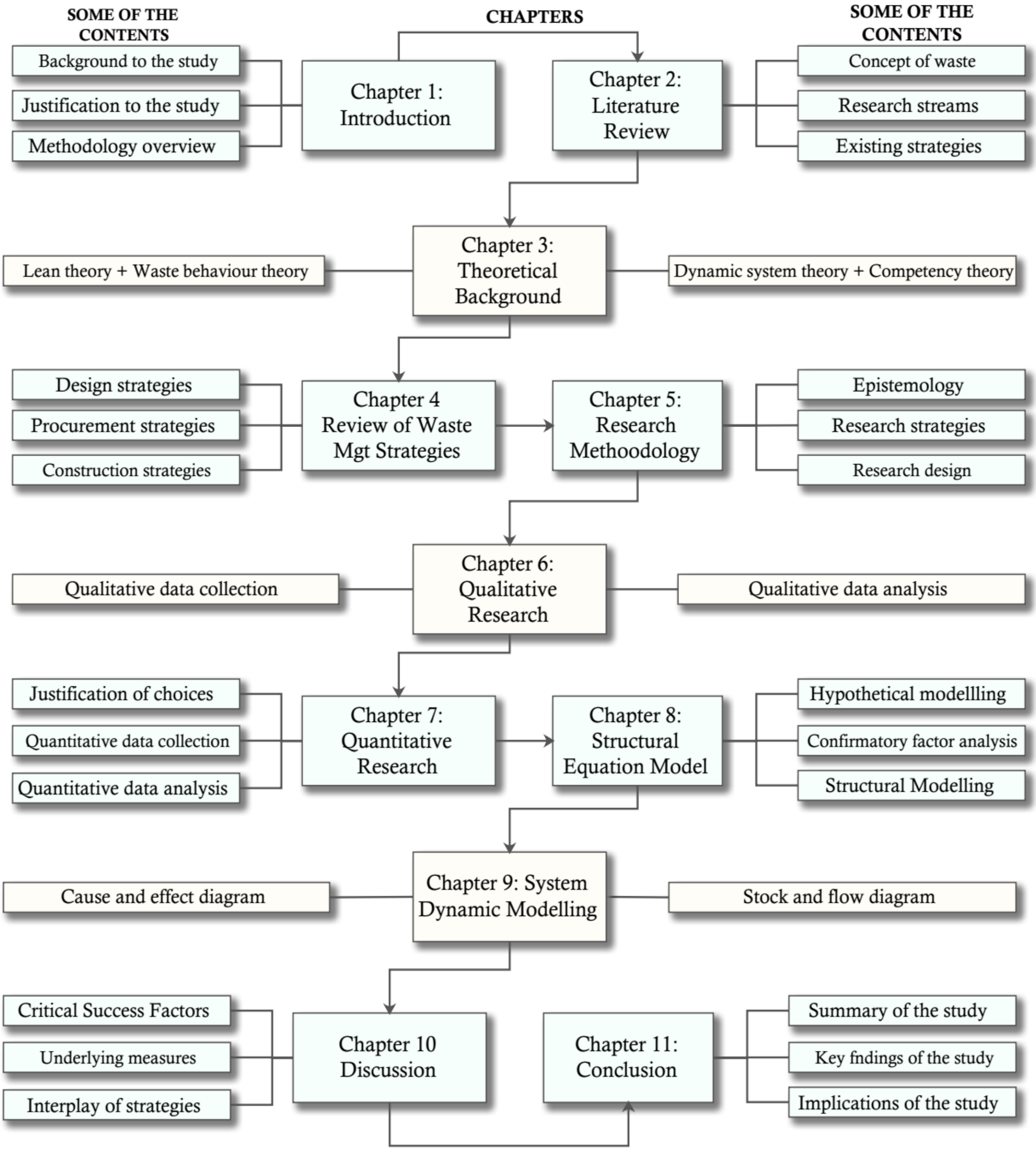


Figure 1.2: Thesis Layout

CHAPTER 2: CONSTRUCTION WASTE MANAGEMENT

2.1 Chapter Overview

Need to understand the rudiment of waste generation and management in the construction industry informed this chapter, which initially provides an overview of the global construction industry, with some bias in the UK. It then looks into impacts of the industry from economic and environmental perspectives as well as its contribution to the global development. To provide theoretical and methodological insights for the study, existing waste management studies are categorised based on the perspectives from which waste management was approached. Each of the categories is then evaluated to determine their contribution, effectiveness and weaknesses towards tackling the menace of waste in the construction industry. A critical literature review, which evaluated effectiveness of existing waste management strategies towards a holistic framework for effective waste management strategies, is then presented. It identified and critically evaluated prevailing waste management strategies and developed a requisite framework required for waste management strategies to be effective and widely adopted in the industry. This chapter forms a theoretical foundation and methodological guidelines upon which the study is built.

2.2 Overview of the Construction Industry

The construction industry is a highly fragmented project-based industry that seeks to meet demands of its customers within limited budget, resources and time-frame. The industry contributes significant portion of the global economy and employs large population across the globe. It accounts for 13% of the global economy and contributes annual amount of $12trillion, which is expected to increase to $15trillion in 2025 according to a year 2013 analysis by Global Construction Perspectives. As at the year 2008, the UK construction industry accounts for 8% of Gross Domestic Products (GDP), generating employment for over three million workers and contributing annual value of £100billion (HM Government, 2008). The output of the construction industry, such as public and private buildings, road, rail, dams and irrigation, bridges, and so on, are indispensable to the survival of other sectors and sustainability of the global economy.

The industry is large, complex and diverse, and covers a broad range of micro, small, medium-sized and large business activities, all united by their output, which are buildings or infrastructural facilities. The industry comprises of the client who funds and drives projects, the designers who produce details of what to be constructed, materials suppliers, contractors as well as the government that regulates activities of the industry.

The lifecycle of the industry's activities ranges from project briefing, through design and construction to demolition or deconstruction of the project. However, due to the diversified and dynamic nature of construction activities, designers and contractors often have to make some decisions based on incomplete information, using experience in their judgement. As the project proceeds, this sometimes results in reworks that contribute to waste generation. The industry is believed to contribute about a third of waste in EU landfill sites (Kozlovská and Spišáková, 2013). Also, recent years has witnessed increased environmental impacts of construction activities. These impacts among others include emission of toxic gases, contribution to environmental pollution, and environmental depletion that is due to its consumption of large volume of mineral resources. In a bid to minimise its waste generation as well as resulting environmental impacts, while maximising the indispensable benefits of the industry, various research efforts have gone into waste minimisation, with many still in progress.

2.3 Concept of waste and its management

Construction waste refers to materials laid unwanted onsite after the purpose for which it is acquired is met. As such, they are meant to be discarded from the site. This could range from materials purchased for different construction activities to those generated onsite, such as excavated and demolished materials. In either case, it becomes unwanted (Oyedele et al., 2013) and it is required to be discarded (European Commissions, 2008). Evidence suggests that between 1-10% of total materials purchased by weight usually end up as waste (Bossink and Brouwers 1996).

While it is arguable that increasing construction activities are indispensable to urbanisation and economic growth, there is a growing concern about environmental impacts usually associated with its waste generation. For instance, as construction waste forms substantial proportion of waste to landfill, a typical landfill site produces CO_2, which contribute to greenhouse gases and environmental pollution (Manfredi et al., 2009). Atmospheric pollution resulting from waste transportation is also no trivial. As this suggests that implementation of appropriate waste management strategy is requisite to preventing impending environmental problems, it also suggests tendencies for economic benefits owing to effective waste mitigation. This would result in savings in terms of cost of acquiring the wasted materials, cost of storage, cost of transportation and disposal and the landfill tax (Coventry and Guthrie, 1998). The precious value of land voted for landfilling is also less considered. Unfortunately, these set of hidden costs associated with material waste have been misunderstood and wrongly underestimated only as cost of disposal and landfill tax (Coventry and Guthrie, 1998). Also, the associated costs are usually being shifted to the clients who finance the projects (Guthrie et al., 1999; WRAP, 2007).

In trying to identify its sources in construction projects, waste has been categorised using varying yardsticks. Coventry et al. (2001) categorised waste into bricks, blocks and mortar, packaging, timber, metal, special waste, dry lining and other wastes. Spivey (1974) used similar classification with addition of garbage and sanitary waste. Faniran and Caban (1998) noted that Gavilan and Bernold (1994) classified waste based on their causes: design, procurement, handling, operation, residual, and others. Guthrie and Mallet (1995) went a step further to categorise waste as valuable and easily reused or recyclable, indirectly recyclable, and those that pose disposal issues, such as asbestos. Other categories have involved materials list such as asphalt, concrete, soil, tiles, bricks, and wood, among others. Nonetheless, irrespective of varying identification models, waste is usually estimated per unit weight of total materials purchased or as percentage of total cost of materials (Ekanayake and Ofori, 2004; Bossink and Brouwers 1996); thus making it always results in financial and environmental cost.

Various causes of waste ranging from design to completion have been identified across the literature. While it has been argued by several architects that waste is only caused by activities during construction (Osmani et al., 2008), evidence shows that design and scheduling remain major known causes of waste, apart from the site-based activities (Faniran and Caban, 1998). This is usually because of design related flaws and complexities, inaccurate materials scheduling and needs for design changes earlier occurring before or during site activities (Faniran and Caban, 1998; Ekanayake and Ofori, 2004; Osmani, 2012). Other causes of waste such as materials leftover from cutting, packaging, poor supply chain management, damages due to weather, poor materials handling, over-packaging, mistakes and reworks, spillage and left over, off-cuts, etc. are associated with procurement, construction operation and management, materials handling and external factors (Formoso et al., 2002; Faniran and Caban, 1998; Dainty and Brooke, 2004: Esin and Cosgun, 2007). This suggests that a holistic approach to minimise project waste is a collaborative effort among all stakeholders, and would consider the design, procurement and construction phases of project delivery process.

2.3.1 Construction Operations and Waste Management

Waste management is becoming an integral part of every project delivery process, especially in developed nations. In the UK for instance, different strategies have been adopted at various RIBA plan of work stages 0-7 comprising Strategic Definition, Preparation and Brief, Concept Design, Developed Design, Technical Design, Construction, Handover and In-Use Stages (RIBA, 2013). These set of strategies include, among others, the use of tools for prediction, development of Site Waste Management Plan (SWMP), legislative and tax measures, sorting and recycling, materials re-use and recovery, design for flexibility and deconstruction, and use of off-site construction techniques. Table 1.1 categorises existing waste management strategies based on their stages of application within 0-7stages of RIBA plan of work.

Table 2.1: Existing waste management strategies

STRATEGIES		PRE-DESIGN STAGES	DESIGN STAGES	CONSTRUCTION STAGE	POST CONSTRUCTION
		0 – 1	2 – 4	5	6 – 7
1	Sorting and Recycling			✓	
2	Reuse and Recovery			✓	✓
3	Use of Waste Prediction Tools		✓		
4	Site Waste Management Plan (SWMP)			✓	
5	Design for Flexibility and deconstruction		✓		✓
5	Off-site construction		✓	✓	
6	Waste-efficient Procurement			✓	
7	Legislative and Tax measures			✓	
8	Design for Flexibility and deconstruction		✓		✓

Meanwhile, earlier studies have identified hierarchical order through which waste could be managed. Also applied to construction industry, the waste hierarchy, shown in Figure 2.1, is a framework suggesting the order of cost effectiveness and environmental friendliness pattern through which waste is best-managed (Faniran and Caban, 1998). As such, strategies for waste management are therefore categorised as reductive measures, re-use, recycling, or in worst-case scenarios, landfilling. While strategies for waste reduction involve processes of minimising waste at source by decreasing it to the smallest possible quantity, re-use approach ensures that waste generated are reused (Faniran and Caban, 1998). This thus prevents monetary loss and energy need for further processing of the waste materials or its disposal.

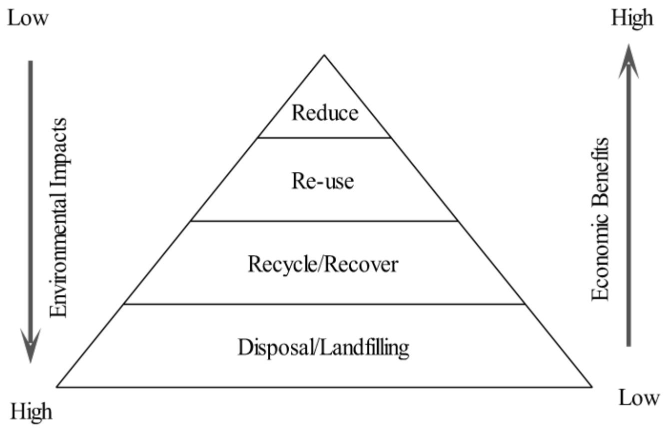


Figure 2.1: The Waste Hierarchy

Alternatively, when “reduce and re-use” become impracticable, processing of the waste materials to produce a derivative product, known as recycling, becomes the best option. Despite criticism that it also consumes a substantial amount of energy that results in environmental pollution (Chong and Hermreck, 2011; Benjamin, 2010; Saraiva et al., 2012), waste recycling reduces the need for extracting raw materials, which affects biodiversity and results in materials depletion (WRAP, 2009b). It also prevents associated energy and pollution, which occurs owing to mining and production processes (Halliday, 2008). These options are usually expected to be explored before the decision to landfill the waste. This is especially as it results in more financial loss and it is characterised by series of negative environmental impacts, asides nations running out of landfill sites (Oyedele et al., 2013).

However, rather than adopting any of the strategies depicted by the waste hierarchy, it has been reasoned that there is a possibility of preventing waste by designing it out using some set of strategies during design stages (Osmani et al., 2005; WRAP, 2007,2009a; Yuan, 2013). UK Government funded WRAP identified five waste spectrums capable of reducing waste burden of construction projects. These according to them involve design for reuse and recovery, off-site construction, deconstruction and flexibility, materials optimisation, and waste-efficient procurement (WRAP, 2009a). In buttressing their importance, Jaillon et al. (2009) and Tam et al. (2007b) argue that wastage reduction level in prefabricated building is up to 52% and 84.7% respectively. Anink et al. (1996) similarly recognised that design for de-constructability ensures building materials are re-used at the end of building lifecycle, thus preventing the need for new material extraction, recycling or landfilling. As such, reducing waste at source, using design stage approaches, is becoming more popular than other approaches captured on waste hierarchy, because it prevents waste while the latter minimises or manages waste after occurrence.

Consequently, there is increasing awareness that instead of the typical system of concentrating on site effort to reduce and manage waste during construction activities, waste minimisation should be considered throughout all stages of building process – design to completion (Ekanayake and Ofori, 2004). This becomes imperative if waste and its associated negative economic and environmental impacts were to be prevented, or in worst-case scenario, minimised. Owing to this, the design stage has become increasingly important as key starting point for studies into waste management.

2.4 Research Streams in Waste Management

Due to the growing importance of construction waste management as a means to achieve the global sustainability agenda, as well as a step towards environmental friendliness and economic benefit, a large body of literature have been dedicated to its study. These sets of studies are categorised and further discussed in this section. The intent is to analyse key findings of the previous studies and to gain methodological insights for this study. The existing body of literature on construction waste are categorised into quantification and source evaluation, waste reuse and recycling, waste minimisation/prevention, and waste prediction. Some studies carried out under each category are assiduously swotted.

2.4.1 Studies on Waste Quantification and Source Evaluation

Arguably, the first step towards problem solving is the identification of the problem as well as its causes and effects. This phenomenon was applied to waste management research when Faniran and Caban (1998) argued that before formulating effective policies and strategies for waste minimisation, there is need for detailed understanding of the factors that bring waste into being. As such, waste causative factors were identified, and they were used in questionnaires administered to groups of industry experts. Their study concluded that change in design, materials' leftover, packaging waste, design errors and damages due to weather are the major causes of waste in construction projects. Meanwhile, earlier studies have overlooked design stage as a possible stage towards waste-efficient projects. Thus the study set a background for further research.

While quantifying and evaluating sources of waste in construction projects, Bossink and Brouwers (1996) carried out case studies of five construction projects. They understood that wastes from individual materials are caused by different activities. Nonetheless, they argued that improper planning of construction activities, design errors, uncertainty in foundation depth, poor materials handling, and over-packaging are the leading causes of construction waste. While carrying out a similar study, Nagapan et al. (2012) believe that *among other thi*ngs, poor site management practices, contractors' inexperience, design flaws and reworks, inadequate planning and scheduling, and mistakes during construction are the major causes of construction waste.

Other studies also buttressed the above set of factors and corroborated the findings with series of interrelated factors (c.f. Lau et al., 2008; Al-Hajj and Hamani, 2011; Esin and Cosgun, 2007; Formoso et al., 2002; Gamage et al., 2009; Kofoworola and Gheewala, 2009). Those factors include spillage and left over, off-cuts, improper handling, poor supply chain management, inadequate storage facilities, etc. as significant causes of construction waste. The studies adopted case studies analysis, direct observation, literature review, and questionnaire survey as their approaches to determining factors contributing to waste generation. Table 2.2 below categorised and itemised waste causative factors identified in the studies.

Table 2.2: Studies on waste causative factors

Group	Causes of Construction Waste	References
Design	• Detailing Errors • Design Changes • Complexities in Design • Lack of dimensional coordination • Poor project coordination • Unclear specification • Non-standardization of spaces	Faniran & Caban, 1998; Coventry et al., 2001; Ekanayake & Ofori, 2004; Bossink & Brouwers, 1996; Polat & Ballard, 2004; Garas et al., 2001; Gamage et al., 2009.
Procurement	• Ordering Errors • Left Over Due to Over Estimation • Packaging Materials • Incorrect quantity estimation • Use of low-quality materials	Faniran&Caban, 1998; Greenwood, 2003; Gavilan&Bernold, 1994; Lu et al., 2011; Wang et al., 2008; Gamage et al., 2009; Esin and Cosgun, 2007.
Construction Operation/ Project Management	• Reworks Due to Errors • Improper project planning • Poor workmanship • Leftover from cutting and shaping • Poor site conditions • Poor supervision • Materials off-cuts • Inadequate knowledge	Tam et al., 2007a; Poon et al., 2004; Formoso et al., 2002; Bossink &Brouwers, 1996; Wahab&Lawal, 2011; Kofoworola &Gheewala, 2009.
Handling	• Poor Materials Storage • Poor Materials Handling	Kofoworola&Gheewala, 2009; Lau et al., 2008; Lu et al., 2011.
External	• Damages Due to Weather • Accident • Theft and Vandalism	Faniran&Caban, 1998; Senaratne& Wijesiri, 2011; Bossink &Brouwers, 1996.

Based on the identified factors, the table shows that total waste generation in construction project is caused by series of inter-related factors ranging from design stage, through materials procurement, to the actual construction stage. Although the actual waste is generated on-site during construction activities, some preliminary factors contributing to it have been identified. This further suggests that holistic efforts towards waste minimisation would not look at causes of waste at unitary level. There is need for understanding the dynamic relationship between various causes and effects of waste in order to generate a holistic model for its minimisation (Esin and Cosgun, 2007; Hao et al., 2008). Figure 2.2 below depicts interplay between various causes of waste in construction.

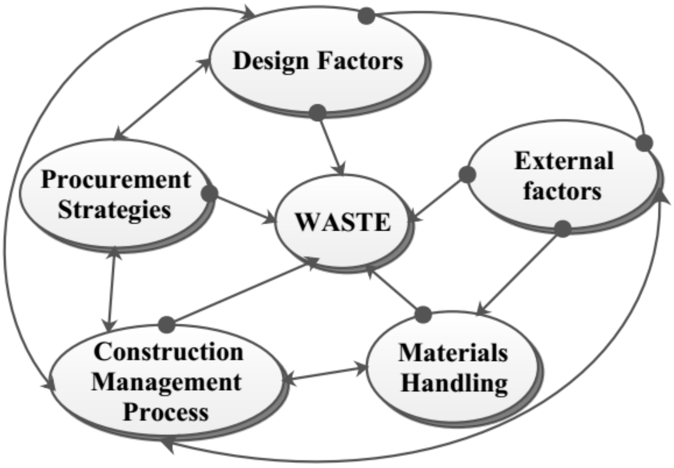


Figure 2.2: Interplay of Waste Causative Factors Categories

Notwithstanding the overall benefits of the studies towards identifying waste causative factors, they have mostly left out strategies for minimising the waste. Although it is crucial to understand the causes of problems before embarking on strategies for solving such problems, the series of studies failed to propose agenda for rectifying the problems identified. Also, Yuan et al. (2012) argue that existing studies have only identified the waste causative factors at unitary level while there is a dynamic interplay between factors that resulted in waste.

2.4.2 Studies on Waste Reuse and Recycling

In construction management, some schools of thought believe that waste could not be eradicated. As such, solutions were proffered to waste after it occurred so as to reduce burden on landfill site, thus moving down to lower part of the waste hierarchy (see figure 2.1). Several research efforts have been made in this perspective, by concentrating on reuse and recycling of waste generated. Examples of such studies include Medina et al. (2014), Oyedele et al. (2013), Chick and Micklethwaite (2004), Bolden et al. (2013), Dunster (2012), Cavalline and Weggel (2013), Dolan et al. (1999), and Chen et al. (2003), among others. While recycled products refer to those materials that are processed to produce a derivative material in such a way that their physical and/or chemical properties are altered, a material is reused with little or no alteration to its present form, and usually without change to its chemical properties (Guthrie and Mallet, 1995; Ho and Choi, 2012).

Apart from the fact that these set of studies provide end of pipe treatment for waste, the quality of recycled materials has been a subject of controversial literature. According to Medina et al. (2014), while some studies (such as Yang and Kim, 2005; Mefteh et al., 2013; Etxeberria et al., 2007) claim that the quality of concrete reduces with increasing recycled concrete aggregate, others (e.g. Yang et al., 2011; Thomas et al. 2013) argue that the quality of concrete remains unaffected as a result of recycled aggregate. Additionally, waste recycling has done little or no favour to the environment until the recycled materials are used in further activities. However, existing practices suggest that there has been a slow development of recycled materials market (Mansikkasalo et al., 2014). This is because; apart from no guaranteed market and standard specifications for recycled products, designers feel that it requires additional time to source for the products (WRAP, 2010).

2.4.3 Studies on Waste Minimisation and Prevention

Another area through which waste management has been investigated is through minimisation and preventive measures. This category of studies is based on the philosophy that the best approach to waste management is through preventive and minimisation strategies. The studies suggest that instead of conventional industry practices which concentrate on efforts to manage waste after it is generated; there is tendency of designing out waste during design stage or using some waste-efficient strategies during procurement and construction stages (Faniran and Caban, 1998; WRAP, 2007, 2009a; Yuan, 2013). Based on this paradigm, the UK government’s funded WRAP identified five spectrums through which waste could be effectively designed out. These include design for reuse and recovery, design for offsite construction, design for deconstruction and flexibility, design for materials optimisation, and design for waste-efficient procurement (WRAP, 2009a).

Other waste preventive measures identified in the literature include Just-in-Time (JIT) mode of materials delivery, reduction in materials packaging (Dainty and Brookes, 2004), modular design, and dimensional coordination of design elements (Formoso et al., 2002). According to Esin and Cosgun (2007), the most effective means of reducing environmental impacts of waste is using waste preventive measures. This would reduce the need for materials reuse, recycling and waste disposal thus resulting in more economic and environmental benefits. Although several stones remain unturned towards minimising waste in construction projects, series of studies carried out within this perspective offer promising approach to tackling construction waste.

2.4.4 Studies on Waste Prediction

One of the approaches through which construction waste have been investigated is from predictive perspective. Evidence shows that the best attempt to mitigate waste in construction projects is those made at early stages (Poon, 2007). Chen and Chang (2000) argue that both planning and design of effective solid waste management system require adequate prediction of likely waste from different sources. As such, this category of study attempted to furnish the industry with tools and techniques for predicting likely waste from projects so that preventive measures could be taken to reduce it.

Produced by the UK Building Research Establishment (BRE), SMARTWaste is a product of one of such research efforts towards waste prediction. The study was based on data gathered from previous construction projects, and it estimates and predicts likely waste from projects in 13 categories. The SMART Waste is an online waste management tool that obtains certain information about proposed projects and predicts possible waste from such project based on its statistically rich database. It has been widely used in the UK construction industry. Solís-Guzmán et al. (2009) also produced a Spanish model based on Andalusian Construction Cost Database. Enriched with data from 100 construction projects, the model is designed to predict likely waste from projects up to 10 floors. Poon et al. (2001) similarly produced a waste index that predicts the amount of waste (in volume or weight) generated per m^2 of Gross Floor Area (GFA).

Although criticised due to its involvement of manual input, Jalali (2007) proposed “Component Index” and “Global Index”. The former predicts likely waste per square metre of project floor area based on data from multiple projects across the globe, while the latter estimates possible waste from projects based on types and quantity of each component used in the project. The set of studies offers different approaches to waste prediction, and furnished industry practitioners with baseline waste expected from their projects. However, the studies lack platform and guideline for waste minimisation, which could have improved their ingenuity. Again, manual input of design data and incompatibility with design tools questions the success of studies in this perspective.

2.4.5 BIM-Based Waste Management Studies

Building Information Modelling (BIM) is an emerging technology that is revolutionising the global construction industry. The use of BIM is becoming the standard design and simulation platform in the construction industry, using Industry Foundation Class (IFC) as interoperability platform (Porter et al., 2014). Although less effort has been made to incorporate waste minimisation into existing BIM tools and platform such as Revit, Micro station, ArchiCAD, and Tekla, attempt has been made to develop BIM tools for waste estimation. For instance, Cheng and Ma (2013) developed a BIM solution capable of extracting building materials and volume information for detailed waste estimation and planning. Despite the study aiming at the use of the BIM solution for predicting cost of waste disposal, it establishes the tendency for manipulating material ontology of the existing BIM tools or developing BIM-interoperable tools for waste minimisation functions. As the wind of BIM adoption continuously blows in the industry, it is expected that more research attention is focussed on the use of BIM technology for waste minimisation.

2.5 Review of Strategies for Diverting Waste from Landfill

Although studies by Shen and Tam (2002) and Oyedele et al. (2013) suggest that waste management strategies receive less attention than cost and project duration, different waste management strategies have been adopted in the industry over the years. This is probably influenced by increasing stringency of government fiscal and legislative measures aiming at reducing total amount of waste to landfill. In this section, existing strategies for diverting construction waste from landfill sites were reviewed. The overall approach used in the section is a critical review and analysis of existing literature on strategies for diverting waste from landfill. The existing waste strategies were grouped under eight categories with each having its shortcomings. These sets of strategies, depicted in Figure 2.3, are evaluated for waste mitigation capacity, environmental friendliness and economic benefits, among others.

2.5.1 Sorting and Recycling

Waste recycling has been widely adopted in many industries, among which the construction industry is not left out. This strategy has been recognised as the next line of action in a bid to prevent waste landfilling, the oldest and most environmentally harmful form of waste treatment (Manfredi et al., 2009). Recycling is one of the strategies adoptable after waste has occurred and it involves sorting of the waste materials into "recyclable and non-recyclables" during the construction activities or at the recycling site (Barros et al., 1998). The option of site sorting has been widely encouraged across the UK, as it eases recycling operations and ensures accurate separation of inert and non-inert materials (Poon et al., 2001). The strategy is not necessarily an approach for reducing waste in construction activities, but it proves valuable due to its tendency to divert waste from landfill sites. Also, recycling as a waste management strategy ensures that waste materials are reprocessed to produce derivative materials, thereby preventing the need for the use of virgin materials for materials production. This thus saves the environment from pollution due to materials excavation, transportation and processing (Davidson, 2011; Treolar et al., 2003).

Peng et al. (1997) argue that substantial recycling operation, with respect to construction waste, has helped communities in freeing up large spaces in their landfill sites as construction and demolition usually generate significant waste. Corsten et al. (2013)

believe that an efficient recycling operation saves an additional annual emission of 2.3MtCO_2 in Netherland. A typical Japanese building constructed of recycled materials would save at least 10% of energy need according to Gao et al. (2001). Other benefits in forms of job creation and economic gains are also claimed to the credit of recycling as a strategy for waste management. However, several pre-requisites are critical to the success of recycling operation. A substantially large area of land of not less than 0.8 hectares, easily accessible site, experienced recycling specialists as well proper recycling equipment such as screeners, crushers and wind-sifting are expected of a typical recycling site (Peng et al., 1997).

Nonetheless, as a strategy for waste management, waste recycling has some factors to its detriments. Its need of energy for transporting the waste to recycling yard as well as for recycling operation means that although physical waste is managed, CO_2 and other hazardous emissions are produced (Saraiva et al., 2012; Chong and Hermreck, 2011). Also, apart from the fact that waste recycling is only a means of treating waste after it occurred, preference of time and cost over environmental policies (Oyedele et al., 2013) among construction operatives suggest that recycling strategies could not be seen as a holistic strategy for waste management in the industry. This is because, successful recycling operation requires dedicated sorting arrangement which required cost, time, site space, labour and dedication, while typical sorting process interferes with other site operations (Teo and Loosemore, 2001; Poon et al., 2001). Also, some materials such as windowpanes, excavated soil, insulation materials, etc. remain mostly unrecyclable due to their compositions, making recycling inadequate strategy for managing them.

Consequently, while waste recycling has been helpful in diverting substantial volume of waste from landfill sites (Oyedele et al., 2013), more holistic efforts is required in adequately managing construction waste in manners devoid of environmental negativity, process delay, economic loss, and with ease of practice and general applicability.

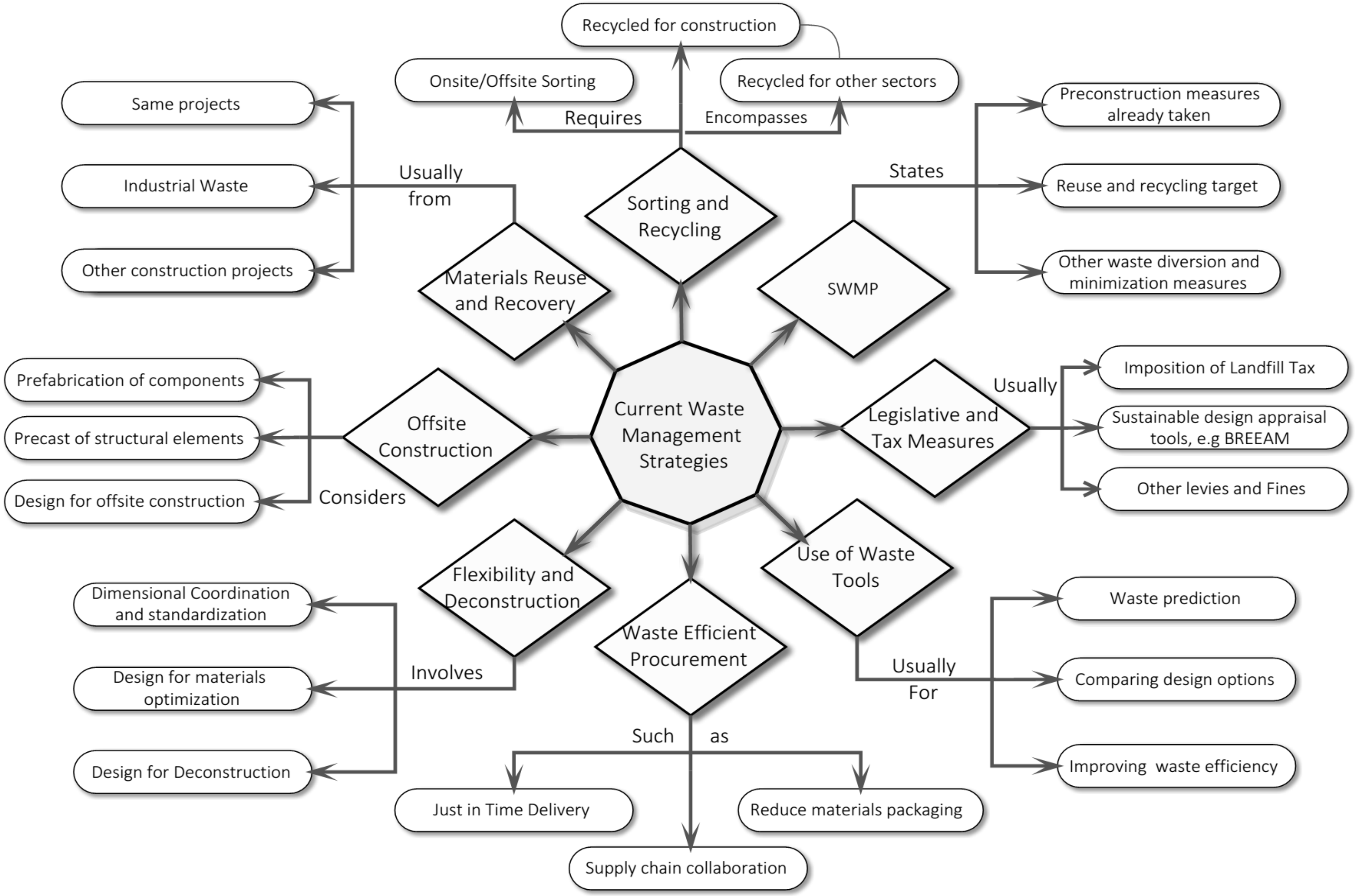


Figure 2.3: Existing Waste Management Strategies

2.5.2 Materials Re-Use

Materials reuse is an essential approach to diverting waste from landfill sites. Unlike recycling, materials reuse involves use of the materials with little or no alteration to its physical state, and without any change to its chemical constituents (Guthrie and Mallet, 1995). In the Construction industry, material re-use has been adopted as a means of diverting own waste as well as other forms of waste from landfill. Construction demolition materials have been widely reused for land reclamation, road surfacing, and as constituents of concrete aggregates. Coal fly ash is also a valuable material, of industrial origin, being used to replace percentages of cement in concrete mix and rendering materials (Halliday, 2008). Materials leftover, off-cuts, excavated soil, etc., generated from construction sites are also being used in projects.

Materials reuse is seen as a better alternative to recycling as the waste finds places in projects. However, while certain waste materials are reusable without further processing, many others require different forms of processing, crushing, washing and transportation. Although it substantially reduces pollution compared to recycling and landfilling as waste management strategies, waste reuse sometimes involves environmental pollution, apart from being an attempt to manage waste after occurrence rather than preventing it in the first place. Asides, different materials have its lifecycle, and a material tends to become non-reusable after certain numbers of use. While certain off-cuts are reusable, some are too small to find place in further construction, resulting in landfilling. Time constraints in projects could also mean that operators would rather use new materials to save time than combining pieces of reusable materials, especially as they usually see waste as unavoidable problems of managers (Teo and Loosemore, 2001). As such, concentrating on waste reuse as waste management approach could only prevent some quantities of waste from being landfilled or recycled, and it does not necessarily tackle waste at all-inclusive level.

2.5.3 Use of Waste Prediction Tools

In order to manage waste effectively in construction projects, different means of measuring and predicting possible project waste have emerged in the industry. It involves the use of various tools, usually at the design stage, to predict potential waste arising from the construction process. NetWaste is one of the most popular tools used in the UK for waste prediction. It assists designers in estimating the cost and quantities of waste from the project and helps in selecting a suitable strategy for improving waste effectiveness of the project (WRAP, 2008). Developed by the UK WRAP, NetWaste collects necessary project information such as building volume and materials types to perform its waste evaluative function. Design-Out Waste Tools for Building/Civil Engineers, DOWT-B/DOWT-CE are other tools developed by the same body for identifying the potentials for designing out waste and recording design solution for waste mitigation. It also helps in calculating the impacts of such solution and comparing impacts of different design alternatives for building and civil engineering projects (WRAP, 2010).

Other tools and approaches have been used for projecting construction waste outside the UK. A Spanish model for waste prediction was developed by Solís-Guzmán et al. (2009) based on data from 100 construction projects. Components and Global Index measuring waste per square metre and material types respectively were proposed by Jalali (2007). A Singaporean Model for waste score determination, BWAS, was also developed by Ekanayake and Ofori (2004). BWAS was developed for comparing different design scenarios for their waste effectiveness so that adequate mitigation strategies could be taken. These set of tools are employed during the concept and developed design stages of building delivery process.

The consensus that waste is best addressed at design stage where the cost of change is minimal points to the fact that these set of strategies have adequately contributed towards construction waste management (Faniran and Caban, 1998; Ekanayake and Ofori, 2004; Osmani, 2012). They help in projecting likely quantity of waste, and sometimes their causes so that the industry practitioners would act towards minimising the waste by using alternative design, or plan for waste reuse and recycling. However, apart from the fact that some of the tools in use only predict likely waste without information about their likely causes and predictive measures, the tools work based on manual input of project information. This, therefore, means that they heavily rely on the accuracy of the input data. Also, accuracy of data input becomes challenging when buildings combine multiple shapes in its form. This suggests that as this strategy proves requisite to effective waste minimisation at source, more efforts is needed to improve mode of capturing building information.

2.5.4 Site Waste Management Planning (SWMP)

SWMP is a legislative requirement for construction activities in many nations. In the UK for instance, a legislative framework, SWMP regulation (2008), required every project above £300,000 to produce SWMP before actual construction activities. Every maintenance, demolition, excavation, alteration, civil engineering project and decoration above the amount was required to provide SWMP before the regulation was repealed in December 2013. Until date, industry professionals are still expected to produce voluntary SWMP for effective waste management, or as a means of ensuring compliance with green certifications such as BREEAM. Similarly, in Hong Kong, Site Waste Plan was introduced to the construction industry in 2003. It has however received negative feedback from industry practitioners, as it is believed to reduce productivity (Tam, 2008). Waste Management Plan has also become an essential requirement for planning approval of significant projects in Australia (Hardie et al., 2007).

A typical SWMP involves statement of pre-construction strategies previously taken to ensure waste minimisation as well as detail statement of proposed strategies for waste management during and after construction activities. The SWMP is typically aimed to set waste diversion target, avoid flying tipping, ensure proper waste auditing and segregation, improve efficiency and profitability, and to ensure that adequate measure is taken for waste reduction, reuse and recycling. Usually prepared and managed by site waste managers, the plan proposes the proportion of waste to be reused and recycled, onsite area for waste storage, methods for waste sorting and reduction as well as the stakeholders that would be responsible for waste removal from site (Tam, 2008; McGrath, 2001; Mcdonald and Smithers, 1998).

However, industry practices suggest that rather than adopting SWMP as a holistic plan of diverting waste from landfill, the plan has been viewed as a means of imposing financial burden on the industry (Tam, 2008). In the UK for instance, the SWMP was being prepared as part of legal requirements without adequate measures of implementation. This means that rather than the plan helping in waste reduction; it has been used only to fulfil legal requirements and to attain required BREEAM points in some projects. This again was influenced by the general industry belief that waste minimisation is costlier than waste generation. It is held that waste sorting does not only requires substantial space on site, but it also affects project delivery time, requires many waste skips with its planning requiring additional employees. As the SWMP is perceived as an undue legal imposition before it was repealed in the UK, industry practices suggest that well-meant strategy for waste management would not only go beyond SWMP, it would be easily implementable and devoid of additional financial expenses and time consumption.

2.5.5 Design for Flexibility and Deconstruction

One of the proven approaches to construction waste management is to design the building for flexibility and deconstruction. A design is flexible if it can adapt to both external and internal change. This occurs when a design is optimised to the industry's standard so that its materials could be easily removed and reused at the end of its lifecycle. During design, the elements of the building system are usually coordinated and standardised, preventing waste due to offcuts which is one of the major causes of waste in projects (Formoso et al., 2002). Industry practices submit that change is less costly at pre-construction stages, thus suggesting that dimensional coordination, as a design stage strategy, is a useful precautionary measure to ensuring waste prevention during construction activities. It is clear that while materials reuse and recycling seek to manage waste after it occurred, design coordination offers preventive measures which are both environmentally and financially preferable. As such, standardising design for waste efficiency through dimensional coordination tends to be a promising strategy for waste management when combined with construction stage strategies.

Demolition waste contributes a significant proportion of construction waste. A holistic attempt to reduce end of life waste is through the consideration of deconstruction during the design stage (WRAP, 2009a). Deconstruction differs from demolition in that while the former involves careful dismantling of the building components in such a way that large proportion of the materials and components supports reuse and recycling, the latter usually lacks consideration for primary reuse of the building components. Adequate planning for the buildings' end of life, by considering deconstruction, would ensure that a significant proportion of the materials and components is reused, thereby diverting a substantial portion of demolition waste from landfill. Nevertheless, apart from the claim that design for deconstruction requires careful planning and additional time consumption on the part of the designers (Durmus and Gur, 2011); deconstruction is about 17-25% more expensive than demolition (Dantata et al., 2005).

2.5.6 Waste-efficient Procurement

Procurement stage is a vital stage for waste management planning in construction projects. Several causes of construction waste such as packaging materials, double handling, and inappropriate materials storage are all associated with procurement stage (Formoso et al., 2002). Owing to this, different strategies have been used to ensure waste-efficient procurement in the construction industry, this among others include Just in Time delivery (JIT), reduced packaging and improved collaboration between the supply chains.

Introduced by Toyota in 1987 as a means of shifting from estimation to demand driven production, JIT has been applied to the construction industry with various forms of alteration owing to the complexity and uncertainty that characterised the industry (Ballard and Howell, 1997). It ensures that materials are delivered to the site in batches when they are needed, thereby reducing the length of time the materials are stored as well as eliminating the likelihood of over-ordering and double handling that could result in breakages (Dainty and Brooke, 2004). However, despite the tendency of JIT for waste reduction, the strategy has been criticised from environmental and financial perspectives. It is believed that delivering materials on a minimum-maximum inventory basis, known as pull system, as against just in time, would help in saving the cost of transportation and reduce burning of fossil fuel which in turns result in environmental pollution.

Although reduced packaging is a means of reducing waste due to materials procurement, it also poses a threat of materials breakage. This suggests that a proper balance needs to be reached between packaging reduction and adequate packaging, especially in a case of fragile materials. Meanwhile, as procurement strategy, improved collaboration between the supply chains has been encouraged as means of waste reduction in construction projects (Dainty and Brooke, 2004). Its call for an enhanced alliance between designers, suppliers, recycling companies and other stakeholders would help in excluding design errors that would have resulted into over-ordering.

2.5.7 Off-site Construction

Some design and construction techniques are identified as means of reducing waste generation in the industry; these include prefabrication and off-site construction (Tam et al., 2005; Jaillon et al., 2009; Lu and Yuan, 2013a). Although it is noted that such technique as the use of precast materials might not be purposely done for waste reduction, evidence shows that they are very efficient for waste reduction. Jaillon et al. (2009) and Tam et al. (2007b) suggests that waste minimisation tendency of prefabrication construction is up to 52% and 84.7% respectively. This means that building elements are manufactured offsite, assembled onsite, while several factors that cause waste such as materials handling, poor storage as well as design changes have been entirely prevented. However, although prefabrication reduces waste and ensures timely delivery, a financial premium is paid for it, as it could be more slightly expensive than in-situ construction (Jaillon and Poon, 2009).

2.5.8 Legislative and Tax Measures

Various legislative and tax measures have been imposed by governments towards diverting waste from landfill. One of such measures is the "Pay as You Throw", which is a polluter pays principle through which governments have diverted substantial volume of waste from landfill across many nations. PAYT is a unit based pricing through which charges is paid per unit volume or weight of all waste disposed on a landfill site, with the ultimate aim of discouraging waste landfilling and encouraging waste reduction, reuse and recycling. Before the adoption of variable landfill tax, other landfill penalties have been imposed without success. In the US for example, a fixed billing that does not vary with the quantity of waste have been used. However, it did not show a significant reduction in waste compared to the PAYT scheme (Skumatz, 2008). Evidence from other countries such as Greece, Sweden, Canada, Netherland, Switzerland, and the UK show that PAYT scheme substantially reduces the burden on landfill sites (Dahlén and Lagerkvist, 2010; Browna and Johnstone, 2014; Morris, 1999).

The variable landfill tax, PAYT, has been used to inculcate reuse and recycling attitudes in construction professionals. In the UK for instance, cost per tonnage of waste disposed has continuously been upwardly reviewed since it was imposed in 1996, up from £7 and

£2 in 1996 (Read et al., 1997), to £84.4 and £2.65 in 2016 per unit tonnage of active and inert waste respectively. This has made the industry have a rethink of how waste is managed, particularly since financial gains determine the industry's commitment to any waste management strategy (Al-Hajj and Hamani, 2008). As such, most construction firms have formed an alliance with recycling and waste disposal companies who help in segregating and processing waste to divert a substantial portion from landfill sites.

Meanwhile, apart from landfill tax that is aimed at reducing waste to landfill, other legislative measures have raised the construction industry’s awareness about waste management. These are not necessarily in forms of strategies, but they have helped in reducing construction waste. Aggregate Levy introduced in 2001 by the UK government imposes a levy of £1.60, up by £0.4 to £2 per tonne since 2009. It was aimed at reducing consumption of virgin aggregates thereby encouraging reuse of recycled aggregates. The increasing use of recycled concrete could be claimed to the success of the aggregate levy.

Similarly, sustainable design appraisal tools such as BREEAM and Codes for Sustainable Homes in the UK and LEED in the US play parts towards waste diversion from landfill sites. Different points are allocated for various sustainable building practices, among which waste management is considered. The tools have driven sustainable design activities within the construction industry as minimum standards are set for building design approval and commencement of construction activities. Also, acquisition of “outstanding” BREEAM rating or “platinum” level in the case of LEED has become a means of competitive advantages for businesses occupying the buildings as well as professionals in charge of the projects. Although, higher rank could be achieved by concentrating on other sustainable design and construction practices, consideration of waste management in such tools has engendered effective waste management.

2.6 Framework for Effective Waste Management Strategies

After analysing the existing waste management strategies, it is clear that each of the strategies has its strengths and weaknesses, which could be improved by using one to corroborate the other and by building on their weaknesses. Based on the review and analysis, a requisite framework of future construction waste management strategy is produced and discussed in this section (See Figure 2.4). The framework does not necessarily propose strategies for waste management. Rather, it postulates necessary requisite factors that must be considered in waste management strategies to ensure the effectiveness of such strategies.

2.6.1 Multi-dimensional Holistic Solutions

Project delivery activities are in such a way that steps taken at one stage would affect other stages. For instance, an error made during design or scheduling would affect construction accuracy, while a delay at one stage would as well affects other stages of the delivery processes. However, despite interrelationship and interdependence of the activities, most existing waste management strategies consider waste at unitary level while its causes and impacts are dynamic (Yuan et al., 2012). This advocate that multi-dimensional holistic efforts to tackle waste in construction would not only consider the dynamic interplay between different causes and impacts of waste, but it would also suggest the relative effects of adopting one strategy over the other. Put simply, for a waste management strategy to be effective in tackling the enigma of construction waste at both economic and environmental level; there is a need for holistic evaluation of what brings the waste about, using a dynamic and interdependent approach. It is also expected that such solutions provide feedback loops that help practitioners to understand how their strategies have reduced waste and enhance profits, thus helping them in benchmarking one approach against others.

2.6.2 Whole-life Consideration

Causes of waste have been linked to all stages of project delivery process, ranging from design to completion. Although the real waste is generated onsite during construction activities, various pre-construction operations such as design errors, scheduling mistakes, lack of dimensional coordination, etc. have been pointed out as major causes of waste (Faniran and Caban, 1998; Ekanayake and Ofori, 2003; Coventry et al., 2001). However, existing practices show that different strategies are adopted at various stages of building delivery activities. For instance, waste management tools such as WRAP NetWaste are used for waste predictive measures at design stage without the capability to assist onsite during construction activities. Existing site waste management tools such as the US

"Waste Spec" and the UK "Smart Waste" only consider onsite waste, suggesting inadequacy of current solutions in tackling preconstruction causes of waste.

The dynamism of construction activities and increasing collaborative efforts between designers, suppliers and contractor, suggests the need for a holistic strategy that would consider not only all stages of project delivery but also provides guidelines for deconstruction at the project’s end of life. By so doing, it would mean that waste contributing factors have been prevented during preconstruction activities while frameworks for managing construction and post-construction waste are also set. As such, future waste management solution is not only expected to consider all stages, its capability to predict, monitor and prevent waste is expected to be built on most present-day waste management strategies which proffer solutions after waste has occurred.

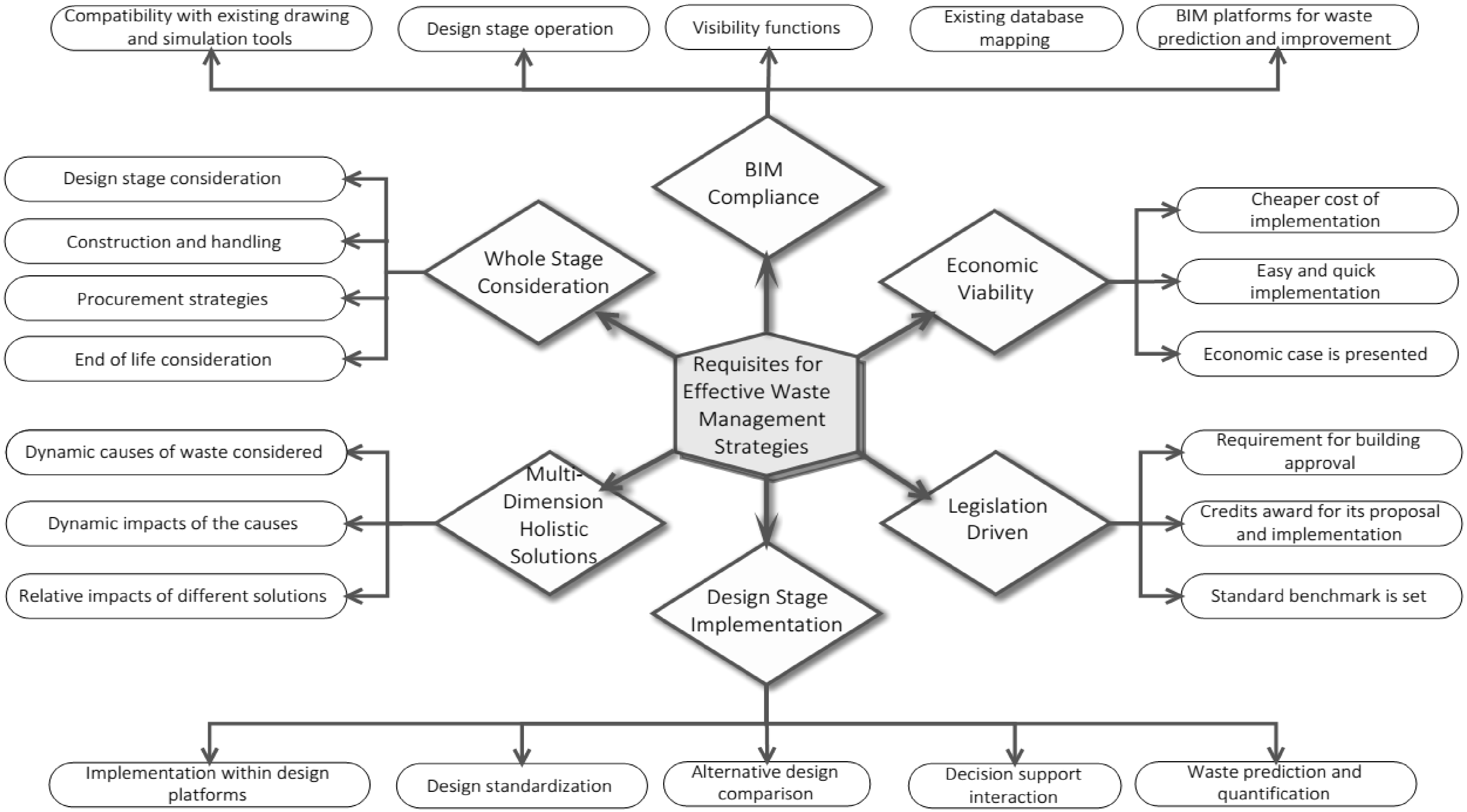


Figure 2.4: A Framework of Requisites for Effective Waste Management Strategies

2.6.3 Building Information Modelling Compliance

The adoption of BIM is becoming commonplace within the construction industry, not only because of its collaborative facilities but also because of the industry's shifts towards its adoption, as influenced by governments' leads. BIM is a technologically enhanced approach that heightens digital representation, storage, management and sharing of building information in a way that allows access to the projects database throughout its lifecycle. The process aspects of BIM give it more popularity than its software technology (Eadie et al., 2013), and its ingenuity is based on its ability to generate adequately coordinated project information that augments information management and collaboration (Race, 2012; Eastman et al., 2011). BIM tools have become standard design and simulation platform in the construction industry.

Meanwhile, the primary challenge of existing waste management tools, such as NetWaste in the UK, is the manual input of project geometry and lack of compatibility with basic design tools. These result in extra efforts to predict and prevent design-related causes of waste. Owing to this, future waste management tools are expected to be BIM compliant as the industry practices shift towards full BIM adoption. Such tools are expected to provide a framework of operation within BIM design platform and compatibility with several other BIM tools for other design related functions. This would ensure that waste prediction and prevention simulation is easily practised as an integral part of building design. Equally, to ensure efficient waste prediction and prevention as well as its broad adoption within the industry, such tool would automatically map its material database with existing BIM database. Its ability to determine the likely waste output of each design portion and alternative design options would establish its environmental and economic benefits.

2.6.4 Economic Viability

Industry practices suggest that the primary driver for adopting waste management strategy is the financial cases it could present. Al-Hajj and Hamani (2011) and Oyedele et al. (2013) suggest that contractors are more likely to adopt waste minimisation strategy if its implementation results in more financial gains than leaving waste to occur. Tam (2008) claims that waste management planning is less adopted in Hong Kong construction industry as it is believed to reduce productivity rather than increasing profit.

Industry practices also show that contractors compare cost of waste minimisation to cost of waste landfilling, thereby adopting cheaper option for each project. This means that for the industry to implement waste management strategies, its economic cases has to be appealing. As such, for any waste management strategy to be adequately adopted and effectively used, such strategy would not only be easily implementable, it must have a cheaper cost of implementation, which presents more financial gains than the cost of waste disposal.

2.6.5 Legislation Driven

One of the major factors that shape the construction industry is the national and regional legislation. By its nature, the construction industry is one of the mostly regulated industries. As planning approval is required before any physical construction activities, it means that the project has to fall within the framework provided by the legislation. In the UK construction industry, for example, compliance with the provision of Code for Sustainable Homes was a requirement for all residential building construction. This had driven sustainable building practices as the code became more stringent before its provision was incorporated into building regulations in 2015. Before the compulsory SWMP was repealed (in December 2013), it has been the industry's standard to prepare and monitor detailed SWMP for all projects above £300,000. These practices suggest relevant impacts of legislation in driving sustainable practices within the construction industry.

However, Osmani (2012) argues that waste management legislation has been practically non-existing with respect to design stage, despite the understanding that some causes of waste are design related (Faniran and Caban, 1998). Equally, although the repealed UK Site Waste Management Regulation (2008) required detailed SWMP, no benchmark was set for minimum waste per unit area of projects, thus making it difficult to evaluate the success of construction projects in waste management. As the legislation continuously drives waste management strategy, it is expected that minimum benchmark is set for projects, while the waste preventive standard is also set for design stage.

2.6.6 Design Stage Implementation

Design stage is a very crucial point for waste preventive measures in construction activities. It is no news that change is cheaper at design stage when there would be no need for any reworks that would have otherwise led to materials and time wastage. Osmani (2012) noted that according to Innes (2004), about 33% of construction waste occurs because of design-related factors. This implies that attempts to tackle waste at design stage would result in substantial reduction in waste. UK government funded WRAP also claims that waste could be designed out in construction projects using some set of tactics known as waste spectrums.

Waste management strategy is expected to be implementable at early design stage where designers would have the best opportunity to optimise their design and compare different design alternatives for waste efficiency. Existing waste minimisation strategies at design stage only allows waste prediction on a platform external to design tools, with many of the tools lacking functionality for decision support waste reduction measures. A platform that allows waste prediction and benchmarking, design optimisation and tendency for setting waste target in user interactive and decision support manner could adequately assist in achieving waste reduction goals for construction projects.

2.7 Chapter Summary

Construction industry contributes significant portion of the global economy and employs large population across the globe. The industry’s outputs, in terms of building and infrastructural facilities, are indispensable to sustainable development of global economy. However, due to the complex nature and multifarious level of typical construction activity, the industry is a major producer of waste to landfill. Also, construction activities consume excessive mineral resources. Thus, reduction of materials consumption and waste generated by construction activities is indispensable to environmental sustainability. Also, evidence also shows that reducing construction waste could substantially reduce project cost.

Owing to the need to manage construction waste, several fiscal and legislative provisions as well as various research efforts have been made. Research streams in construction waste management include waste quantification and source evaluation, waste reuse and recycling, waste minimisation and prevention, BIM-based studies, and waste prediction. Similarly, as a means of minimising global pollution and CO_2 emission associated with waste landfilling, as well as to enhance financial benefits that could accrue from adequately managing waste, several waste management strategies have been adopted over the years. These among others include waste reuse, sorting and recycling, legislative and tax measures, design for flexibility and deconstruction, site waste management plan and waste prediction techniques. However, most of the strategies proffer solutions to waste after it occurs, despite the fact that the best strategies for tackling waste are preventive in nature. Equally, while it is clear that waste is best addressed at design stage when cost of change is minimal, the existing strategies are mostly implemented at construction stage. Few current design-stage waste prediction and prevention tools are majorly external to design tools. Worst still, as governments set waste minimisation targets to protect the environment, industry practitioners are only motivated if waste management strategy is cheaper than waste landfilling.

The analysis suggests that for any waste management strategy to reduce waste to landfill, it must consider six requisite factors. These include multi-dimension holistic solutions, whole life consideration, building information modelling compliance, economic viability, legislation driven and design stage implementation. Consideration of the requisite framework would not only ensure that comprehensive waste management is developed; it would mean that such strategy is extensively adopted in the industry.

CHAPTER 3: THEORETICAL BACKGROUND FOR THE STUDY

3.1 Chapter Overview

Koskela (2000) explicitly illuminates functions of existing theories in research, by pointing out that as theory assist in understanding and explaining an observed behaviour, it serves as a valuable tool in predicting likely direction of future behaviour. When properly postulated, theory provides a common framework, which coordinates people in collective undertakings (Dubin, 1978). As such, theory is a valuable tool that condenses a knowledge area, thus allows novice to carry out things that only experts could have done. Whether validity of theory is tested or it is used to influence further studies, it provides strategic framework for ensuring continuity of learning and knowledge development.

One of the distinctive features of a developed field of study is existence of well-established theory upon which its practices is based (Seymour et al., 1997). Placement of theory in research is a hallmark of academic maturity in a field of study (Hauser, 1988). However, as elusive as it might seem, the field of project management in its entirety (Koskela and Howell, 2002), or construction management (Ibrahim et al., 2010) lacks generally acceptable theories that could be pinpointed as its underlying theory. Studies and literature within the field usually start with description of construction project or the problems intended to be solved, thus lacking significant theoretical or conceptual analysis at the onset (Ibrahim et al., 2010). In the same vein, existing theories are usually limited to a small sector of the field, thereby lacking vigour for wider applicability.

Koskela (2000) however argues that theory formulated in a particular setting have tendency of being applied in another setting. Love (2002) also stress that when developing a theory, it is crucial to integrate theories from other bodies of knowledge. This buttresses the fact that as generally acceptable theories are lacking in the field, there is propensity that theories from other fields of study could be properly channelled to understand and predict behaviours within the field of project management in general or design and construction management in particular. It is on this basis that this chapter is dedicated to a review of existing theories found relevant to the focus of this study, with intent of channelling them to fulfil the goals of this study. As such, the next sub-sections review the identified theories as well as their applicability in developing cutting-edge waste management strategy.

3.2 Review of Pertinent Theories

Several theories on construction, behaviour and management were evaluated for their relevance to both methodological and theoretical basis for the study. While many theories tend to contribute to construction management practices in general, those theories that are found particularly relevant to either methodological or theoretical issues in construction waste management are reviewed in this section. The section considers the theory of waste behaviour, competency theory, Lean production theory and dynamic system theory as the theoretical background to the study. Figure 3.1 depicts the theoretical lenses for the study. The dynamic system theory offers methodological insights for adopting holistic approach for addressing waste generated by construction activities. In line with its philosophy of optimising production processes for waste minimisation, the lean production/construction theory provides dimensions for investigating underlying processes for construction waste minimisation. The theory of waste behaviour suggests human and behavioural dimensions for addressing waste, while competency theory advocates for capacity building as a strategic approach for mitigating construction waste.

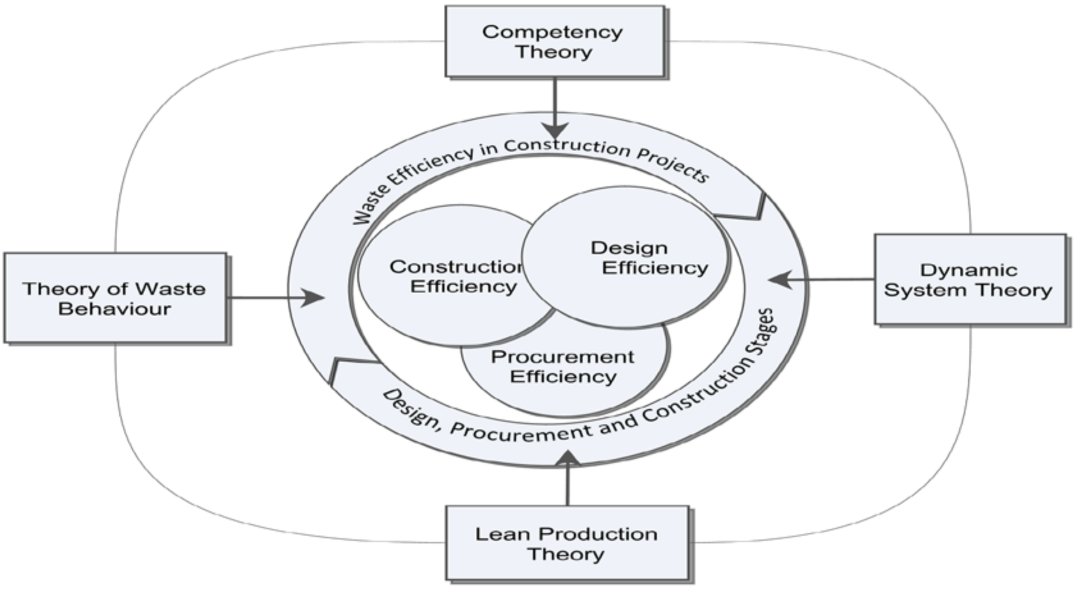


Figure 3.1: Theoretical lenses for the study

3.2.1 Theory of Waste Behaviour

Teo and Loosemore (2001) were credited for significant contribution of theory within the context of construction waste management. Theory of waste behaviour is an important theory that explains waste attitude among construction professionals, towards identifying both impediments and strategic solution to preventing wasteful attitude within the construction industry. Built on theory of planned behaviour (Azjeb, 1993), the theory identified attitudes, subjective norms and perceived behavioural control as three main components of behavioural intention that constitute actual waste behaviour of construction operatives.

As Teo and Loosemore (2001) argued, attitudinal causative of waste behaviour includes belief that waste is inevitable, scepticism of waste reduction, few or no incentives, and poor knowledge of waste management. Perceived behavioural control factors are time pressure, cost pressure, lack of waste facilities and poor market for waste materials among others. Subjective norms causative of waste behaviour, according to the theory, are wasteful culture in the industry, lack of clear policies, low waste priority, lack of waste diversion target, etc. Overall, the theory suggests that operatives have great sense of waste inevitability and that they are unlikely to take waste management strategies important, particularly since they believe waste is managers' problems.

Meanwhile, apart from the theory being centred on waste management, its contribution in achieving effective waste management strategy is enormous. Similar to findings by Lingard *et al. (*2000), it understands the fundamental roles of top management in ensuring cultural change towards waste management. It also introduced the behavioural dimension to construction waste mitigation. This implies that in order to proffer solutions to construction waste generation, human and attitudinal factors should be adequately considered. In order to ensure broad adoption and effectiveness of any proposed waste management strategies, the building operatives and all members of supply chain should be duly involved.

3.2.2 Theory of Lean Production/Construction

Lean production theory is a philosophy that categorised all non-value added production activities as wasteful, thus the need for their elimination in the process. Its underlying principle is to eliminate/avoid all categories of waste, be it time, space, human resources or materials that do not contribute to the value and quality of finished products. With its origin in Japanese manufacturing industry (Bartezzaghi, 1999), Lean production system was popularised by Toyota, having developed their manufacturing system in conformity with Lean principles (Salem et al., 2006). The Lean production theory that eventually serves as the underlying principle for Toyota Production System (TPS) was developed by Toyota engineer Ohno (1988) based on earlier work of Monden in 1983.

TPS was characterised by four main elements, which are Just-in-Time (JIT), autonomation, workforce flexibility, and creative thinking (Salem, 2006). JIT is based on arrangement that units should only be made available when needed. Autonomation is a cost and quality management measure that ensures prevention of defects in products and removal of defective materials in the production process. Workforce flexibility allows company to organise their workforce based on level of demand for their products, using standard operation and multifunctional layout design (Yang and Peters, 1998). Creative thinking involves continuous improvement of production process through feedback and support, in order to prevent defects.

Within the framework of Lean production, Ohno (1988) identified overproduction, reworks, materials movement, processing, inventory, waiting/delay, and unnecessary motion as seven categories of waste, which are to be eliminated for quality assurance, cost reduction and respect for humanity (Salem, 2006). While adding "goods and services that do not meet customer needs" as the eighth category of waste, Womack and Jones (1996) introduced five principles of Lean production. The principles include specification of value, identification of steps in value system, creation of smooth flow, customers pull system, and pursuit of perfection in the process. They reiterated that along with characteristics of Lean production established by Monden (1983) and Ohno (1988), these principles are the core features of Lean system.

Lean construction is grounded in Lean production process as a philosophy that helps in improving efficiency of construction process by reducing waste and providing values to clients. Koskela (2000, 2004) argues that although construction differs from production process due to uniqueness of its individual products and its static products, among others, the seven categories of waste exist in construction operation. According to Koskela

(2004), construction activities usually involve eight category of waste known as “make-do waste”, which is described as waste that occurs when construction activities started without complete project documentation.

Application of Lean production theory has attracted significant research efforts, which resulted in what is now known as Lean construction theory. Tommelin (1998) stressed that the development of Lean construction theory was due to complexities in direct application of Lean production theory into construction process. For instance, while managing the combined effects of variation and dependence is the first goal in Lean production, the goal of construction project is to meet customer's need in timely manner (Howell, 1999). Nonetheless, effect of variation and dependence in project supply chain is paramount when the concept of Lean is applied to construction projects. This is expected to call for a rethink of how work is distributed and how procurement is organised, to ensure timely project delivery, while avoiding waste.

Salem et al. (2006) describe basic tenets of Lean system that makes up Lean construction. Flow variability concept would assist in preventing lagging, which could otherwise affect other project activities. They stress that adoption of "Last Planner" technique, involving investigation and prevention of factors that could bring delay (Ballard and Howell, 2003), would assist in applying the valuable concept of Lean production in construction activities. Although it is very hard to use autonomation as practised in production process owing to difficulty in finding defects before actual construction, the concept could be focused on defect prevention during construction activities (Salem et al., 2006). This would prevent waste due to rework, a major source of waste in construction. In the same vein, the concept of transparency ensures that waste is eliminated through standardisation (Moser and dos Santos 2003). This would ensure transparent job site through effective and adequate materials flow that involve the use of innovative visualisation techniques.

Despite the claim that there are missing links between overall Lean theory and construction activities (Green, 1999; Shah and Ward, 2007), its application in construction process is a means of identifying and eliminating activities that lead to waste generation. Its different categories of waste point to the new dimension by which waste should be considered in construction. Likewise, application of its basic elements (JIT, autonomation, workforce flexibility) and principles in case study projects shows reduction in project cost and earlier project delivery (Salem et al., 2006). Thus, in developing waste management approach, consideration of Lean principles and its waste categories could enhance waste mitigation.

3.2.3 Competencies and Competency-Based Framework

Due to diverse philosophical approaches used in its studies, the term competency has been used to mean different but similar things across several studies (Zemke, 1982). According to Spencer and Spencer (1993) however, competency refers to a set of skills, abilities and individual characteristics that have causative influence on effective job performance. Competency is taken as "a descriptive tool that identifies the skill, knowledge, personal characteristics and behaviour needed to effectively perform a role in the organisation and help the business meet its strategic objectives" (Lucia and Lespinger, 1999, p.5). Holtkamp et al. (2015) also defined competency as a set of abilities, skills and attitudes required for solving problem in a particular context. This description strongly suggests that competency is context-dependent, and it could vary from one job role to another. It covers observable and testable abilities such as skills and knowledge, as well as those that are less obvious such as personal characteristics and qualities (Vazirani, 2010).

Suggesting competency as an effective measure for predicting workplace success, McClelland (1973) is credited with the notion of competency-based measures rather than using IQ test as a yardstick for recruitment and training (Getha-Taylor, 2008). Since McClelland’s work, competency has attracted significant research efforts leading to development of various forms of competency models. According to Dubois (1988), competency models are in four categories, which are organisational, occupational, job/functional/role and leadership competency models. This is in line with the claims of Spencer and Spencer (1993) who argue that competency models could be developed for specific job role, organisation, job groups, occupation or industry.

Built through a process of continuous development, organisational competency addresses the capability required for achieving a competitive business advantage. Resource based view (Wernerfelt, 1984), core competency theory (Prahalad and Hamel, 1990), and dynamic capability theory (Teece et al. 1997) are examples of competency models in this perspective. Occupational competency models, such as OCM by Shaw and Polatajko (2002), cover critical skills and capacity required for broad occupational areas such as engineering and medicine among others. Leadership competency models address set of competencies required of leaders to articulate coherent vision and translate them into reality by effectively directing and managing employees towards achieving organisational goals. Adair's action-centred leadership model (Adair, 1973) and Hersey-Blenchard model of leadership (Hersey et al., 1988) are examples of models developed in this perspective. Job competency models, on the other hand, seek to capture a set of skills that are specific to a job role or work unit within an organisation. Examples of these include task-contextual model (Motowildo et al., 1997), Boyatzis' model of effective job performance (Boyatzis, 1982) and Iceberg Model (Spencer and Spencer, 1993), which seek to develop foundation for recruiting suitable employees and developing training for achieving effective performance.

The overall occupational role of a designer is not to design out waste; it is rather a functional role or work unit. As such, job or functional competency models such as task-contextual, Iceberg and Boyatzis' model are suitable for identifying and developing skill sets and competencies required for designing out waste. Built on McClelland's Mcber job competency framework, Boyatzis (1982) argue that competency is a mix of different measures such as personal traits, motivation, knowledge and skill, all of which could be evident in job action, job performance, behaviour and relationship with others. While skills and knowledge are the generic competencies that a person brings to a job role, social roles and behaviour could be categorised as competence if they directly influence job performance.

Just like an Iceberg, which has about one-ninth of its volume above water, Iceberg theory posits that competency is partly determined by visible features, while hidden features have a great impact on job competency. Spencer and Spencer (1993) argue that knowledge and skill are at the tip of competency iceberg, while self-concept, trait and motives are deeper down in the hidden part of the iceberg. Although the features at the bottom are difficult to measure, the model posits that they contribute about 80% of job competency, while skill and knowledge contribute the rest. Skill and knowledge refer to observable abilities required for a job position; while self-concept, trait and motives are more personal, attitudinal and could be likened to what Motowildo et al. (1997) refer to as contextual competencies. Drawing on the strengths and weaknesses of these sets of job competency theories, task-contextual theory is adopted for this study.

Originally proposed by Motowildo et al. (1997), task-contextual competency model posit that job performance and effectiveness are determined by individual differences in task and contextual abilities, each of which is made of knowledge, skills and work habits. Whereas task competencies are individual's proficiency in activities contributing to the technical core of an organisation or job role, contextual competencies do not constitute the functional core but support organisational, psychological and social environment within which its goals are pursued (Motowildo et al., 1997). Task performance is the technical core, which is done by executing technical requirements of the job. Contextual competencies are personality, behaviour and motivation related, and is more discretionary or supportive in nature. It also involves ability to cooperate, work with, or assist others towards achieving collective organisational goals. The notion of teamwork, interpersonal facilitation and adherence to organisational goal are all contextual (Ahadzie et al., 2014).

Task-contextual theory suggests that a good approach to determining competencies required for a job role is to understand task and contextual requirements of the job. This would result into six categories of performance, which are task skill, task knowledge, task habit, contextual skill, contextual knowledge and contextual habits. Also, the theory is divided into cognitive ability, which has more to do with task performance, and personality variable, which is more related to contextual performance. The theory, however, predicts that personality variables might have effects on task performance, while cognitive ability could also be related to contextual performance. In particular, personality traits tend to affect task habit, as cognitive ability could have an impact on contextual knowledge. Thus, the task-contextual competency model provides a theoretical framework for exploring and analysing competencies required for effective waste performance throughout the whole process of project delivery.

3.2.4 Dynamic System Theory

Over the last few decades, scientists have embraced new dimensions in studying the patterns by which systems are interrelated and ordered. This focussed attention of scientists on dynamic system, which is an approach where both causes and effects are transformed into one another, rather than studying them as independent entity (Seligman, 2005). The dynamic system is rooted in such fields as mathematics, physics, chemistry, biology, philosophy, etc. (Hohenberger, 2002), and it is associated with such tenets as chaos theory, non-linear system, self-organisation, and dissipative system (Marin and Peltzer-Karpt, 2009). The term dynamism describes a phenomenon producing time chasing pattern in such a way that characteristics of the pattern products at different times interrelated with one another (Luenberger, 1976). The dynamic system incorporates powerful tools that support modelling and conceptualization of both real and developmental time (Hohenberger, 2002).

The Dynamic System Theory (DST) is underpinned by an assumption that "every action at every moment is the emergent product of context and history, and no component has causal priority" (Thelen, 2005:271). It seeks to encompass all possible input for a system to handle both the predictable aspect of every process and those that could be surprising (Thelen, 2005). Generally, DST attempt to describe and depict the nature of relationship existing among various components of a whole phenomenon in such a way that they can inform solutions and predictability of complex system.

Dynamic system theory has successfully transformed several scientific paradigms (Spencer-Wood, 2013; Lerner, 2006; Lowie, 2012) so much that application of its concepts to construction waste has been widely advocated (Yuan et al., 2012; Hao et al., 2008; Love et al., 2000; Ye et al., 2012). Detail recognition and critical understanding of the way waste is generated remains a seemingly insurmountable task. This is because many solutions often focus only on regular, recurring and static pattern (Yuan et al., 2012), thereby disregarding irregular and dynamic patterns, which are capable of proffering holistic waste management solutions. Sterman (1992) argues that multidimensional activities, such as construction operations, usually involve complex processes that stress beyond shallow and fallible capacity of both mental and static models. It requires the use of dynamic based models, which are underpinned by dynamic system theory, in order to compile the logical sequence, and incorporate various interrelated activities usually involved in construction operations.

Love et al. (2000) similarly noted that a mistake made in design could result in errors in procurement and construction, thereby leading to rework and subsequent waste generation. It is, therefore, important that construction project lifecycle is evaluated from system perspective in order to develop causal loops and feedback system of such interdependent processes. This could help in understanding impacts of one activity on the others, as well as on the overall project outcome. Thus, application of system approach, as underpinned by the system theory, would enhance adequate understanding of dynamic impacts of various activities on waste efficiency of construction projects.

3.3 Implication of the Theories for the Study

Critical review and analysis of pertinent theories have raised both theoretical and methodical issues that are central to this study. The theories have provided useful insights that shape both the scope and assumptions of the study. While the dynamic system theory has pinpointed the need to consider the design, procurement and construction stages as a single system for waste mitigation, others have raised issues about measures to be considered. For instance, the theory of waste behaviour does not only propose an adequate consideration of behavioural and human factors in waste management; it suggests the need to involve all stakeholders in developing measures for waste mitigation. The Lean theory, on the other hand, provides a complete school of thought on how construction waste could be adequately tackled at both materials and process levels. The theory does not only identify different categories of waste that must be addressed in waste management strategies, but it also offers principles that are proved useful for identifying and eliminating activities that induce waste. As such, the theory advocates process efficiency as a means of engendering waste effectiveness of construction projects.

The competency-based framework provides a framework for exploring and analysing the various forms of skills and competencies required for driving waste at various stages of project delivery process. It offers an approach for identifying the various dimensions and underlying skills towards tailoring training and personal development for waste-effective projects. Thus, to proffer effective solutions to multidimensional and dynamic-natured problems associated with design, procurement and construction stages, the relevance of dynamic system theory could not be over emphasised. As such, while other theories offer useful insights that would shape the scope and methodological approach of the study, the dynamic system theory underpins the dynamic approach to the study. This informs the use of dynamic system modelling and its subsequent stages of application in proposing holistic construction waste management solutions. Figure 3.2 depicts the theoretical background to the study.

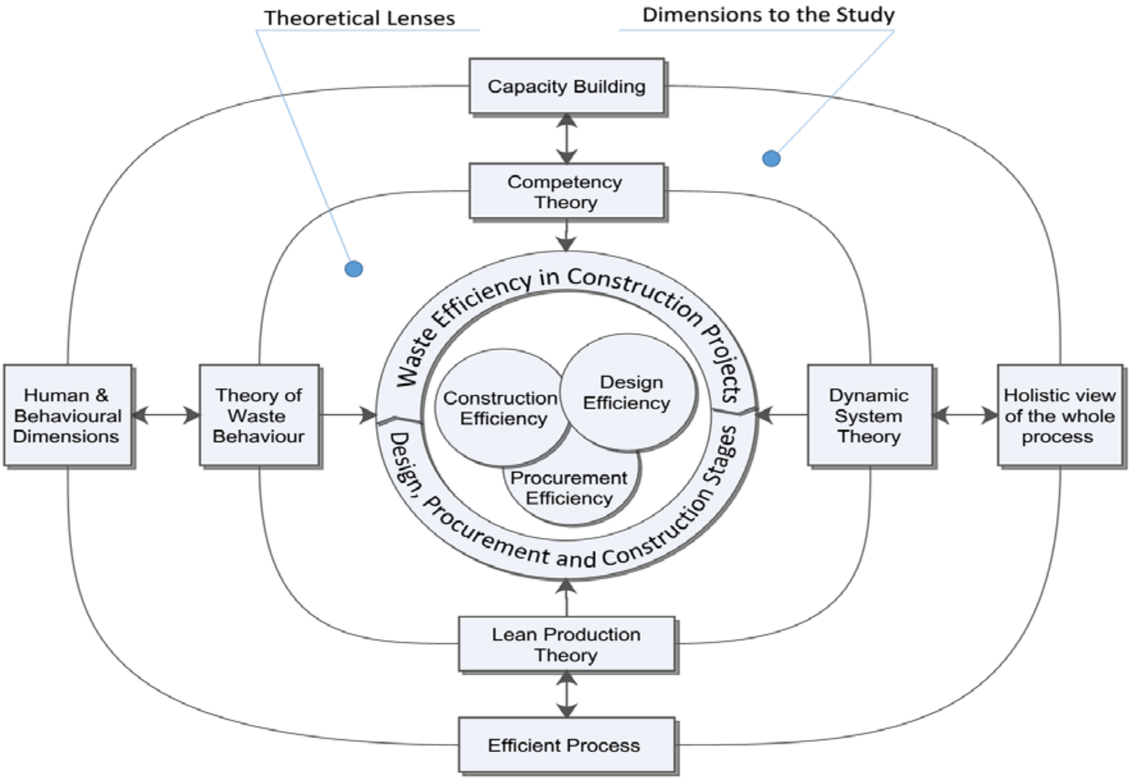


Figure 3.2: Theoretical Background to the Study

3.4 Chapter Summary

This chapter provided theoretical lenses to the study of construction waste minimisation strategies. It reviewed theories that provided various perspectives and methodological insight to the study. While the theory of waste behaviour, Lean construction theory and competency theory offered different dimensions from which the study could be approached, the dynamic system theory provided a holistic methodological approach for investigating construction processes. The relevance of each of the theoretical lenses is evaluated in the chapter.

CHAPTER 4: SYSTEMATIC REVIEW OF STRATEGIES FOR CONSTRUCTION WASTE MINIMISATION

4.1 Chapter Overview

Notwithstanding the interrelationship and interdependency of every stage of building delivery process, most waste management studies have addressed waste from unitary perspective. This usually results in stage-based solutions that lack consideration of the interrelationship and dynamic impacts of one stage on the other. It instigates the need to produce a coherent, comprehensive and holistic framework of factors affecting waste that aggregate existing studies and integrate all stages of construction projects. Meanwhile, the robustness of waste management strategy in achieving waste-efficient projects depends on the level of awareness of waste preventive approaches while developing such solution. In a bid to produce a holistic strategy for driving waste-efficient construction projects, this chapter delves into existing waste management literature towards compiling and analysing factors impacting waste. The next section describes the approach used in identifying all the factors, while section 4.3, 4.4 and 4.5 itemised and analysed design, procurement and construction factors affecting waste in construction projects. Section 4.6 summarises and culminates the chapter.

4.2 Identification of Strategies for Waste Minimisation

The aim of this chapter is to identify and categorise waste-efficient measures that should be well thought out and adequately considered, throughout all stages of project delivery process. As such, the presentation in this chapter requires identification, scrutiny and analysis of extant literature that are relevant to the scope of the study. To achieve a comprehensive understanding of the existing waste-efficient practices, literature retrieval process was carried out on two major citation indexing platforms (Wu et al., 2014), which are Engineering Village and Web of Knowledge. The databases included in the search were Compendex, GEOBASE, Web of Science, BIOSIS, MEDLINE and SciELO without any restriction for the year of publication.

Also, *SC Imago* was used to identify top “waste management and disposal” journal in order to carry out a search on their database. “*Waste management*” and *"Resources,* *Conservation and Recycling"* were selected after a quick evaluation of scopes of the first ten journals on the list. Based on the recommendation in a study by Lu and Yuan (2011), the database of a third journal with wide publications on Construction and Demolition Waste Management, "*Waste Management and Research"* was also searched. To corroborate the identified papers, relevant publications by the UK government-funded Waste and Resource Action Programme (WRAP) were included. Keywords used for searching the databases and journal repositories include *waste-efficient, waste management strategies, reuse, recycling, waste minimisation, waste prevention, design and waste, procurement and waste, construction waste* and *causes of waste*, among others.

Studies based on domestic waste, radioactive waste and other types of waste than construction waste were excluded in the search result. In addition, papers that discuss non-physical/non-materials waste were not included in the study. To ensure robustness of the review process, reference lists of the identified papers were manually scanned to check for relevant papers that may not have been found in the initial search. The papers were read through to identify the design, procurement and construction strategies for mitigating waste.

4.3 Design Factors Impacting Waste in Construction Projects

Osmani et al. (2012) and Faniran and Caban (1998) suggest that most waste management studies tend to concentrate on construction stage while evidence shows that construction waste could be significantly reduced by taking care of several design factors that tend to impact waste (Ekanayake and Ofori, 2004). The earlier a change is implemented in a project lifecycle, the more its positive impact, and the less the cost of such change. This concept is similarly applicable to dedicated effort towards waste management. The earlier such effort, the more likely it would prevent waste occurring at a later stage. As such, the importance of design in minimising waste could not be over emphasised.

Ekanayake and Ofori (2004) and Osmani et al. (2008) argue that the best approach for tackling waste is through dedicated efforts at the design stage of building delivery process. Innes (2004) also claimed that dedicated measures to reduce waste through design process could reduce total waste by up to a third. Based on these, and in order to understand the procedural approach to designing out waste through dedicated design effort, this section presents findings of the literature review that seek to aggregate the design factors capable of influencing waste in construction projects. The section provides a comprehensive list of factors and strategies relevant for effective prevention and management of waste at the design stage of project delivery process. Based on strong and repetitive emergence of certain terminologies from the literature, the factors were grouped into five categories, which are:

- Design team attributes and competencies
- Design documents quality
- Efficacy of the design process
- Buildability/constructability criteria in design
- Responsive design and deconstructability thinking

4.3.1 Design Team Attributes and Competencies

Attributes, competencies and dedication of designers and design management team are important in achieving low waste construction projects. Apart from design stage being a crucial stage for waste preventive effort, adverse environmental impacts of construction activities have been widely blamed on designers (Sassi and Thompson, 2008; Mansikkasalo et al., 2014). For instance, Oyedele at al. (2014) claim that there is still low acceptance and use of recycled products within the construction industry due to a low commitment from designers who drive materials selection and sustainability practices within the industry. Table – 4.1 presents list of design team attributes and competencies that, if well thought out, would enhance waste effectiveness of projects.

Table 4.1: Design Team Attributes and competency factors influencing waste

	Factors/Strategies	***References in Literatures***
	Technical Competencies	
1	Design for standard materials supplies	Ekanayake and ofori (2004); Al-Hajj and Iskandarani (2004)
2	Ability to produce error-free documents	Dainty and Brooke (2004)
3	Careful dimensioning of design to avoid cutting to fit	Faniran and Caban (1998)
4	Careful attention to detail at planning/design	Faniran and Caban (1998)
5	Knowledge of construction method/sequence	Alshboul and Ghazaleh (2014)
6	Awareness and use of standard detail and specifications	Andi and Minato (2003)

Factors/Strategies		*References in Literatures*
7	Ability to produce proper site layout planning	Tam (2008); Yuan (2013b)
8	Clear and comprehensive information	Baldwin et al. (2007)
	Awareness of Materials Attributes	
9	Knowledge/specification of secondary materials	Osmani et al. (2008); Wang et al. (2014)
10	Identify all reusable elements and integrate them into design	Begum et al. (2009); WRAP (2009)
11	Specify durable materials to avoid early refurbishment	Esin and Cosgun (2007); Yuan (2013b)
12	Specify available, suitable and compatible materials	Andi and Minato (2003)
13	Knowledge of alternative materials option	Alshboul and Ghazaleh (2014)
	Commitment to Low Waste Projects	
14	Feasibility studies of waste estimation techniques	Osmani et al. (2008)
15	Adequate training to gain required competencies and experience	Mckechnie and Brown, (2007); Nagapan et al. (2013); Lu and Yuan (2010)
16	Drawings and other documentations are timely supplied when required	Andi and Minato (2003)
17	Environmental impact assessments of the scheme during the design phase	Yeheyis et al. (2013); Dainty and Brooke (2004); Tam (2008)
18	R&D into best WM approaches	Lu and Yuan (2010)
19	Consideration of different design options based on their likely waste output	del Río Merino et al. (2010)

4.3.2 Design Documents Quality / Attributes

The quality of design documents has great impacts on overall effectiveness of the build process (Andi and Minato, 2003; Gann et al., 2003). The extent to which attention is given to detail, as well as completeness of the whole documents, would affect waste output of a project. This is because; design documents do not only affect buildability of the project, its comprehensiveness and accuracy would go a long way in preventing errors that could lead to reworks (Formoso et al., 2002). In this regards, quality and attributes of design documentation, with respect to waste minimisation, have been established in two categories. These include accuracy of the design documents and adequacy/comprehensiveness of the documents. Table 4.2 presents a list of design documents attributes capable of influencing waste in construction projects.

Table 4.2: Design Document Attributes Impacting Waste

	Factors/Strategies	*References in Literatures*
	Accuracy of design information	
1	Drawing documents are free of errors that could otherwise lead to reworks	Osmani et al. (2008), Andi and Minato (2003)
2	Detailed specification devoid of under/over ordering	Begum et al. (2007); Oyedele et al. (2003); Domingo et al. (2009)
3	Designs from all trades are adequately coordinated/integrated	Al-Hajj and Hamani (2011); Andi and Minato (2003)
4	Drawings and other documents are legible	Ekanayake and Ofori (2004); Baldwin et al. (2007)
5	Consistency in detailing language/format	Osmani (2013)
	Comprehensiveness of the documents	
6	Waste management plan to be prepared along with design	Garas et al. (2010); Oyedele et al. (2013)
7	Deconstruction plans as a major element in the design documents	Oyedele et al. (2013)
8	Completeness: Adequate design information for subsequent businesses	Negapan et al. (2013); Alshboul and Ghazaleh (2014); Khanh and Kim (2009)
9	Bar bending list is carefully prepared as part of documentations	Al-Hajj and Hamani (2011)

4.3.3 Efficacy of Design process

The way the design process, contract and the design team are coordinated have effects on waste generated at the construction stage of project delivery. The efficacy of design process determines the extent to which various specialities are coordinated, level of communication between parties as well as stakeholders' meetings, all of which are found to be important to waste prevention (Ikau et al., 2013; Al-Hajj and Hamani, 2011). Design process factors that are capable of impacting waste efficiency of construction projects are presented in Table 4.3.

Table 4.3: Design Process Factors Affecting Waste in Construction

	Factors/Strategies	*References in Literatures*
	Coordination of Design Contracts	
1	Careful Coordination of contract documents to prevent error	Osmani et al. (2008)
2	Early completion of contract documents before construction	Osmani et al. (2008)
3	Ensure design freeze at the end of design process	Oyedele et al. (2013); Negapan et al. (2013)
4	Involvement of contractors at early stage	Oyedele et al. (2013)
5	Clearly specified project goal to avoid flawed planning/design	Faniran and Caban (1998)
6	Pre-design meetings of key stakeholders	Oyedele et al. (2003)

Factors/Strategies		***References in Literatures***
7	Early collaborative agreement before design activities	Osmani (2013)
8	Economic incentives and enablers	Wang et al. (2013); Osmani (2013)
9	Include waste management into assessment of stakeholders	Yuan (2013b)
	Coordination of Design Documents/Teams	
10	Adequate Coordination of various specialities involved in the design process	Ikau et al. (2013)
11	Timeliness: Early distribution of design documents	Negapan et al. (2013)
12	effective coordination of parties during the design stage	Negapan et al. (2013)
13	Design management to prevent over specification of materials	Alshboul and Ghazaleh, (2014)
14	Adequate communication between trades	Al-Hajj and Hamani (2011); Domingo et al. (2009); Oyedele et al. (2003); Osmani (2013)
15	Adequate implementation of sustainable building assessment procedure	Tam (2008); Yeheyis et al. (2013); Andi and Minato (2003)
16	Drawings and other details are adequately coordinated between design discipline	Al-Hajj and Hamani (2011); Yuan (2013b)

4.3.4 Buildability / Constructability Criteria

Improved buildability of design is not only required for early project completion and resource efficiency among others (Lovell, 2012), it is a proven way through which construction waste could be reduced (Yeheyis et al., 2013; Yuan, 2013b). By adopting modern method of construction and other low-waste technologies, complexities that result in waste could be reduced. Factors that directly affect buildability of design, which could subsequently reduce waste outputs, are presented in Table 4.4. Based on evidence from extant literature, the measures are categorised under two headings, which are Modern Methods of Construction (MMC) and Standardization and Dimensional Coordination.

Table 4.4: Buildability/Constructability Criteria Impacting Waste

Factors/Strategies		***References in Literatures***
Design for Modern Methods of Construction		
1	Specification of prefabricated materials	Yuan (2013)
2	Modular coordination of building elements	Formoso et al. (2002); Oyedele et al. (2003)
3	Design for preassembled components	Kozlovska & Splsacova, (2013); Formoso et al. (2002)
4	Specify the use of efficient framing techniques	Osmani et al. (2008)
5	Employ Modular design principles	Wang et al. (2014); Baldwin et al. (2007); Esin and Cosgun (2007)

Factors/Strategies		*References in Literatures*
6	Design with buildability/constructability of the project in mind	Yeheyis et al. (2013); Yuan (2013b); Oyedele et al. (2003)
Standardisation and Dimensional Coordination		
7	Careful integration of building sub-system	Formoso et al. (2002)
8	Ensure simplicity and clarity of detailing	Ekanayake and Ofori (2004); Domingo et al. (2009)
9	Design for standard dimensions and units	Osmani et al. (2008)
10	Standardise building forms and layout	WRAP, (2009); McKechnie and Brown (2007);
11	Ensure drawings consider and integrate site topography and existing utilities	Yuan (2013b); Andy and Minato (2003); WRAP (2009)
12	Dimensional coordination and standardisation of building elements	Dainty and Brooke (2004); Baldwin et al. (2007); WRAP (2009) Ekanayake and Ofori (2004); Alshboul and Ghazaleh, 2014);
13	Optimize tile layout in conformity with design shape	WRAP (2009)
14	Use full height door or door with fanlight to avoid cutting plasterboard	WRAP (2009)
15	Standardise doors, windows and glazing areas	WRAP (2009)
16	Avoidance of overly complex design	Domingo et al. (2009); Yuan (2013b)
17	Ensure adequate detailing of complex design	Negapan et al. (2013); Ekanayake and Ofori (2004); Baldwin et al. (2007); Yuan (2013b)
18	Coordinate structural grid and planning grid	WRAP (2009)

4.3.5 Responsive Design and Deconstructability Thinking

The extent to which design and construction technique is responsive to change, and how well deconstructability has been incorporated into the design, determine waste impacts of the design. Factors that could enhance responsivity and deconstructability of design are in three categories, which are design for ease of deconstruction, specification of durable materials and design for flexibility and change. Some factors capable of influencing responsivity and deconstructability of buildings are presented in Table 4.5.

Table 4.5: Criteria for Responsive design and Deconstructability Thinking

Factors/Strategies		*References in Literatures*
	Responsive Design and Deconstructability Criteria	
1	Use of modular system	Formoso et al. (2002); Wang et al. (2014); Esin and Cosgun (2007)
2	Designers to produce disassembly and deconstruction plans	Oyedele et al. (2013)
3	Design for changes and flexibility	Yuan (2013b); Mckechnie and Brown (2007)
4	Specify durable materials to avoid need for early replacement	Esin and Cosgun (2007); Yuan (2013b)
5	Specify materials and joint system that support disassembly	WRAP (2009)

4.4 Materials Procurement Strategies for Low Waste Projects

Percentages of waste generated in construction activities have been traced to ineffective coordination of materials procurement activities (Greenwood, 2003; Lu et al., 2011; Wang et al., 2008). As the value of construction materials could contribute up to 50% of project cost (Kong et al., 2001). It is, therefore, imperative that adequate measures are taken to prevent waste that could be due to ineffective materials purchase, delivery, handling and storage. However, unlike design and construction related activities that are widely investigated for waste efficiency; little efforts have been made to examine how procurement activities could be optimised to improve waste efficiency of construction projects. Materials procurement factors that are capable of influencing construction waste are only available across scattered studies, which usually concentrate on construction and design stage of building delivery process.

Based on the thorough review of relevant literature, some factors were identified and grouped into five categories. These sets of measures are:

- Suppliers/vendors' attributes
- Handling and storage measures,
- Purchase management
- Delivery management
- Contractual clauses

The identified sets of procurement measures are as presented in Table 4.6.

Table 4.6: Materials Procurement Measures for Reducing Construction Waste

	Factors/Strategies	***References in Literatures***
	Suppliers/Vendors' Attribute	
1	Procurement route that minimises packaging	Oyedele et al. (2013); Yeheyis et al. (2013); Marinelli et al. (2014); Saez et al. (2013)
2	Vendors that supply good quality and recycled materials	Khan and Kim, (2014); Nagapan et al. (2013)
3	Flexibility in providing small quantities of materials	Dainty and Brooke (2004)
4	Modification to products in conformity with design	Bernold et al. (1991)
5	Collecting package materials back by suppliers	Cha et al. (2009)
6	Collecting back recyclable materials	Jingkuang and Yousong (2011)
7	Enhance management of packaging materials	Yuan (2013b)
8	Provision for unused materials to be taken away from site (take back scheme)	Negapan et al. 2013; Cha et al. (2009) Al-Hajj and Hamani (2011); Bernold et al. (1991).
	Contractual Factors	

Factors/Strategies		*References in Literatures*
9	Waste minimisation clauses in contract documents	Osmani (2013)
10	Consistency in contract documents	Domingo et al. (2009)
11	Resolve contract document before procurement	Ekanayake and ofori (2004)
12	Contract completion before procurement activities	Negapan et al. (2013)
13	Freeze design before procurement processes	Osmani et al. (2008)
14	Discuss methods of waste minimisation with suppliers/sub-contractors	WRAP (2009)
	Effective materials management	
15	Procurement and use of preassembled components	Formoso et al. (2001)
16	Purchase pre-cut materials	McKechnie and Brown (2007)
17	Optimisation of Materials Purchase to avoid over/under ordering and excess waste allowance	Hassan et al. (2012); Faniran and Caban (1998); Dainty and Brooke (2004); Marinelli et al. (2014)
18	Purchase repairable, reusable and durable materials	Khanh and Kim (2014); Begum et al. (2007)
19	Buying materials with reused packaging	WRAP (2009); Faniran and Caban (1998)
20	Purchase secondary materials and reuse materials	Begum et al. (2007)
21	Effective materials take-off	Nagapan et al. (2013)
22	Good quality materials to be purchased	Nagapan et al. (2013)
23	Purchase materials in conformity/adherence to carefully prepared specification	Bernold et al. (1991); Muhwezi et al. (2012)
24	Avoid frequent variation order	Nagapan et al. (2013)
25	Order material with high content of recycled product	Teo and Loosemore (2001); Cha et al. (2009)
26	Recycled aggregate to be procured	WRAP (2009); Wang et al. (2010)
27	Use of correct materials, thus preventing replacement	Muhwezi et al. (2012)
	Effective materials delivery	
28	Sufficient protection of materials during loading/unloading	Faniran and Caban (1998); Hassan et al. (2012); Al-Hajj and Iskandarani (2011)
29	Good site access for delivery vehicle	Osmani et al. (2008)
30	Avoidance of loosely supplied materials	Nagapan et al. (2013); Hassan et al. (2012)
31	Adequate and efficient delivery schedule	Marinelli et al. (2014); Khanh and Kim (2014)
32	Planning for good delivery system onsite	Formoso et al. (2001)
	Waste effective handling and storage	
33	Waste-efficient procurement such as JIT	Dainty and Brooke (2004); Al-Hajj and Hamani (2011); Marinelli et al. (2014)
34	Vocational training on sorting and handling of materials	Yuan (2013)
35	Improvement of materials handling system	Oyedele et al. (2013); Adams et al. (2011); Faniran and Caban (1998); Hassan et al. (2012);
36	Suitable and safe storage of materials	Dainty and Brooke (2004); Al-Hajj and Hamani (2011); Ekanayake and Ofori (2004)
37	Mechanical movement of materials	WRAP (2007)
38	Logistic management to prevent double handling	Al-Hajj and Hamani (2011); Cha et al. (2009)
39	Reduce excess of ordered material to avoid breakage	Del Río Merino et al. (2010)

4.5 Construction Strategies for Waste Minimisation

Although several pre-construction activities and measures have been traced to waste generated in construction industry, the undisputable fact remains that the actual waste is not generated until during the construction stage of project delivery. Owing to this, various onsite waste causatives and preventives activities have been identified. These set of measures spread across both activities that could be carried out to reduce waste output of projects as well as the management measures that could be taken towards diverting waste from landfill sites. Through a dedicated review of extant literature, some factors, activities and measures that could influence waste at the construction stage of building delivery process were identified. The factors are grouped into seven categories of related factors. These include:

- Contractors/sub-contractors' attributes and competencies
- Contractual arrangement
- Construction techniques
- Construction site management practices
- Industry cultural changes
- Legislative and fiscal framework
- Human resources management

They are further expatiated and referred in the next subsections.

4.5.1 Contractors/Sub-contractors' Attributes and Competencies

Competencies and readiness of contractors and sub-contractors are very important in achieving low waste construction projects. It is important that construction professionals are aware of waste preventive and causative activities, while they are also dedicated to ensuring low waste in projects. Some competencies and activities that indicate competencies and readiness of contractors for low waste projects are as summarised in Table 4.7.

Table 4.7: Indicators of contractors' readiness and competencies for low waste projects

	Factors/Strategies	***References in Literatures***
1	Improved technical knowledge of construction professionals	Zhang et al. (2012); Oyedele et al. (2003)
2	Improved major project stakeholders' awareness about resource saving and environmental protection	Yuan (2013b)
3	Detect the construction activities that can admit reusable materials from the construction	Del Río Merino et al. (2009)
4	Carefully planned work sequence to prevent damages to previously completed work	Muhwezi et al. (2012)
5	Understanding and adoption of right work sequence and technology	Zhang et al. (2012)
6	Commitment of contractors' representatives onsite	Cha et al. (2009)
7	Adequate knowledge of construction methods and sequence	Muhwezi et al. (2012)
8	Cooperation of subcontractors	Cha et al. (2009)

4.5.2 Contractual Arrangement

Various means through which contractual arrangement could be used to influence waste management at the construction stage have been suggested across the literature. While it is hard to estimate the actual proportion of waste that could be diverted from those measures, evidence shows that contractual clauses could help in significantly reducing waste generated by construction activities (Dainty and Brooke, 2004). Table – 4.8 shows a list of contractual provisions that could assist in waste mitigation efforts.

Table 4.8: Contractual provisions for waste-efficient projects

	Factors/Strategies	***References in Literatures***
1	Contractual clauses to penalise poor waste performance	Dainty and Brooke (2004)
2	Making sub-contractors responsible for waste disposal	Domingo et al. (2009)
3	Incentives and penalties for waste management and casualties respectively	Adams et al. (2011); Li et al. (2003); Al-Hajj and Hamani (2011)
4	Waste target set for sub-trades	Marinelli et al. (2014)
5	Incentive in bidding for a contractor having a plan about decreasing waste and increasing recycle	Jinkuang and Yousong (2011); Cha et al. (2009)
6	Clearly communicated waste management strategies	Teo and Loosemore (2001)
7	Additional tender premiums for waste management	Dainty and Brooke (2004)
8	Recycling target to be set for every project	Oyedele et al. (2013)

4.5.3 Waste Effective Construction Techniques

Construction methods and coordination are important measures in addressing waste effectiveness of a construction project. Jaillon et al. (2009) argue that use of precast materials could reduce waste output by up to 84%. Other low-waste technologies or modern methods of construction are also proven to reduce construction waste significantly (Poon et al., 2003). Table – 4.9 itemises a list of construction techniques and factors that support waste-efficient project.

Table 4.9: Construction techniques for low waste projects

Factors/Strategies		***References in Literatures***
1	Use of reclaimed materials	Domingo et al. (2009)
2	Use of appropriate and quality equipment	Khanh and Kim (2014); Zhang et al. (2005)
3	Use of hanging cradle	Poon et al. (2003)
4	Reduced use of wet trades	Baldwin et al. (2007)
5	Use pallet for landscape top mulch	WRAP (2009)
6	Ensure conformity with design dimension	Formoso et al. (2002)
7	Construction with standard materials	Cha et al. (2009)
8	On-site materials compactors	Dainty and Brooke (2004)
9	Precast bathroom	Poon et al. (2003)
10	Innovative/reusable formwork and falsework	Yuan (2013); Al Hajj and Hamani (2011)
11	Use of metal formwork	Jaillon et al. (2009); Tam (2008);
12	Easy replacement of building element	WRAP (2009)
13	Steel Scaffolds	Wang et al. (2014)
14	Metal/ non-timber hoarding	Baldwin et al. (2007); Tam (2008)
15	Avoid gluing	WRAP (2009)
16	Reuse of off-cuts materials (such as wood)	Al-Hajj and Hamani (2011)
17	Large panel formwork	Poon et al. (2003)
18	Use lime mortar to ensure easy dismantling	WRAP (2009)
19	Drywall partition and infill	Poon et al. (2003)
20	Demountable building techniques	Yeheyis et al. (2013)
21	Aluminium and plastic formwork	Poon et al. (2003)
22	Avoid cut corners	Yuan (2013)
23	Efficient framing	Yeheyis et al. (2013)
24	Machinery sprayed plaster	Poon et al. (2003)
25	Adopting modular	Yuan (2013); Esin and Cosgun (2007)
26	Easily disassembled building elements	WRAP (2009)
27	Adoption of low waste tech and Modern Methods of Construction	Poon et al. (2003); Begum et al. (2009); Lu and Yuan (2010); Osmani (2013)
28	Use of demolition and excavation materials for landscape	WRAP (2009)
29	Employ offsite construction	Oyedele et al. (2013); Dainty and Brooke (2004); Kozlovska and Splsacova (2013)
30	Precast Cladding, units and modules	Poon et al. (2003)
31	Use of mechanical fixtures	WRAP (2009)
32	Prefabricated construction method	Lachimpadi et al. (2012); Chen et al. (2002)

4.5.4 Construction Site Management Practices

Effective coordination of site activities is crucial to waste effectiveness of construction projects. This is especially as decisive actions capable of reducing waste or incorporating secondary materials could be taken by the site management teams. The site management decision is not limited to construction activities; it also includes adequate coordination of both human and material resources towards achieving project goals, among which cost effectiveness and sustainability might be included. Table 4.10 presents a list of site management practices that are capable of reducing waste and diverting substantial waste from landfill.

Table 4.10: Construction Management Strategies for Low Waste Projects

	Factors/Strategies	***References in Literatures***
1	Establish a task group for onsite CWM	Yuan (2013b)
2	Prefabrication space in the work site for the correct management of the C&D waste	Lu and Yuan (2013)
3	Logistic management to prevent double handling	Al-Hajj and Hamani (2011)
4	Follow the project drawings designs to prevent carrying out unexpected mistakes	Lu and Yuan (2010); Saez et al. (2013)
5	Develop and implement waste management plans	Garas et al. (2010); Hassan et al. (2012)
6	Effective coordination of project participants	Khanh and Kim (2014)
7	Installing an information board to notify categories for separating waste	Cha et al. (2009)
8	Periodic checks on the use of C&D waste containers	Saez et al. (2013)
9	Preventing waste mixture with soil	Jingkuang and Yousong (2011)
10	Providing bins for collecting wastes	Cha et al. (2009)
11	Dedicated space for sorting of waste	Wang et al. (2010); Lu and Yuan (2010)
12	Ensure fewer design changes during construction	Al-Hajj and Iskandarani (2011);
13	Sorting wastes at an easily accessible area	Cha et al. (2009)
14	Setting up temporary bins at each building zone	Jingkuang and Yousong (2011)
15	Timely and effective communication of design changes	Faniran and Caban (1998)
16	A thorough review of the project specifications by the contractor at the construction stage	Faniran and Caban (1998)
17	Adequate site access for materials delivery/movement	Negapan, et al. (2013)
18	Waste auditing to monitor environmental performance	Dainty and Brooke (2004)
19	Educate clients about measures to reduce waste levels	Dainty and Brooke (2004)
20	Central areas for cutting and storage	Tam (2008)
21	Provision of waste skips for specific materials	Del Río Merino et al. (2010)
22	Reuse material scraps from cutting stock-length	Faniran and Caban (1998)
23	Ensure effective communication of site activities	Osmani et al. (2008); Yuan (2013b)
24	Adequate on-site materials control system	Osmani et al. (2008)
25	Effective coordination between all specialities onsite	Garas et al. (2010)
26	Soil remains to be used on the same site	Begum et al. (2009)
27	Maximisation of onsite reuse of materials	Marinelli et al. (2014) Yuan (2013b)
28	Discussion with sub-contractors/ other consultants on the reuse of materials/components	WRAP (2013)
29	Well planned site layout prepared and discussed	WRAP (2013)
30	Prepare site layout before construction activities	Khanh and Kim (2014); Yuan (2013b)
31	Sorting and reuse/recycling of waste	Hassan et al. (2012); Yeheyis et al. (2013)

4.5.5 Industry Cultural Change

While proposing theory of waste behaviour, Teo and Loosemore (2001) illuminated the prevailing culture of waste inevitability that characterised the construction industry. The same opinion was echoed by Ikau et al. (2013) and Osmani et al. (2008) who reiterated that a major reason for insurmountable waste intensiveness of the construction industry is that workers believe in waste inevitability, thereby giving less attention to waste management. In order to drive the necessary cultural change in the industry, there is a need for a more dedicated workforce, clearly defined and communicated waste management approach, and top management commitment to waste management (Teo and Loosemore, 2001).

On the other hand, the construction industry is highly fragmented, and it involves various trades carrying out their supposedly collaborative activities independent of one another. This thus results in information loss and ineffective communication among the stakeholders. Just as there is a need for promoting effective communication (Yuan 2013b), supply chain alliance with materials suppliers and recycling companies is required (Dainty and Brooke, 2004; Oyedele et al., 2014). This would not only result in adequate materials information, but it would also ensure that excess materials are removed and reprocessed for further construction activities. This would as such help in diverting substantial waste from landfill. Table 4.11 presents some cultural changes that are capable of reducing waste generated by construction activities.

Table 4.11: Cultural Changes required for driving construction waste minimisation

	Factors/Strategies	*References in Literatures*
1	Use of collaborative procurement route such as IPD	Isikdag and Underwood (2010);
2	Supply chain alliance with materials suppliers	Dainty and Brooke (2004)
3	Early involvement of contractors at design stage	Oyedele et al. (2013); Arain et al. (2004)
4	Blame and gain sharing philosophy among parties	Osmani et al. (2008); Fewing, 2013
5	Completion of design document before construction	Koskela, (2004)
6	Design freeze before construction activities	Oyedele et al. (2013)
7	Use of collaborative platform for information sharing	Ilozor and Kelly, 2011

4.5.6 Legislative Framework

Governments' legislative and fiscal measures have been developed to instil waste management habits in the construction industry. Among others, these measures include landfill tax, aggregate levy, compulsory SWMP, and sustainable design assessment frameworks such as BREEAM. Although these measures have significantly reduced waste landfilling (Skumatz, 2008; Browna and Johnstone, 2014; Dahlén and Lagerkvist 2010; Al-Hajj and Hamani, 2008), other measures through which legislative frameworks could be ameliorated to promote waste management have been proposed in recent studies. Table – 4.12 presents a list of fiscal and legislative measures capable of promoting waste management practices within the construction industry.

Table 4.12: Legislative measures for improving waste effectiveness of construction

	Factors/Strategies	*References in Literatures*
1	Developing market structure for recycled materials	Oyedele et al. (2009); Cha et al. (2009)
2	Raising fees for mixed wastes	Cha et al. (2009)
3	Reducing fees for separated wastes	Cha et al. (2009)
4	Tax break for waste treatment equipment	Jinkuang and Yousong (2011)
5	Improved database management for construction wastes	Cha et al. (2009)
6	Improved Waste management regulations	Lu and Yuan (2010)
7	Integrate CWM into the assessment of contractor	Yuan (2013b)
8	Increase the landfill disposal fee	Lu and Yuan (2010)

4.5.7 Human Resources Management

Effective management of human resources is central to productivity, cash flow, and market value of a firm (Huselid, 1995). The more an organisation adequately channelled its human resources to its desired goals, the more likely for such organisation to achieve its goals (Becker, 1996). Owing to this, it is important that construction industry adequately prepares and coordinates their workforce for effective outcome of the project, among which waste minimisation is important for both financial and environmental concerns. Based on literature review, some suggested human resources management practices for reducing construction waste are presented in Table – 4.13.

Table 4.13: Human resources coordination for waste-efficient project

	Factors/Strategies	*References in Literatures*
1	Supervising waste management by a residential officer	Cha et al. (2009)
2	Appointment of labour solely for waste management	Jinkuang and Yousong (2011)
3	Little or no overtime for construction workers	Nagapan et al. (2013)
4	Employing workers responsible for on-site waste collection	Yuan (2013)
5	Waste management and materials handling vocational training for operatives	Wang et al. (2014); Esin and Cosgun (2007); Tam (2008); Ikau et al. (2013)
6	Dedicated site team or specialist sub-contract package for on-site waste management	Dainty and Brooke (2004)

4.6 Summary of the Chapter

Tendencies of waste management strategies to reduce construction waste depends on the extent to which it considers factors capable of impacting waste generated by construction activities. In order to develop a holistic strategy for a waste-efficient project, a comprehensive review of factors capable of influencing waste was carried out using a systematic review search methodology. The identified factors were grouped based on their respective stages of implementation, which could be design, procurement or construction stage of project lifecycle.

As efforts made at design stage could reduce overall waste, some design measures for reducing waste landfilled by construction activities were identified and grouped into five categories. These are design teams' attributes and competencies, design document quality, efficacy of the design process, longevity and deconstructability thinking in design and buildability/constructability of the design.

Meanwhile, certain percentage of waste generated in construction activities is attributed to ineffective coordination of materials procurement. In order to ensure waste-efficient procurement, which is capable of reducing construction waste and diverting generated waste from landfill, several factors need to be considered. These set of factors were established and grouped into five categories. These categories include suppliers/vendors' attribute, contractual clauses, materials handling and storage measures, materials purchase management, and materials delivery management. Similarly, construction strategies for diverting waste from landfill were identified and grouped into seven important categories. These include contractors/sub-contractors' attributes and competencies, contractual arrangement, waste effective construction technique, construction management practices, industry cultural change, legislative framework and human resources management. The factors established under each category were presented in Tables 4.1 to 4.12.

CHAPTER 5: RESEARCH METHODOLOGY

5.1 Overview of the Chapter

The purpose of this study is to develop a holistic design, procurement and construction protocols for waste-efficient construction projects. In this chapter, epistemological assumptions underpinning the whole study as well as the methodological approaches adopted in undertaking the study are presented. The chapter explicates various interrelated elements of the study in a manner that portrays their sequence. Possible strategies and methods to the study were identified and evaluated, and justifications for preferring one approach to others were made. The chapter addresses three major elements which are theoretical assumptions underpinning the study, strategy of enquiry and the research design.

The methodological and epistemological assumptions, which cover the research philosophy and research strategies, are addressed in the first two sections. The strengths and weaknesses of each philosophical school of thoughts were evaluated, with respect to the focus of the study to theorise the study within suitable worldview and epistemological perspectives. This was then followed by a critical evaluation of research strategies, otherwise known as research methodologies, to determine which and which congruent with the focus of the study. Suitability of the research strategies for this study was analysed, and justification in favour and against each of them preceded selection and explanation of appropriate methodological viewpoint.

Further in the chapter, different research design approaches, in terms of qualitative, quantitative and mixed method designs, were swotted in a bid to develop an appropriate design for the study. After a critical analysis, a combination of both qualitative and quantitative methods of data collection and analysis is deemed suitable for the study. On adopting and justifying the need for exploratory sequential mixed method design, a brief summary culminates the chapter.

5.2 Research Paradigms

Research paradigms or theoretical perspective is an important phenomenon that shapes the way research is formulated and implemented (Mackenzie and Knipe, 2006). Kuhn

(1962) defines paradigm as the assumptions and intellectual structure that underlie research and development in a field of enquiry. Just like structural elements to buildings, paradigm determines the integrity of a research activity (Fellows and Liu, 2008). Although scholars separated research methods from paradigms, it still holds that modes of data collection, data analysis, the relationship between researchers and the researched, among others, are largely influenced by the research paradigms (Crotty, 1998; Creswell, 2014). As such, it is important that matters of paradigms are resolved at the inception of a research project. By doing this, the expected relationship would be established between the researchers and the participants, with an appropriate mode selected for data sampling, data collection and data analysis. According to Guba (1990), research paradigm encompasses matter of ontology, epistemology and methodology. This section evaluates various aspects of research paradigms in a bid to view the study with right lenses. It addresses matters of ontology, epistemology, research philosophy as well as the logic of reasoning.

5.2.1 Ontological Assumption of the Study

Ontology is the study of being (Crotty, 1998). Blaikie (2000, p.8) provides a more encompassing explanation, suggesting that ontological claims are ‘claims and assumptions that are made about the nature of social reality, claims about what exists, what it looks like, what units make it up and how these units interact with each other'. He further stressed that ‘ontological assumptions are concerned with what we believe constitutes social reality'. It is a science of being, that reflects how an individual interprets what constitute a fact, and it essentially addresses whether an entity is perceived as being real or relative. The concept of realism holds that there are social phenomenon and realities that exist independent of the social actor. Contrarily, relativism posits that there is no any pre-existing reality than those constructed and being continually accomplished by the social actors (Blumer, 1984).

Meanwhile, different approaches are being used in design, procurement and construction processes towards mitigating waste generation. However, the use of these approaches has achieved less in reducing construction waste. It is however believed that there is that procedural approach that could reduce waste intensiveness of the construction industry. This means that to tackle waste at a holistic level; there is a need to unravel those procedural approaches and protocol for achieving low waste projects. This tends to an assumption that whether we have known it or not, there is an existing approach capable of achieving waste-effective projects. Relating the above analogy from ontological perspectives, it could be argued that reality in this perspective could not be multiple, notwithstanding the possibility of perceiving the optimum approach in a different way. Based on these, relative ontology, which assumes that there is no absolute validity (Blumer, 1984), could not underpin a study that seeks to unravel what is believed to be an optimum approach to waste management. Conversely, a suitable ontological belief underpinning the study is that of realists, which claim that there is only single mind-independent reality (Guba and Lincoln, 2005). According to this ontological perspective, the aim of a research is to unravel that reality which, in the case of this study, is an optimum approach capable of minimising construction waste at design, procurement and construction stages of building delivery processes. Thus, to develop evidence-based waste efficiency protocol; there is a need for value free ontology rather than value-laden assumption, which is otherwise based on conjecture instead of factual evidence.

5.2.2 Epistemological Requirements of the Study

While seeking to understand, predict, explain or control a phenomenon, there are two basic ways of knowing; these are objective and subjective approaches (Dancy *et al*., 2010). The objective approach holds that the researcher should be independent and able to study the research entity without being influenced or influencing the entity (Guba and Lincoln, 2005). As such, Objectivists use pre-defined research instrument, such as questionnaires and structured interview among others, for data collection. Contrarily, subjective research involves understanding and construction of meaning through interaction between the researcher and subjects of study (Collis and Hussey, 2009). Subjective research is devoid of pre-defined research instruments, as reality and meaning are believed to be inter-subjectively constructed (Burrell and Morgan, 1979).

Considering the focus of the study, the two ways of knowing are capable of enriching the outcome of the study. Subjective approach becomes more valuable at the inception of the study, to gain an in-depth understanding of various waste causative and preventive measures through inter-subjective interaction with the industry professional. The overall purpose of the subjective approach at this stage is to ensure that research instrument at the later stage is as exhaustive as possible. This approach would be used at the early stage of the study, when there is little knowledge of the concept under investigation, as the approach is deemed more suitable in a situation where an important phenomenon has been poorly or wrongly conceptualised (Van Manen, 1990; Jasper, 1994). This would, therefore, help in unravelling comprehensive list of measures and factors, which could be further tested through a more objective approach.

While seeking to ensure a generalizable result, there is a need for research sample to be representative of the research population (Creswell, 2014). Ability to arrive at a generalizable result would enhance the value of the study. However, in order to reach out to a representative population, which requires a large number of participants, a cost and time-effective measure is to make use of pre-designed research instrument (Gay *et al*., 2008). While using this, a researcher becomes an objective participant in the study. Owing to this necessity, the study requires subjective and objective epistemologies at its intensive and extensive stages respectively. As the subjective approach would assist in obtaining a comprehensive list of waste mitigating measures, a more objective approach would assist in testing the practicability of those measures, towards proposing practically confirmed protocols for waste-efficient projects.

5.2.3 Philosophical Approach to the Study

A review of extant literature (Pym, 1993; Guba and Lincoln, 1994, 2005; Blumer, 1984; Bhaskar, 1998) shows that paradigms have been explained and exemplified from one another through three basic measures, which are the purpose of enquiry, ontological belief and epistemological perspectives. Based on these distinctive features, each of the research paradigms has its area of suitability, which is determined by what researchers seek to unravel. Irrespective of one's position, justification of researchers' choice of underpinning paradigms gives credibility to their studies (Crotty, 1998). As such, research paradigms are to be considered at the inception of research projects in order to provide a basis for subsequent choice of research methods and research design.

Research paradigms describe pattern of beliefs and assumptions regulating inquiry in a discipline, by providing the framework within which investigation is accomplished (Weaver and Olson, 2006). It provides lenses for viewing and interpreting issues and holds principles and vocabularies governing research approaches. Hinshaw (1996) claims that paradigms are developed by communities of scholar having shared beliefs and presuppositions about what constitutes reality as well as pattern and mode of knowledge acquisition and construction. Adherence to a paradigm connotes that knowledge acquisition, direction of theory development and suitability of research approach and knowledge acquisition procedure are delimited by the paradigm. Thus, each paradigm defines how knowledge is acquired, processed and developed within its tenet.

Different models have been used to categorise existing paradigms in social and natural science. While Burell and Morgan (1979) categorised research paradigms into radical humanism, radical structuralism, interpretivism and functionalism, Guba and Lincoln (1994) categorised paradigms into positivism, post-positivism, critical theory and constructivism. Using similar model as Guba and Lincoln, Crotty (1998) described constructivism as "interpretivism" and included postmodernism and feminism while categorising what was termed as theoretical perspectives. Based on works of Habermas, critical theory is another popularly known philosophical approach to research (Alvesson and Willmott, 2012). According to Krauss (2005) post-positivism as described by Guba and Lincoln (1994), Neopost-positivism described by Manicas and Secord (1982) and what Healy and Perry (2000) described as realism is what is also referred to as critical realism by Hunt (1994). Summing up on these different classifications, positivism, interpretivism, critical theory, postmodernism, and critical realism are evaluated for their relevance to this study.

5.2.3.1 Positivism

Positivism paradigm posits that reality exists independent of the researcher (Guba and Lincoln, 1994). As such, it is epistemologically objective, by holding that the researcher should be independent and able to study the research entity without being influenced or affecting the entity. The primary purpose of positivists' enquiry is to explain, predict and control (Krauss, 2005) by identifying and measuring relevant factors to establish causes and effects of certain relationship. Adherents of positivism philosophy argue that only information derived from logical and mathematical approach could be referred to as the real knowledge (Guba and Lincoln, 1994), with knowledge being based on universal laws that are believed to be unchanging. As positivism involves the use of scientific and mathematical approach, as well as operationalization of words into numbers that could be measured, it also leans more towards a deductive approach to enquiry (Tribe, 2001).

A study underpinned by pure positivist philosophy is characterised by its mind-independent reality (realism ontology), objective epistemology, theory/hypothesis testing rather than generation, extensive use of quantitative approaches to data collection and analysis, systematic approach to data validity, and operationalization of words, among other features (Guba and Lincoln, 1994; Gage, 1989).

Notwithstanding the capacity of positivism in ensuring generalizable results through its objective approach to research, the need for inter-subjective relationship between the research and practitioners could not be over-emphasised in a poorly understood and less explored research area. This need, as required by the study, is, however, antithetical to positivist research which is based on objectivism. Also, while the purpose of positivist research is to explain, predict and control, the study seek to unravel and explain factors/practices capable of reducing waste generated by construction activities. Although the explanatory power of positivism could enhance the study, its prediction and control aspect is not required, just as the paradigm lacks potential for in-depth understanding that is needed at the inception of the study. Thus, positivism paradigm has capacity for addressing the research problem at the later stage of the study and, therefore, it could not provide holistic solution to the research problems.

5.2.3.2 Interpretivism

Interpretivism paradigm is widely known as an antithesis of positivism in that, rather than believing in single mind-independent reality as claimed by positivists, interpretivists argue that there are multiple realities that it is constructed inter-subjectively while meaning is developed through social interaction (Blumer, 1984). As such, to understand meaning of the world, the researcher becomes part of research process (Collis and Hussey, 2009). An interpretive research usually aims at understanding a phenomenon by focussing on social construction and reproduction of meanings, symbols and languages through an inductive reasoning (Myer, 2008; Burell and Morgan, 1979; Berger and Luckmann, 1967). A research underpinned by interpretive philosophy could be identified by its ontological relativism, inter-subjective epistemology, focus on pattern and text, primary use of qualitative approach, value judgement based on individual and group consensus as well as common emphasis on understanding (Burell and Morgan, 1979; Blumer, 1969; Neuman, 2000).

Although there is need to adopt a subjective epistemology towards understanding and achieving comprehensive list of testable factors at the inception of the study, the research is not underpinned by the relative ontology. Again, there is need to generate practically tested measures devoid of individual biases and conjectures that are valued by interpretivists. This suggests that interpretivism philosophy is only capable of addressing the research problems at the early stage of the study, and it lacks objectivism required at the later stage of the study. As such, holistic solution could not be achieved for the research problem through a sole adoption of interpretivism as a philosophical approach.

5.2.3.3 Critical Theory

Critical theory is a philosophical commitment and school of thought that is concerned with criticism of social status quo with a view to change and redistribution of power. Unlike positivism and interpretivism, the purpose of critical theory is not to understand, mirror or predict, but to change it. As such, a critical theory research is expected to be explanatory, practical and normative. This means that it must explain what is wrong with the existing practices, identify change agent and provide strategies required for the desired social transformation (Cohen et al., 2007). Ontologically, critical theory adopts historical and critical realism beliefs, while its epistemology is transactional and contextual (Guba and Lincoln, 1994). It accumulates knowledge through revision/history of existing entities towards transforming, regulating or changing it while allowing the use of both qualitative and quantitative approaches as means of achieving desired results.

Construction management researchers rarely adopt this philosophical approach in their studies, as most research in the field seems to be interested in causal relationship. Construction management studies are also usually interested in improving, generalising and predicting measures capable of advancing professional practices, which might not be fully captured by interpretivist approach and critical theory. The infrequency of this approach in construction management could also be due to great resistance to change that characterised the profession. An example of this resistance is exemplified in the need to repeal the compulsory site waste management plan in the UK, as well as protest of the same regulation by construction professionals in Hong Kong (Shiers *et al*., 2014; Tam, 2008). Thus, construction research is dominated by studies seeking to improve the situation, rather than changing or regulating the industry. Nonetheless, as this study is not seeking to propose change or legislate the current practices within the industry, critical theory, as a paradigm, is deemed inappropriate for the study.

5.2.3.4 Postmodernism

Postmodernism is a movement in philosophical assumptions, as well as arts and architecture, which shifts from generalisation tendencies of the modern era to particularisation, relativism and discontinuity (Crotty, 1998). Unlike other philosophical assumptions, postmodernism posits there is no absolute truth that could explain all things. Rather, truth is believed to be approximate and constantly evolving (Crook, 1991). Postmodernists believe that truth could not be represented by what it is perceived to be. As such, truth is constructed at individual level, and it could not be valid for all groups, races and cultures among others (Burell, 1988). Thus, postmodernism assumes that truth is relative, as what constitutes truth for a group might not be true for others (Feyeraband, 1990). Studies underpinned with postmodern perspective usually make explicit reference to relativism, reflexivity and deconstruction, and are more likely to employ unconventional textual forms with possible citation of its theorists. This approach is not relevant to this study as the study is aimed at constructing what seems to be evidence, rather than deconstructing existing claim as preferred in postmodern philosophy.

5.2.3.5 Critical Realism as the Paradigmatic Approach to the Study

Also referred to as an ontological assumption of post-positivism philosophy (Guba and Lincoln, 1994), critical realism has received significant attention as a research paradigm (Krauss, 2005; Yeung, 1997). The purpose of critical realism is neither to uncover general law nor to understand irregularities; it seeks to uncover, understand and explain mechanisms that underlie an event (Bygstad and Munkvold, 2011). While positivism and interpretivism believe in single and multiple realities respectively, critical realism is concerned with multiple perspectives to a single reality, which is mind-independent (Krauss, 2005; Sayer, 1992). Thus, the philosophical stance possesses realist ontology in similitude to positivism and subjective epistemology like interpretivism. However, ontological entity takes preference over epistemologies in critical realism perspectives (Yeung, 1997).

While seeking to research underlying mechanism that drives an effect and action within the realm of critical realism, both qualitative and quantitative approaches could be used (Healy and Perry, 2000). As such, a critical realist research could feature both unstructured and structured data as well as statistical analysis and modelling (Krauss, 2005). The essential features of a study underpinned by critical realism philosophy include its interest in cause and effects, investigation of mechanism underlying an event or action, causal explanation, use of qualitative and quantitative approach – each at intensive and extensive scales respectively – as well as multiple perspectives to single reality (Sayer, 2000; Krauss, 2005).

As in the case of this study, critical realism has an overwhelming relevance to a study seeking to understand a mechanism producing an event (Sayer, 2000). It has realist ontology and posits that there could be multiple understanding of a single mind-independent reality (Yeung, 1997). Although it is usually described as having subjective epistemology (Krauss, 2005), it supports the use of both qualitative and quantitative approaches to data collection and analysis (Sayer, 2000; Hunt, 1991; Healy and Perry, 2000). As such, it supports both the subjective and objective approaches required by the study at earlier and later stages respectively. Just as the purpose of critical realism is to uncover a mechanism underlying an event, the purpose of the study is to unravel factors capable of producing a waste-efficient project.

According to Sayer (2000), a wide scope critical realist study would start with an intensive approach and end with a broad approach. The purpose of intensive study is to start with subjective and qualitative research of individuals, groups or cases under investigation using interactive interview, ethnography and qualitative analytical procedures (Sayer, 1992). While the intensive approach is to explore what makes things happen in specific cases, extensive research investigates vastness of an occurrence within a large population (Sayer, 2000). A large-scale survey, structured interview, questionnaire, statistical analysis and other quantitative tools could be used at extensive stage of critical realist study (Hunt, 1991).

Value-cognizant nature of critical realism would assist in uncovering mechanism capable of driving low waste projects by considering multiple understanding of appropriate strategies for driving waste-efficient project. This would be achieved by using qualitative approach to data collection and data analysis, such as unstructured interview, focus group discussion and archival analysis. At later stage of the study, which is aimed at exploring extensiveness of the identified factors within the construction industry, objective status would be taken, and quantitative approach to data collection and analysis is more appropriate (Sayer, 2000). While elements of interpretivism and positivism would be employed at early and later stages of the study respectively, powerful explorative, explanatory and analytical tools offer by intensive and extensive nature of critical realism aid its suitability for the study. Therefore, the study is underpinned with the philosophy of critical realism.

5.2.4 Research Approach and Reasoning Technique

Interpretivism involves an inductive reasoning (Berger and Luckmann, 1967), while positivism involves a deductive reasoning (Tribe, 2001). Based on its philosophical underpinning, the reasoning technique of the study would follow retroductive pattern, which allows researcher to refine and redevelop social theory in a continuously evolving and dynamic process (Sæther, 1998; Ayim, 1974). It would also assist in identifying circumstances that are critical to existence of an event (Lawson, 1997). At the early stage, the study would follow the process of induction, which would assist in generating certain theories and propositions that could be improved through further deductive research. At the later stage, the theory and propositions would be further refined and redeveloped, as circumstances required for its validity would be established through an extensive study. As such, the study would not only identify measures capable of improving waste efficiency of projects; it would refine and redefine the measures, thereby identifying circumstances that are required for achieving the desired output.

5.3 Research Strategy

Otherwise catalogued as research methodology, research strategy is an essential element of research that determines overall direction through which the study is conducted. The choice of a research strategy is determined by research question, extent of available knowledge of the research area, philosophical assumption of the researcher as well as the length of time available for the study (Saunders *et al.*, 2009). Similarly, Yin (2003) suggests that the choice of a research strategy is informed by the extent of researcher's control over behavioural event, nature of the research question as well as whether the study focuses on contemporary or historical events. Although there are various interrelationships among the research strategies (Yin, 2003), common research strategies with distinctive characteristics are case study, experimental, action research, ethnography, grounded theory, phenomenology, narrative and survey research (Saunders et al., 2009; Collis and Hussey, 2009). Nevertheless, it is important that a researcher evaluates the focus of the study in a bid to adopt the right strategy for the enquiry (Walliman and Baiche, 2005).

5.3.1 Case Study Research

Case study strategy involves an in-depth investigation of a person, event or a phenomenon in a bid to gain detail understanding of the concept under investigation. It is a systematic enquiry into an event, or series of related event, that is usually aimed at describing and explaining certain phenomenon (Yin, 2003). While carrying out a case study research, a variety of data collection approaches could be used over a time bounded period (Creswell, 2014). According to Yin (2003), a case study research could be exploratory, explanatory or descriptive in nature. Research might adopt single or multiple case studies as an approach to enquiry. Although the study required information from experts within the construction industry, it is not specific to any case study. Rather, experts' knowledge is explored across different cases to determine best practices that are independent of building types, materials, procurement routes and construction techniques, among others.

5.3.2 Experimental Research

Experimental research is another strategy to enquiry that involves manipulation of a variable to determine its impacts on another (Taylor *et al.,* 2006). The purpose of experimental research is to determine effects of change and control in one variable on the outcome of the other variable. However, because the goal of this study is neither to test impact of change in any variable on another, nor to test any theory or hypothesis, this strategy is not applicable in the study.

5.3.3 Action Research

Also known as problem-solving research, action research is a research strategy that is usually employed when a researcher seeks to effect a change or solve an immediate problem (Taylor *et al.,* 2006). The main assumption behind this strategy is that a mere research, and explanation by uninvolved researcher, is inadequate to implement the desired change. Rather, those usually refer to as research subjects should actively participate in studies (Stringer, 2014). It starts by identifying a real life problem, and then research into the mode of solving the problem, with the researcher being part of the practices or collaborating with actively involved practitioners. The purpose of an action research is to effect a change in practice. Although this strategy is effective as a change-driven approach, the purpose of the study is not to implement any change but to determine the measures that could improve waste efficiency of design, procurement and construction processes. As such, this strategy is not suitable for the study.

5.3.4 Ethnography

Ethnography research is a study of social interaction and perception that occur among group of people in their natural settings over a prolonged length of time (Reeves *et al*., 2008; Creswell, 2014). It is a branch of anthropology whereby researchers immerse themselves into the setting under investigation to gain an emic perspective and first-hand information about a phenomenon or people under investigation, with participant observation being the main mode of data collection (Hammersley and Atkinson, 1995). As the focus of this study is neither to understand social interaction or perception of any group, nor to gain an emic view of the concept under investigation, but rather to gain an etic view of the experts, ethnography research is not suitable for the study.

5.3.5 Grounded Theory

Grounded theory is an inductive research strategy of inquiry that involves systematic generation of theory from data. It involves iterative and multiple stages of data collection and refinement with the sole purpose of generating abstract theory that is grounded in the views of research participants (Creswell, 2014). According to Goulding (1999), the main impetus behind the grounded theory is to ensure that theory is grounded in data rather than empirically uninformed theory. Nonetheless, because the sole purpose of the study is not to ground theory in data through an iterative approach, grounded theory strategy is not applicable in the study.

5.3.6 Phenomenological Research

Phenomenological research is a strategy of enquiry whereby the researcher describes the experience of the research participant with respect to a phenomenon under investigation (Creswell, 2014). According to Crotty (1998), the concept of phenomenology is based on tenet that a particular situation could not be truly understood until all presuppositions and preconditions are suspended by a researcher (Holloway and Wheeler, 1996) in a bid to devise new meanings. It recognises the researchers as interpreters of the participants' experience and actions, and it is concerned with the individual's perception and account of the events under investigation (Edie, 1987), devoid of objective meanings imposed by the researcher (Smith and Osborn, 2007). The phenomenological approach, therefore, avails the researchers an opportunity to understand the existing waste management practices and waste causative factors from practitioners' point of view, devoid of every presupposition. This is deemed relevant to the study, as the approach is suitable in a situation where a significant phenomenon has been poorly or wrongly conceptualised (Jasper, 1994; Van Manen, 1990). Thus, the phenomenological approach would assist in understanding waste impacting factors from practitioners' point of view.

5.3.7 Narrative Study

As the name implies, narrative research is a strategy of enquiry that is relevant when the life of an individual is studied in a bid to retell the story in a narrative chronology (Creswell, 2014). This strategy is not applicable in the study, as the study is not aimed at unearthing lived experience of any individual.

5.3.8 Survey Research

Survey research is another research methodology that involves collection of quantifiable data through a standardised instrument (Sapsford, 2007). It is a standardised mode of collecting information from a population by selecting a sample of respondents from the population and administering questionnaire to them (De Vaus, 2002). The research strategy is very useful in reaching out to a large population by distributing the same questionnaire towards establishing wider view of the population. At the later stage of this study, survey research strategy would be employed to elicit broader opinion of large population on findings of earlier qualitative studies. By doing this, there is tendency for generalizability of the findings of the study.

5.3.9 Summary of Pertinent Strategies for the Study

Having evaluated a wider range of research strategies, two strategies that were chosen for this study are phenomenology and survey research. For each of the research strategies, different modes of data collection and analytical procedures would be used. The phenomenological research was carried out at the early stage of the study, and its findings were integrated into survey research that culminated the study.

5.4 Research Design

When designing research, a researcher is faced with options of selecting either qualitative or quantitative approach to data collection and analysis. In recent time, studies that involve integration of the two methods have become commonplace (Bryman, 2006). Creswell (2014) argued that qualitative or quantitative are not necessarily rigid and distinct dichotomy, a study could be either more of qualitative or more of quantitative approach. While irreducible boundary exists between people who claim that knowledge is uniquely constructed by individuals (relativists) and those who argue that reality is external and only awaits human discovery (realists), less significant division exist between users of different methods as they belong to all researchers irrespective of epistemological differences (Bernard, 2000). Neither of the two methods is better than the other (Tashakkori and Teddlie, 2010), the choice of methods heavily relies on what the researcher intends to unravel as well as the wider theoretical and methodological lenses within which the study is viewed (Creswell, 2010; Crotty, 1998; Grix, 2004). Nonetheless, the two methods are evaluated for their relevance to this study.

5.4.1 Qualitative Method of Enquiry

Qualitative research is a method of enquiry that is focussed on exploring and understanding certain phenomenon by developing a holistic picture of the meaning ascribed to human or social problems by research subjects (Denzin and Lincoln, 2011; Creswell, 2003). This method relies heavily on text and image data collected in the natural settings where the participants experience the problems under study. Thus no research instrument is pre-defined (Creswell, 2014). The qualitative method of enquiry is rooted in constructivist perspective (Guba and Lincoln, 1994), which tends to claim that knowledge is socially constructed (Crotty, 1998). Owing to this, no theory is usually placed at the beginning of the study, but as the meaning evolved from interpretation of the participants' viewpoints, it honours an inductive style of inquiry (Psathas, 1973; Bloomberg and Volpe, 2012). Thus, qualitative method offers exploratory approach to knowledge acquisition.

While adopting qualitative methods of enquiry, the researcher becomes a key research instrument who posits to examine documents as well as the behaviour and reaction of the participants (Creswell, 2014). Sources of qualitative data may include audio-visual information, observations, interview and other forms of document, which are recorded, organised and reviewed in a bid to understand the data based on interpretation of the participants (Bernard, 2000; Berg and Lune, 2004). Data could then be analysed using different methods of analysis, which could involve content analysis, discourse analysis, domain analysis and thematic analysis, among others (Adams et al., 2007; Bryman, 2006; Attride-Stirling, 2001). Irrespective of these approaches, analytical process usually involves data familiarisation, coding, search for themes, review of themes and definition of themes (Braun and Clarke, 2006). The ultimate goal of qualitative study is to gain a comprehensive understanding of the phenomenon (Denzin, 2009; Schutt, 2006).

5.4.2 Quantitative Method of Enquiry

Quantitative research seeks to examine relationship between variables to explain a phenomenon (Cohen et al., 2007; Charles and Metler, 2002). Rather than the use of words as could be important in qualitative approach, quantitative researchers are convenient with the use of numbers and operationalization of words (Crotty, 1998). Qualitative method is underpinned by positivist claim that tends to believe in "out-there-ness" of reality and knowledge (Kidder and Jud, 1986). As such, the approach is to explain cause and effects using set of tactics such as theory testing, hypothesis and question, measurement and observation. It relies on numerical instruments that are designed independently of the research subjects (Creswell, 2014).

Unlike in qualitative studies, a quantitative researcher is external to the research and is objective in relationship and judgement of research phenomenon (Pym, 1993). Quantitative data are collected with structured research instruments that could include close-ended questionnaire, structured interview, among others (Cohen et al., 2007). It usually involves larger sample that is representative of research population. Data is then analysed using various techniques of statistical analysis because of its preference for numerical data and operationalization (Schutt, 2006). In short, the overall purpose of quantitative research could be descriptive, which is to explain phenomenon, or experimental, which is to establish causality and predictions, using various sets of numerical data.

5.4.3 Mixed Method as the Pertinent Approach to the Study

A mixed method research involves the use of both qualitative and quantitative method at any point or throughout the course of research (Saunders et al., 2009; Tashakkori and Teddlie, 2010). A study adopts mixed method if it involves both qualitative and quantitative data collection and analysis (Creswell, 2014), or it analyses qualitative data quantitatively or vice versa (Saunders et al., 2009). Other terminologies that have also been used to describe this form of research design include “multi-method” (Saunders et al., 2009), “integrating” and “synthesis” (Creswell, 2014), with mixed method becoming its standard terminology (Tashakkori and Teddlie, 2010). Methods could be combined for different purpose, which may be triangulation (corroboration), complementary (elaboration), development, initiation and expansion (Bryman, 2006; Greene at al., 1989).

Considering the relevance of each method to this study, there is clear indication that both qualitative and quantitative methods would help in unravelling different aspects of the study. Because of complex focus of this study, neither qualitative nor quantitative approach is robust enough to capture the need for understanding, development, prediction and explanation that is required in complex management of construction waste. Understanding the factors influencing waste requires exploration of existing studies and expertise knowledge at the inception. This would help to acquire knowledge that could metamorphose into a further research tool that is capable of explaining and predicting holistic patterns of project coordination. Again, while there is serious need to understand the phenomenon, prediction and explanation of what constitutes effective design, procurement and construction process for a waste-efficient project is required of the study. Also, applied research requires combination of both qualitative and quantitative methods (Creswell, 2014). Thus, the study adopts a mixed method for data collection and analytical process, and as such, it involved both formative and summative evaluation procedure. The value of a mixed method design is that a method does not only corroborate flaws in one another, it is also suitable in revealing high quality and complex inference (Ivankova and Kawamura, 2010)

While designing a mixed method research, a researcher needs to address three core issues, which are priority, implementation and integration of the methods (Creswell et al., 2003; Creswell et al., 2004). Priority is concerned with which of the methods is given heavier weight and utmost attention, implementation addressed the issue of which comes first in the sequence or whether they are concurrent, while integration refers to the stage at which integration of the methods takes place (Ivankova et al., 2006; Green et al. 1989). Based on these yardsticks, a mixed method could be convergent parallel mixed method design, when a researcher collects both qualitative and quantitative data, analyse them separately and then compares the results for the purpose of triangulation (Creswell, 2014). If a research involves two—phase process where quantitative data collection and analysis is followed up with a qualitative study for further explanation, such design is an explanatory sequential mixed methods design (Ivankova et al., 2006). This design appeals more to adherents of quantitative design with interests in mixed approach (Creswell, 2014).

The last approach to mixed method design that is adopted in this study is exploratory sequential mixed methods design. It involves initial exploration of research phenomenon, using qualitative data and analysis, with use of the qualitative findings in the second phase of the study where quantitative data collection and analysis is employed (Creswell, 2014).

The aim of this type of research design is to develop a robust research instrument from the initial qualitative study and further test if the initial finding is generalizable to a larger population. In such case, the first stage could involve focus group and interview data (or other qualitative data). It is then analysed, and its findings are used to develop a quantitative research instrument (such as questionnaire) that would be administered to larger population (Creswell, 2014). As depicted in Figure 5.1, this sequential exploratory study involved two phases, involving exploratory study at the qualitative level and the use of questionnaire for quantitative data collection. The data was then analysed through various means of quantitative data analysis and modelling.

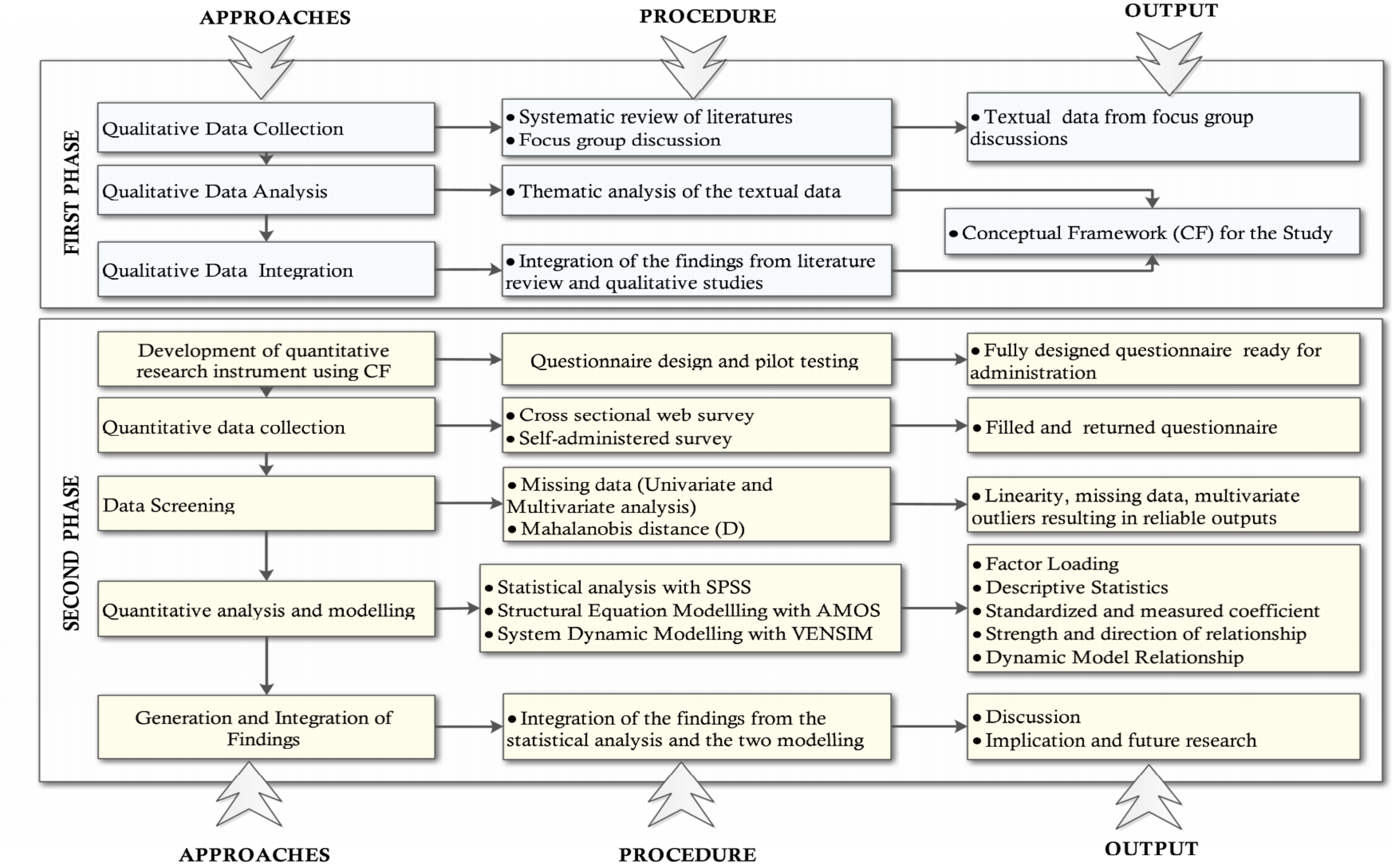


Figure 5.1: Phases of the exploratory sequential mixed method research

5.4.4 Role of the Researcher

Both subjective and objective roles were taken at the early and later stages of the study respectively. At the level of qualitative data collection, the researcher took a participatory role by interacting with the research participants towards exploring new concepts (Creswell, 2003). However, care was taken to prevent biases that could be due to this nature of interaction by ensuring that researcher only served as moderator without influencing free expression of participants' opinion. Coding and analysis of data evolved from specific terminologies used by the research subjects. At the quantitative phase of data collection, objective approach was taken. Data was collected with a pre-tested research instrument, capable of self-explanation, thereby devoid of subjective interpretation and interaction with the participant. The data was collected, analysed and validated through rigorous statistical analysis and established value for statistical significance. This, therefore, prevented likely bias that could rather mar the outcome of the study.

5.5 Chapter Summary

In order to employ the right method of enquiry for the study, various research concepts including paradigms, approaches, methods and strategies have been evaluated for relevance to this study. Based on the critical evaluation, justification has been made for the use of critical realism, as a philosophical lens for the study. As the tenet of critical realism supports the use of qualitative and quantitative approach, the two methods of data collection and analysis were found to be relevant at intensive and extensive stages of the study respectively. Based on this, an exploratory sequential mixed method design is the most suitable research design for fulfilling the aim of the study. At the early stage of the study, phenomenological approach, in support with systematic review of the extant literature, provides avenue for collecting rich information required for the study. Survey research is justified to be the most suitable strategy for extensive investigation at the later stage of the study. Thus, the exploratory sequential mixed method research is underpinned by critical realism as paradigmatic perspective to the study. Table 5.1 summarises the available choice of epistemological and methodological approaches for studies; choices made for the study and justification of the various choices.

Table 5.1: Research epistemological and methodological choices for the study

Areas of Choices	Available Choices	Choices Made	Justifications for the Choices Made
Research Strategies	Narrative; Phenomenology; Grounded Theory; Case Study; Ethnography; Experimental; Quasi-Experiment; Action Research; Survey Research	• Phenomenology • Survey Research	At the inception of the study, phenomenological research (and its variances) avails an opportunity to understand the existing waste management practices and waste causative factors from practitioners' point of view, devoid of every presupposition (Moustakas, 1994). At the later stage of the study, survey research provides a means of testing the generalizability of measures identified through literature review and phenomenology (Creswell, 2014).
Research Approach/Logic	Induction; Deduction; Abduction; Retroduction	• Retroduction	The study seeks to work from qualitative data to develop a conceptual framework. This would then be followed by further quantitative studies to generate findings. This need involved the use of both inductive and deductive reasoning at early and later stages of the study. As such, the study requires retroductive reasoning, which includes the two reasoning logics (Ayim, 1974).
Methods of Inquiry	Qualitative; Quantitative; Mixed Method	• Mixed Method	The study adopts both qualitative and quantitative approaches for collecting and analysing data. While qualitative method results in subjective data, quantitative method is highly objective. By combining the methods, error inherent in one would be prevented by the other (Collins, 2007).
Types of Mixed Method Design	Exploratory Sequential Explanatory Sequential Parallel Sequential	• Exploratory Sequential	As the study starts from qualitative approach and ends up in quantitative approach to data collection and analysis, this mixed method technique is referred to as exploratory sequential mixed method research (Creswell, 2014).
Sources of Data/Evidence	Documentation; Interview; Focus Group; Observation; Questionnaires; Artefacts; Archival Records	• Focus Group • Questionnaires	In addition to the literature review, focus group discussion served as a means of collecting qualitative data at the intensive stage of the study. At the later stage (extensive), findings from the qualitative data were put into a questionnaire survey, which served as a means of collecting quantifiable data.
Means of Data Analysis	Statistical Analysis; Structural Equation Modelling (SEM); Cognitive Mapping; Thematic Analysis (TA); System Dynamic Modelling (SDM); Content Analysis; Case Description	• Statistical Analysis; • SEM • TA • SDM	The thematic analysis offers an approach for bringing out emerging themes from qualitative data collected through focus group discussions (Braun and Clarke, 2006). The quantitative data analysis involved the use of statistical packages for data screening, preliminary analysis and descriptive statistics. Apart from providing input into SDM of the interplay between stages of project delivery, SEM was valuable for Confirmatory Factor Analysis.
Research Philosophy	Positivism; Interpretivism; Critical Realism; Critical Theory; Pragmatism; Postmodernism	• Critical Realism	The thinking of this study would be shaped by critical realism. Unlike interpretivism which allows a sole use of subjective epistemology, and positivism which allows only the use of objective approach, critical realism allows the use of both qualitative and quantitative methods at intensive and extensive levels (Sayer, 2000). At earlier stage (intensive), it allows the use of a subjective medium, while also allowing the use of objective medium at a later (extensive) stage.

CHAPTER 6: QUALITATIVE STUDY AND FRAMEWORK DEVELOPMENT

6.1 Chapter Overview

As an exploratory sequential mixed method research, this study commenced with qualitative study and ended with quantitative data collection and analysis. The procedural approach used for the first stage of the study is presented in this chapter. This involved justification and detailed description of the research processes, which covers research population and sampling techniques, types, medium and process of data collection, modes of data analysis as well as matters of trustworthiness and ethical considerations. Findings from previous systematic literature review are also integrated with the findings from the qualitative study to develop conceptual framework for further studies. A brief and concise concluding summary culminates this chapter.

6.2 Sample and Sampling Techniques

The overall goal of this study is to develop a holistic protocol capable of reducing waste generated by construction activities. Owing to this, the target population for the study are the stakeholders in the construction industry. A person is deemed fit for the study if his/her job description fall within, or working for, any of architects, civil/structural engineer, contractor, sub-contractor, construction project manager, and site waste manager. Whether the job is office or site based, such person must have been working within the construction industry for a couple of years before deemed information rich for the study. In this regards, a delimiting factor of 5 years was selected to ensure that all participants have adequate experience in the construction industry.

Sampling for the qualitative phase of the study was done through a technique referred to as purposive (Merriam, 1998) or judgement sampling (Gay et al., 2006). This sampling technique is suitable for a qualitative research (Patton, 1990), as it allows researchers to freely select information-rich participants to gain an in-depth understanding of the phenomenon under investigation. However, the group of participants were selected based on critical sampling, which ensures that professions involved from project planning to completion are involved. This sampling technique was used based on Creswell’s (1998) assertion that it ensures logical applicability of the finding to other cases. As such, architects, civil/structural engineers, construction project managers and site waste managers were involved in the focus group discussions.

Two major sources that assisted in reaching out to the research participants are databases of certified construction professionals and network of contacts enjoyed. Other studies that have employed this sampling technique within the design and construction management include Akintoye et al. (1998), Oyedele (2013), Ajayi et al. (2015), and Hodgson et al. (2011), among others. The databases include Royal Institute of British Architects (RIBA), Institution of Civil Engineers (ICE), Chartered Institute of Building (CIOB), Royal Institute of Chartered Surveyors (RICS), Association of Consulting Engineers (ACE), Association of Project Mangers (APM), Institution of Structural Engineers (IStructE) and Chartered Institute of Wastes Management (CIWM).

6.3 Data Collection Method

While carrying out an exploratory data collection in qualitative research, in-depth interview with individual participant or focus group discussions could be employed (Creswell, 2013). These approaches are particularly relevant for exploratory research as they allow emergence of new concepts (Wimpenny and Gass, 2000), which is against limiting the researchers to ranking of pre-defined factors that might not be comprehensive. In this study, focus group discussions were used as it allows exploration of inter-subjective opinion among the research participant to arrive at their common understanding. Also, focus group discussion was preferred to individual interviews as it allows the participants to build on one another's opinion throughout the course of discussions (Kvale, 1996).

Before the focus group discussions, the participants were invited through a written invitation that explained the purpose of the study. They were also intimated about the nature and scope of the focus group discussions before the scheduled meeting. In all, 36 participants were involved in four cross-disciplinary focus group discussions. The cross-disciplinary nature of the discussions avails the opportunity of establishing common understanding of those involved from design to completion of construction projects.

Designers, contractors, project managers, and other expertise professions were purposely included in each discussion as evidence shows that they usually shift the blame to the designers (Osmani et al., 2008; Oyedele et al., 2014). Having them together in a focus group discussion assisted in critical examination of intersubjective opinions, thereby arriving at consensual opinion. The participants were selected from across UK design and construction firms ranging from small to large organisation, and they have years of experience ranging from seven to 27 years. All the participants have been involved in various projects within the last five years, and they are committed to waste minimisation in construction projects. Table 6.1 shows the distribution of 30 participants involved in all the discussions. Each of the discussions spanned between 102 and 120 minutes, and they were recorded for facilitation of data analysis.

Table 6.1: Overview of the focus group discussions and the participants

FG	*Categories of the Participants*	*Total No of experts*	*Years of experience*	*Duration (in minutes)*
1	• 2 architects and design managers • 2 structural/civil engineers • 1 site waste manager • 2 project managers • 1 Others**	8	7 – 26	*111*
2	• 2 architects and design managers • 1 structural/civil engineer • 1 site waste manager • 2 project managers • 1 Others**	7	11 – 23	*102*
3	• 2 architects and design managers • 1 structural/civil engineer • 2 site waste managers • 2 project managers • 1 Others**	8	10 – 27	*119*
4	• 2 architects and design managers • 1 structural/civil engineer • 1 site waste manager • 2 project managers • 1 Others**	7	9 – 25	*120*

*** "Others" refers to sustainability experts, supply chain managers and lean practitioners in construction.*

6.4 Data Analysis

While carrying out a qualitative data analysis, the first step is reading and exploration of the data to ensure adequate familiarisation (Braun and Clarke, 2006). This is then followed by coding of the data, which is done by segmenting and labelling the text data. Similar codes are then aggregated to develop themes, which are to be thoroughly reviewed before connecting interrelated themes with one another (Creswell, 2002). In line with this process, the recorded interview was converted into written scripts, which was then analysed to establish both strategies and competencies for facilitating low waste projects. This was achieved through qualitative analysis of the focus group transcripts with the aid of Atlas-ti version-7. Owing to the need to go beyond word counting, content driven thematic analysis was used for data analysis, as it considers both explicit and implicit ideas within the data (Braun and Clarke, 2006).

6.4.1 Coding Scheme and Categorization

The coding scheme and final categorization of identified factors were based on dominant themes that emanated from individual and combined analysis of data from all focus group discussions. The coding scheme was used to identify the strategies for engendering low waste projects as well as the broad categories of strategies and competencies. Generation of initial codes was facilitated through "word cruncher" facility provided by Atlas-ti qualitative data analysis tool. Apart from a thorough reading of the transcribed data, the word cruncher enhances a general overview of commonly used words that existed in the data. As such, the study employed a data-driven coding technique, which ensures a holistic processing of all themes evolving from the data (Braun and Clarke, 2006).

In line with Gu and London (2010), and as further recommended by Silverman (2006) and Burnard et al. (2008), coding system and theme identification were engendered through the use of labelling. In this case, the labels used for the analytical processes were code, the number of occurrences, specific quotation, summed up statement (theme) and the number of summation. "Code" marks the words that resulted in the identification of waste-efficient measures at design, procurement and construction stages. "Number of occurrences" defines the number of time that the code existed in the data. "Specific Quotation" refers to a typical respondent's statement that is associated with the code, while summed up statement is a phrase used to denote what is intended by the respondents’ statement. “Number of summations” on the other hand refers to the number of quotations that could be summed into each of the identified unique statement (theme).

In order to demonstrate how the themes emerged from the interview data, Table 6.2 shows examples of coded segments.

Based on the previously reviewed literature, similar themes were mapped together to form broader themes. The themes explain more holistic measures that are generated by combining very similar factors emanating from the data. For instance, knowledge of real life site layout and knowledge of construction processes are an integral part of a larger theme referred to as "construction related knowledge".

Table 6.2: Examples of coded data segment

Code or supercode	Number of occurrences	Examples of specific quotation (from the focus group discussion transcript)	Summed up statement	Number of summations
Take-back scheme	79	"…. most of the waste we generate onsite are due to materials left unused after the projects. You will not only reduce waste if you have take-back agreement with your suppliers, but you will also save some money…."	Commitment to **take back scheme**	29
Just-in-Time	65	"Most of us do not use Just-in-Time delivery because it is cheaper to transport your materials in bulk. But if you estimate the cost of waste it prevented, you will realise that it is a better option."	Use of **Just-in-Time** delivery system	28
Flexible	49	"...for us to reduce demolition and renovation wastes, it is important that designers are good at flexible and adaptable designs…."	Design for **flexibility and adaptability**	16
Reuse	116	If a designer lacks knowledge of what and what are reusable onsite, they will fail to integrate them into their designs…."	Integrate **reusable elements** into design	14

6.5 Issue of Trustworthiness

In order to enhance methodological credibility of the qualitative study, the research design is not only evidence-informed, but data from focus group discussions were also combined with findings from systematic review of literature. A combination of these approaches ensures adequate exploration of required phenomenon. Interpretive validity was ensured by using codes that are representative of original terminologies used by the research participants, as this enhance overall dependability of the analytical process (Guest et al., 2011). A search for discrepant evidence and peer review was made as recommended by Lincoln and Guba (1985). Also, other measures for enhancing credibility were adopted. These include recruitment of people to check for accuracy of themes, external audit system where a person external to the study carried out its evaluative review (Creswell, 2003).

6.6 Ethical Consideration

Ethical issues relating to protection of research participants are important consideration in every research (Merriam, 1998). Although such groups as under-aged, disabled and other vulnerable groups were not involved in this study, effort was made to inform and protect the respondents in an ethical manner. The study followed basic ethical guidelines in gaining consents and permission, briefing of the participants as well as in ensuring anonymity of the participants. The research sought written consent from participants before participating in the study and their right not to answer certain question or to withdraw from the study was made known.

Since the goal of this study is not to link findings to individual participants or companies, no traceable link has been made to any of the participants; and as such, anonymity of the research participants and participating firms and organisations is assured. Research related data was also stored and managed in a way that is solely available to the researcher.

6.7 Qualitative Research Findings and Conceptual Frameworks

The qualitative research findings are combined with earlier literature review findings presented in chapter 4. As the study covers the design, procurement and construction stages of project delivery process, the combined findings are presented under the three sections.

6.7.1 Design Measures and Competencies

Based on the focus group discussions and literature review, 78 factors were established and group into four main categories, with each having further sub-groupings. Table 6.3 presents the list of the design factors and competencies.

Based on underlying latent factors influencing design efficiency for low waste projects, a conceptual framework for designing out waste is presented in Figure 6.1. The Figure provides a list of phenomenon influencing waste, and it is further tested through quantitative approach.

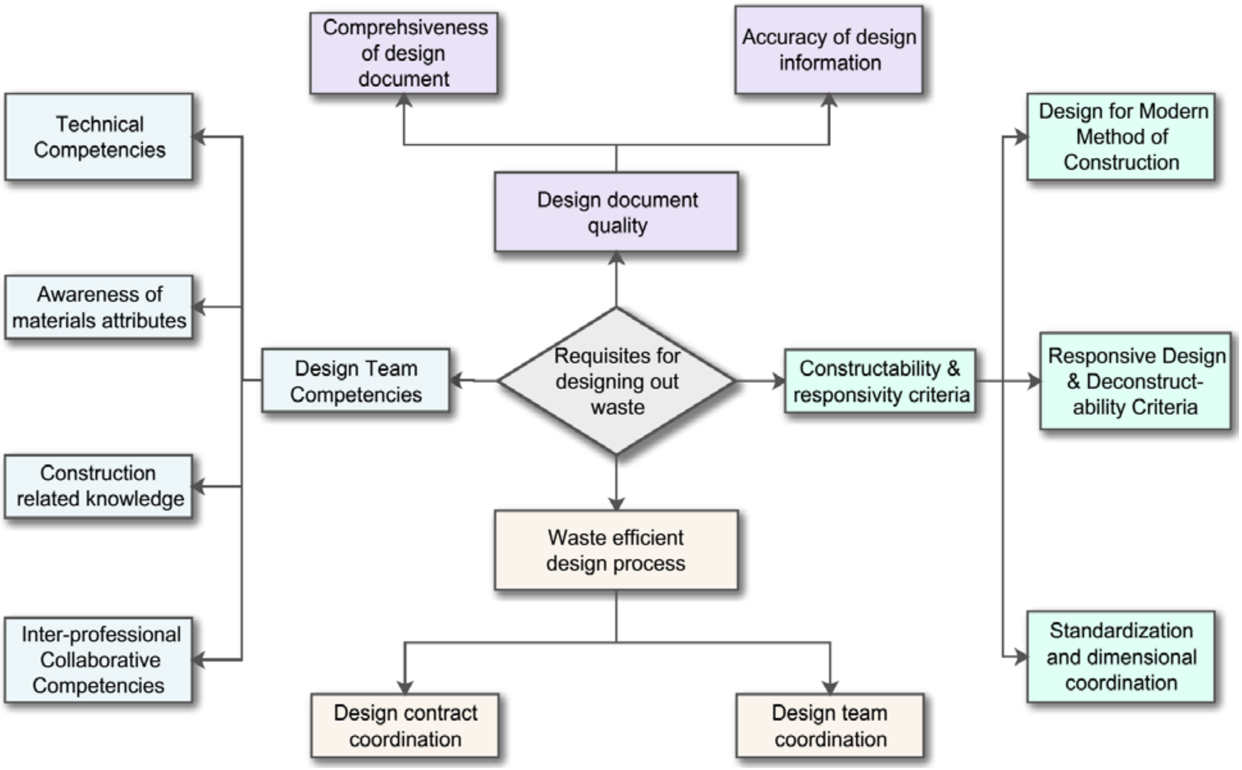


Figure 6.1: Framework of strategies for designing out waste

Table 6.3: Design factors and competencies for low waste construction projects

Underlying Features	***Design Measures and competencies for reducing construction waste***	***References from extant literature***	***Focus Groups***			
			1	**2**	**3**	**4**
Design Team Competencies						
Technical Competencies	Design for standard materials supplies	Ekanayake and Ofori (2004)		✓	✓	✓
	Ability to produce error-free documents	Dainty and Brooke (2004)	✓	✓	✓	✓
	Careful dimensioning of design to avoid cutting to fit	Faniran and Caban (1998)		✓	✓	✓
	Careful attention to detail at planning/design	Faniran and Caban (1998)	✓	✓	✓	✓
	Proficiency in materials specification to avoid over ordering		✓	✓	✓	
	Awareness and use of standard detail and specifications	Andi and Minato (2003)	✓	✓	✓	✓
	Ability to correctly integrate design with site topography		✓			✓
	Clear and comprehensive information	Baldwin et al. (2007)	✓	✓	✓	✓
	Ability to ensure constructability of design		✓		✓	✓
Awareness of Materials Attributes	Knowledge/specification of secondary materials	Wang et al. (2014)	✓	✓	✓	✓
	Identify all reusable elements and integrate them into design	Begum et al. (2009)	✓		✓	
	Specify durable materials to avoid early refurbishment	Esin Cosgun (2007); Yuan (2013)	✓	✓		✓
	Specify available, suitable and compatible materials	Andi and Minato (2003)	✓	✓	✓	✓
	Knowledge of alternative materials option	Alshboul and Ghazaleh (2014)	✓		✓	
Construction related Knowledge	Knowledge of real life sites layout	Tam (2008); Yuan (2013b)	✓	✓	✓	
	Knowledge of construction processes and sequence	Alshboul and Ghazaleh (2014)	✓	✓	✓	✓
	Knowledge of standard materials size and its correct specification					
	Ability to specify suitable and compatible materials	Andi and Minato (2003)				✓
	Awareness of materials quality and durability	Dainty and Brooke (2004)	✓			✓
	Knowledge of construction methods		✓	✓	✓	✓
Interprofessional collaborative competencies	Ability to coordinate design from all trades	Al-Hajj and Hamani (2011)	✓		✓	
	Inter-professional conflict resolution			✓	✓	
	Knowledge of roles and responsibility of all team members				✓	✓
	Effective communication of design information within/across trades	Osmani (2013); Domingo et al. (2009)	✓	✓	✓	✓
	Ability to detect and prevent clash in design		✓	✓	✓	✓

Underlying Features	*Design Measures and competencies for reducing construction waste*	*References from extant literature*	*Focus Groups*			
			1	**2**	**3**	**4**
	Ability to successfully collaborate with the project team		✓	✓		✓
Design Document Quality for Low Waste Projects						
Accuracy of design information	Drawing documents are free of errors to prevent reworks	Andi and Minato (2003)	✓	✓		✓
	Detailed specification devoid of under/over ordering	Begum et al. (2007); Oyedele et al. (2003); Domingo et al. (2009)	✓	✓	✓	
	Designs from all trades are adequately coordinated/integrated	Al-Hajj and Hamani (2011)			✓	✓
	Drawings and other documents are legible	Baldwin et al. (2007)	✓		✓	✓
	Consistency in detailing language/format	Osmani (2013)		✓		✓
Comprehensiveness of the documents	Waste management plan to be prepared along with design	Garas et al. (2010)	✓	✓	✓	
	Deconstruction plan as part of design documents	Oyedele et al. (2013)		✓	✓	✓
	Waste scenario planning		✓	✓		✓
	Completeness: Adequate design information for subsequent businesses	Negapan et al. (2013); Khanh & Kim (2009)	✓			✓
	Bar bending list as part of documentations	Al-Hajj and Hamani (2011)				
Efficacy of Design Process						
Coordination of Design Contracts	Careful Coordination of contract documents to prevent error	Osmani et al. (2008)	✓	✓	✓	
	Early completion of contract documents before construction	Osmani et al. (2008)	✓		✓	✓
	Ensure design freeze at the end of design process	Oyedele et al. (2013); Negapan et al. (2013); Lu and Yuan (2010)	✓	✓	✓	✓
	Involvement of contractors at early stage	Oyedele et al. (2013)	✓	✓	✓	✓
	Clearly specified project goal to avoid flawed planning/design	Faniran and Caban (1998)				✓
	Pre-design meetings of key stakeholders	Oyedele et al. (2003)				✓
	Early collaborative agreement before design activities	Osmani (2013)	✓		✓	✓
	Economic incentives and enablers	Wang et al. (2013); Osmani (2013)	✓		✓	
Coordination of Design Teams	Adequate coordination of various specialities involved in the design process	Ikau et al. (2013)	✓			✓
	Timeliness: Early distribution of design documents	Negapan et al. (2013)				
	Design management to prevent over specification of materials	Dainty and Brooke (2004)				
	Adequate communication between trades	Domingo et al. (2009); Al-Hajj & Hamani (2011); Osmani (2013)	✓	✓	✓	✓
	Adequate implementation of sustainable building assessment procedure	Tam (2008); Yeheyis et al. (2013)		✓		✓
	Drawings and other details are adequately coordinated between design discipline	Al-Hajj and Hamani (2011); Yuan (2013b)		✓	✓	
Buildability/Constructability and Responsivity Criteria						

Underlying Features	***Design Measures and competencies for reducing construction waste***	***References from extant literature***	***Focus Groups***			
			1	**2**	**3**	**4**
Design for Modern Methods of Construction	Specification of prefabricated materials	Yuan (2013)	✓	✓	✓	✓
	Modular coordination of building elements	Formoso et al. (2002); Oyedele et al. (2003)	✓	✓	✓	✓
	Design for preassembled components	Kozlovska and Splsacova, (2013); Formoso et al. (2002)	✓			✓
	Specify the use of efficient framing techniques	Osmani et al. (2008)	✓	✓	✓	
	Employ Modular design principles	Wang et al. (2014); Baldwin et al. (2007); Esin and Cosgun (2007)	✓	✓	✓	✓
	Specify the use of drywall partitioning and joint system		✓		✓	✓
	Design with buildability/constructability of the project in mind	Yeheyis et al. (2013); Yuan (2013b); Oyedele et al. (2003)	✓	✓	✓	✓
Standardisation and Dimensional Coordination	Careful integration of building sub-system	Formoso et al. (2002)			✓	✓
	Ensure simplicity and clarity of detailing	Ekanayake and Ofori (2004); Domingo et al. (2009)				
	Design for standard dimensions and units	Osmani et al. (2008)	✓	✓	✓	✓
	Standardise building forms and layout	WRAP, (2009); McKechnie and Brown (2007);		✓	✓	✓
	Ensure drawings consider and integrate site topography and existing utilities	Yuan (2013b); Andy and Minato (2003); WRAP (2009)	✓	✓	✓	✓
	Dimensional coordination and standardisation of building elements	Dainty and Brooke (2004); Baldwin et al. (2007); Ekanayake & Ofori (2004)	✓	✓	✓	✓
	Optimize tile layout in conformity with design shape	WRAP (2009)	✓			✓
	Use full height door or door with fanlight to avoid cutting plasterboard	WRAP (2009)	✓			
	Standardise doors, windows and glazing areas	WRAP (2009)	✓		✓	
	Avoidance of overly complex design, where possible	Yuan (2013b)		✓	✓	
	Ensure adequate detailing of complex design	Ekanayake & Ofori (2004); Yuan (2013b); Baldwin et al. (2007)		✓	✓	✓
	Coordinate structural grid and planning grid to avoid offcuts/conflict	WRAP (2009)				
Responsive Design and Deconstruct-ability Criteria	Use of modular system	Formoso et al. (2002); Wang et al. (2014); Esin and Cosgun (2007)	✓	✓	✓	✓
	Designers to produce disassembly and deconstruction plan of the building	Oyedele et al. (2003)	✓	✓		✓
	Design for standard dimensions and units	Osmani et al., 2008	✓		✓	✓
	Design for changes and flexibility	Yuan (2013b); Mckechnie and Brown (2007)	✓	✓	✓	
	Specification of collapsible elements for flexibility		✓	✓	✓	✓
	Specify durable materials to avoid need for early replacement	Esin and Cosgun (2007); Yuan (2013b)	✓			✓
	Specify materials and joint system that support disassembly	WRAP (2009)	✓	✓	✓	✓

6.7.2 Procurement Measures

A combination of the findings from focus group discussions and systematic literature review resulted in 39 procurement measures for enhancing construction waste minimisation, under five categories. These set of measures are as presented in Table 6.4.

Based on the underlying features identified in Table 6.4 above, a conceptual framework of requisite procurement measures for low waste project is presented in Figure 6.2. The framework suggests that five key measures underlie waste-efficient procurement. These measures include contractual factors, suppliers'/vendors' attributes, effective materials management, effective materials delivery, and waste-efficient handling and storage. Generalizability of these set of measures is further tested through quantitative studies as presented in subsequent chapters.

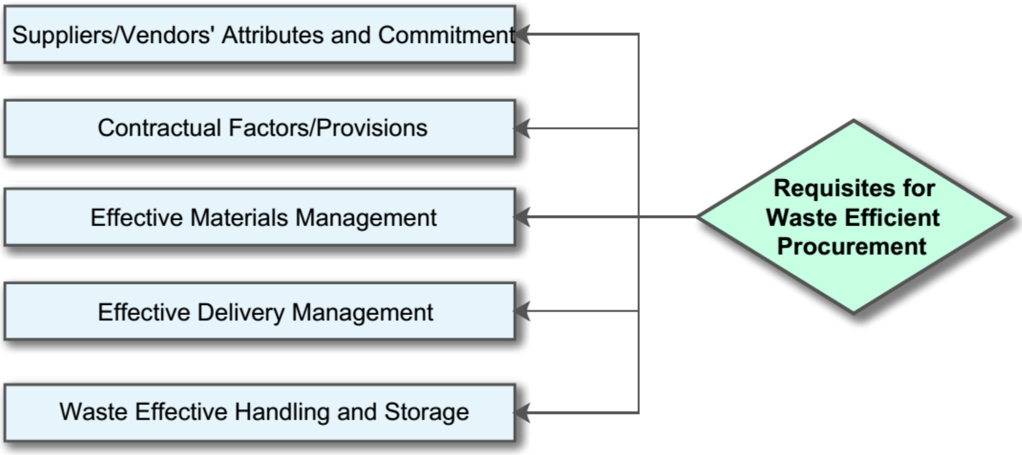


Figure 6.2: Framework of Procurement Measures for Low Waste Projects

Table 6.4: Procurement measures for engendering low waste construction projects

Underlying Features	***Procurement Measures for reducing construction waste***	***References from extant literature***	***Focus Groups***			
			1	**2**	**3**	**4**
Suppliers/ Vendors' Attribute	Procurement route that minimises packaging	Oyedele et al. (2013); Yeheyis et al. (2013); Marinelli et al. (2014); Saez et al. (2013)	✓	✓	✓	✓
	Vendors that supply good quality and recycled materials	Khan and Kim, (2014); Nagapan et al. (2013)	✓			✓
	Supplier flexibility in providing small quantities of materials	Dainty and Brooke (2004)	✓	✓		✓
	Modification to products in conformity with design	Bernold et al. (1991)	✓		✓	✓
	Collecting package materials back by suppliers	Cha et al. (2009)	✓	✓	✓	✓
	Collecting back recyclable materials	Jingkuang and Yousong (2011)	✓			
	Enhance management of packaging materials	Yuan (2013b)				
	Provision for unused materials to be taken away from site (take back scheme)	Osmani et al. (2008); Negapan et al. 2013; Cha et al. (2009) Al-Hajj and Hamani (2011); Bernold et al. (1991).	✓	✓	✓	✓
Contractual Factors	Waste minimisation clauses in contract documents	Osmani (2013)	✓	✓	✓	✓
	Consistency in contract documents	Domingo et al. (2009)				
	Resolve contract document before procurement	Ekanayake and ofori (2004)			✓	
	Contract completion before procurement activities	Negapan et al. (2013)				
	Freeze design before procurement processes	Osmani et al. (2008)	✓	✓	✓	✓
	Discuss methods of waste minimisation with suppliers/sub-contractors	WRAP (2009)		✓	✓	
Effective materials management	Procurement and use of preassembled components	Formoso et al. (2001)	✓	✓	✓	✓
	Purchase pre-cut materials	McKechnie and Brown (2007)	✓		✓	✓
	Optimisation of Materials Purchase to avoid over/under ordering and excess waste allowance	Hassan et al. (2012); Faniran and Caban (1998); Marinelli et al. (2014); Saez et al. (2013)	✓	✓		
	Purchase repairable, reusable and durable materials	Khanh and Kim (2014); Begum et al. (2007)				
	Buying materials with reused packaging	WRAP (2009); Faniran and Caban (1998)	✓		✓	✓
	Purchase secondary materials and reuse materials	Begum et al. (2007)	✓	✓	✓	✓
	Effective materials take-off	Nagapan et al. (2013)		✓		
	Good quality materials to be purchased	Nagapan et al. (2013)				✓
	Purchase materials in conformity/adherence to carefully prepared specification	Bernold et al. (1991); Muhwezi et al. (2012)	✓	✓	✓	✓

Underlying Features	***Procurement Measures for reducing construction waste***	***References from extant literature***	***Focus Groups***			
			1	**2**	**3**	**4**
	Avoid frequent variation order	Nagapan et al. (2013)	✓	✓		
	Order material with high content of recycled product	Teo and Loosemore (2001); Cha et al. (2009)	✓		✓	✓
	Recycled aggregate to be procured	WRAP (2009); Wang et al. (2010)	✓	✓	✓	✓
	Use of correct materials to prevent replacement	Muhwezi et al. (2012)				
Effective materials delivery	Sufficient protection of materials during loading and unloading	Garas et al. (2010); Hassan et al. (2012); Al-Hajj and Iskandarani (2011); Muhwezi et al. (2012)		✓	✓	
	Good site access for delivery vehicle	Osmani et al. (2008)		✓		✓
	Avoidance of loosely supplied materials which usually lead to breakage	Nagapan et al. (2013); Hassan et al. (2012)	✓		✓	✓
	Adequate and efficient delivery schedule	Marinelli et al. (2014); Khanh and Kim (2014)	✓			✓
	Planning for good delivery system onsite	Formoso et al. (2001)			✓	✓
Waste effective handling and storage	Waste-efficient procurement such as JIT	Dainty and Brooke (2004); Marinelli et al. (2014)	✓	✓	✓	✓
	Vocational training on sorting and handling of materials	Yuan (2013)				
	Improvement of materials handling system	Oyedele et al. (2013); Adams et al. (2011); Hassan et al. (2012)	✓			✓
	Suitable and safe storage of materials	Al-Hajj and Hamani (2011); Ekanayake and Ofori (2004)	✓	✓		✓
	Mechanical movement of materials	WRAP (2007)				
	Logistic management to prevent double handling	Al-Hajj and Hamani (2011); Cha et al. (2009)	✓		✓	
	Reduce excess of ordered material to avoid fracture of the material at the work site	Del Río Merino et al. (2010)		✓	✓	✓

6.7.3 Construction Measures

After combining measures identified through literature review and focus group discussions, 93 construction measures for low waste projects were established. These were grouped into five key categories of measures for engendering waste-efficient projects, with each having sub-underlying measures. They are as presented in Table 6.5.

Based on the underlying features identified in Table 6.5 above, a conceptual framework of requisite construction measures for low waste project is presented in Figure 6.3. Apart from four key categories of measures, the framework suggests that 12 key measures underlie waste-efficient construction. Generalizability of these set of measures is further tested through quantitative studies as presented in the subsequent chapters.

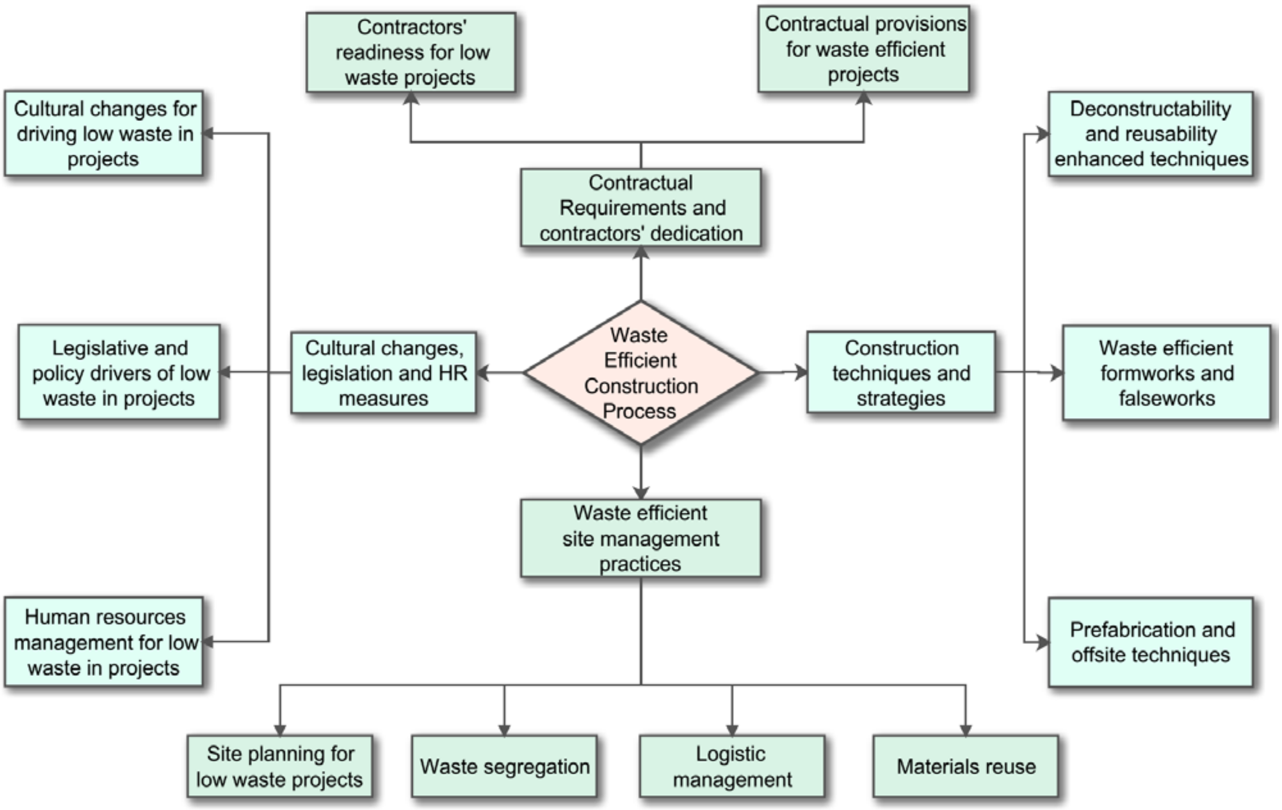


Figure 6.3: Framework of Construction Measures for waste minimisation

Table 6.5: Construction Measures for Engendering Low Waste Construction Projects.

Key Features	***Construction Measures and competencies for reducing construction waste***	***References from extant literature***	***Focus Groups***			
			1	**2**	**3**	**4**
Contractual Provisions and Contractors' Dedication						
Contractors' readiness for low waste projects	Improved technical knowledge of construction professionals	Zhang et al. (2012); Oyedele et al. (2003)	✓			✓
	Improved major project stakeholders' awareness about resource saving and environmental protection	Yuan (2013b)			✓	✓
	Detect the construction activities that can admit reusable materials from the construction	Del Río Merino et al. (2009)	✓	✓	✓	✓
	Carefully planned work sequence to prevent damages to works	Muhwezi et al. (2012)			✓	✓
	Understanding and adoption of right work sequence and technology	Zhang et al. (2012)			✓	✓
	Commitment of contractors' representatives onsite	Cha et al. (2009)				
	Adequate knowledge of construction methods and sequence	Muhwezi et al. (2012)	✓	✓	✓	✓
	Cooperation of subcontractors	Cha et al. (2009)				
Contractual provisions for waste-efficient projects	Contractual clauses to penalise poor waste performance	Dainty and Brooke (2004)	✓	✓	✓	✓
	Making sub-contractors responsible for waste disposal	Domingo et al. (2009)	✓		✓	✓
	Incentives and penalties for waste management and casualties respectively	Adams et al. (2011); Li et al. (2003); Al-Hajj and Hamani (2011); Chen et al. (2002); Cooper (1996); Cha et al. (2009)	✓	✓	✓	✓
	Waste target set for sub-trades	Marinelli et al. (2014)				
	Incentive in bidding for a contractor having a plan about decreasing waste and increasing recycle	Jinkuang and Yousong (2011); Cha et al. (2009)	✓	✓	✓	✓
	Clearly defined/communicated waste management strategies	Teo and Loosemore (2001)			✓	
	Additional tender premiums where waste initiatives are to be implemented	Dainty and Brooke (2004)				
	Recycling target to be set for every project	Oyedele et al. (2013)	✓	✓	✓	✓
Construction Techniques and Strategies for Low Waste Projects						
Deconstruct-ability and reusability enhanced technique	Use of hanging cradle	Poon et al. (2003)				
	Reduced use of wet trades	Baldwin et al. (2007)	✓		✓	✓
	Construction with standard materials	Cha et al. (2009)	✓	✓	✓	✓
	Ensure easy replacement of building element	WRAP (2009)	✓	✓		
	Avoid gluing	WRAP (2009)	✓		✓	✓

Key Features	***Construction Measures and competencies for reducing construction waste***	***References from extant literature***	***Focus Groups***			
			1	**2**	**3**	**4**
	Demountable building techniques	Yeheyis et al. (2013)	✓	✓	✓	✓
	Easily disassembled building elements	WRAP (2009)	✓	✓	✓	✓
	Use lime mortar to ensure easy dismantling	WRAP (2009)				
	Efficient framing	Yeheyis et al. (2013)				
Waste-efficient Formworks and falseworks	Innovative/reusable formwork and falseworks	Yuan (2013); Al Hajj and Hamani (2011)		✓	✓	✓
	Use of metal formwork	Jaillon et al. (2009); Tam (2008);	✓	✓	✓	✓
	Steel scaffolds	Wang et al. (2014)	✓	✓	✓	✓
	Metal/ non-timber hoarding	Baldwin et al. (2007); Tam (2008)				
	Large panel formwork	Poon et al. (2003)	✓	✓	✓	
	Aluminium and plastic formwork	Poon et al. (2003)		✓		✓
Prefabrication and offsite techniques	Adopting modular construction techniques	Yuan (2013); Esin and Cosgun (2007)	✓	✓	✓	✓
	Precast bathroom	Poon et al. (2003)	✓	✓	✓	✓
	Adoption of Modern Methods of Construction	Poon et al. (2003); Begum et al. (2009); Lu and Yuan (2010); Osmani (2013)				✓
	Employ offsite construction	Kozlovska & Splsacova (2013); Dainty & Brooke (2004)	✓	✓	✓	✓
	Precast Cladding, units and modules	Poon et al. (2003)	✓	✓	✓	✓
	Use of mechanical fixtures	WRAP (2009)				
	Prefabricated construction method	Chen et al. (2002); Jaillon et al. (2009); Baldwin et al. (2006)	✓		✓	✓
Construction Site Management Practices						
Site Planning for Low Waste Projects	Establish a task group for onsite CWM	Yuan (2013b)	✓			
	Follow the project drawings designs to prevent carrying out unexpected mistakes	Lu &Yuan (2010); Saez et al. (2013)	✓		✓	
	Develop and implement waste management plans for every project	Yuan (2013); Osmani et al. (2008); Garas et al. (2010); Hassan et al. (2012)		✓	✓	✓
	Ensure fewer design changes during construction	Al-Hajj and Iskandarani (2011);	✓	✓	✓	✓
	Timely and effective communication of design changes to all parties concerned	Faniran and Caban (1998)		✓	✓	
	A thorough review of the project specifications by the contractor at the construction stage	Faniran and Caban (1998)			✓	✓
	Ensure effective communication and coordination of construction activities	Osmani et al. (2008); Yuan (2013b)				

Key Features	***Construction Measures and competencies for reducing construction waste***	***References from extant literature***	***Focus Groups***			
			1	**2**	**3**	**4**
	Prepare carefully planned site layout before construction activities	Khanh and Kim (2014); Yuan (2013b); Formoso et al. (2002)	✓	✓		✓
	Effective coordination between all specialities onsite	Garas et al. (2010)	✓			✓
Waste segregation	Provision of waste skips for specific materials (waste segregation)	Al Hajj and Hamani (2011); Marinelli et al. (2014); Del Río Merino et al. (2010)		✓	✓	✓
	Prefabrication space in the work site for the correct management of the C&D waste	Lu and Yuan (2013)			✓	✓
	Setting up temporary bins at each building zone	Jingkuang and Yousong (2011)	✓			✓
	Providing bins for collecting wastes for each subcontractor	Cha et al. (2009)			✓	✓
	Dedicated space for sorting of waste	Wang et al. (2010); Lu and Yuan (2010)	✓	✓		✓
	Sorting wastes at an easily accessible area	Cha et al. (2009)	✓	✓		
	Installing an information board to notice categories for separating waste	Cha et al. (2009)				
	Preventing waste mixture with soil	Jingkuang and Yousong (2011)	✓		✓	✓
Logistic Management	Adequate site access for materials delivery and movement	Negapan, et al. (2013)	✓	✓	✓	✓
	Logistic management to prevent double handling	Al-Hajj and Hamani (2011)			✓	✓
	Central areas for cutting and storage	Tam (2008)	✓	✓		
	Waste auditing to monitor and record environmental performance on-site	Dainty and Brooke (2004)				
	Adequate on-site materials control system	Osmani et al. (2008)				
Materials reuse	Well planned site layout prepared and discussed with site workers	WRAP (2013)	✓		✓	✓
	Discussion with sub-contractors/ other consultants on the reuse of materials/components	WRAP (2013)	✓	✓		
	Reuse material scraps from cutting stock-length material into shorter pieces	Faniran and Caban (1998)				
	Maximisation of onsite reuse of materials	Marinelli et al. (2014); Yuan (2013b)	✓	✓	✓	✓
	Periodic checks on the use of C&D waste containers	Saez et al. (2013)				✓
	Soil remains to be used on the same site	Begum et al. (2009)	✓	✓	✓	✓
	Educate clients about measures to reduce waste levels	Dainty and Brooke (2004)	✓			✓
Cultural Change, Legislation and Human Resources Management						
Cultural changes for	Use of collaborative procurement route such as IPD	Isikdag and Underwood (2010);	✓	✓		✓
	Supply chain alliance with materials suppliers	Dainty and Brooke (2004)		✓	✓	✓

Key Features	***Construction Measures and competencies for reducing construction waste***	***References from extant literature***	***Focus Groups***			
			1	**2**	**3**	**4**
driving low waste projects	Early involvement of contractors at design stage	Oyedele et al. (2013); Arain et al. (2004)	✓	✓	✓	✓
	Blame and gain sharing philosophy among parties	Osmani et al. (2008); Fewing, 2013				
	Completion of design document before construction	Koskela, (2004)	✓	✓		✓
	Design freeze before construction activities	Oyedele et al. (2013)	✓	✓	✓	✓
	Use of common collaborative platform for information sharing	Ilozor and Kelly, 2011	✓	✓	✓	
Legislative and policy drivers of low waste projects	Developing market structure for recycled materials	Oyedele et al. (2009); Cha et al. (2009)				
	Raising fees for mixed wastes	Cha et al. (2009)	✓			✓
	Reducing fees for separated wastes	Cha et al. (2009)			✓	✓
	Tax break for waste treatment equipment and secondary materials manufacturers/suppliers	Oyedele et al. (2014); Jinkuang and Yousong (2011)	✓	✓		✓
	Improved database management for construction wastes	Cha et al. (2009)				
	Award of points to waste management practices in sustainable design appraisal tools such as BREEAM		✓	✓	✓	✓
	Deconstruction plans as a legal requirement		✓	✓		✓
	Require the use of proportion of recycled products in project		✓	✓	✓	✓
	Increased stringency of waste management regulations	Lu and Yuan (2010)				
	Integrate CWM into the assessment of construction contractor	Yuan (2013b)		✓		✓
	Increase the landfill disposal fee	Lu and Yuan (2010)	✓		✓	✓
Human resources coordination for waste-efficient project	Supervising waste management by a residential officer	Cha et al. (2009)				
	Appointment of labour solely for waste management	Jinkuang and Yousong (2011)				
	Little or no overtime for construction workers	Nagapan et al. (2013)				
	Employing workers responsible for on-site waste collection	Yuan (2013)	✓		✓	
	Waste management and materials handling vocational training for operatives	Wang et al. (2014); Esin and Cosgun (2007); Tam (2008); Ikau et al. (2013); Begum et al. (2009)	✓		✓	✓
	Dedicated site team or specialist sub-contract package for on-site waste management	Dainty and Brooke (2004)				

6.8 Chapter Summary

The qualitative research data collection processes, analytical approaches and findings were justified and presented in this chapter. Data was collected from 30 conveniently sampled participants, representing professionals involved from inception to completion of building construction projects, in four focus group discussions. To develop robust conceptual frameworks for the study, findings from the qualitative research were integrated with earlier findings from systematic review of the extant literature. A conceptual framework of waste-efficient process was drawn for each of design, procurement and construction stages of project delivery process. A combined framework of the design, procurement and construction measures and competencies for engendering low waste projects is as presented in Figure 6.4.

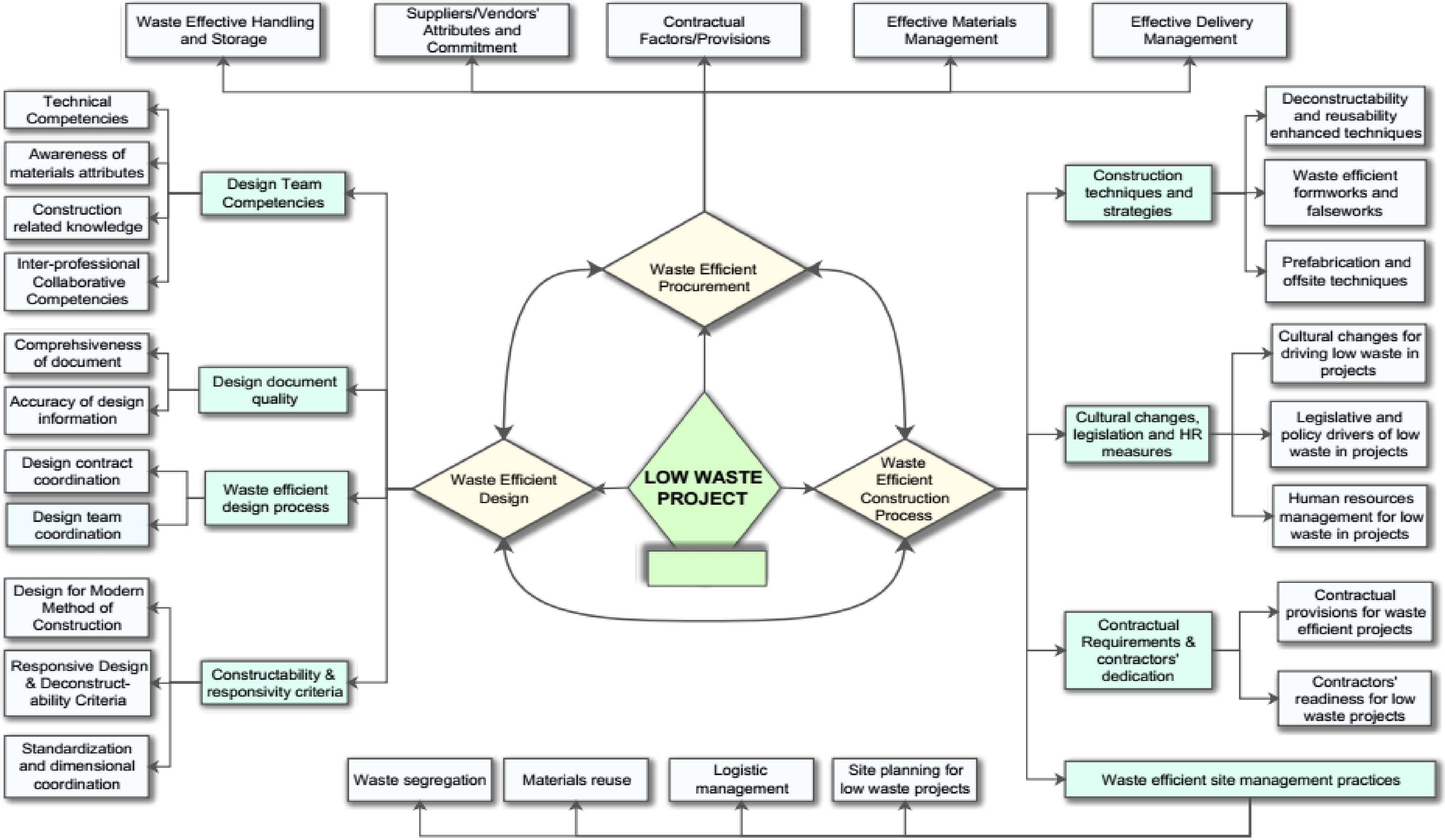


Figure 6.4: Holistic framework of design, procurement and construction requisites for low waste projects

CHAPTER 7: QUANTITATIVE STUDY

7.1 Chapter Overview

This research involved both qualitative and quantitative studies at intensive and extensive level respectively. While the research processes and findings of the qualitative study have been presented in the previous chapter, overall processes involved in quantitative data collection and analysis are presented in this chapter. The research population and sampling techniques were justified and explained in the next section, which is followed by the processes involved in designing the quantitative research instrument. The approach to data collection and analysis are then justified and discussed before the findings of the statistical analysis are presented. A brief summary culminates the chapter.

7.2 Population and Sampling Techniques

Because of yearning for generalizability of the findings of this study, sampling of job professions was based on critical sampling technique (Creswell, 1998), requiring that every stakeholder involved in building delivery process and its waste management be represented. At this stage of data collection, two sampling techniques were used for reaching out to the research participants. To prevent potential bias in the study, random sampling technique was used as the main mode of recruiting participants for the study (Gravetter and Wallnau, 2013). Using directories of eight UK professional bodies and list of the top 100 construction companies as a sampling frame, 475 questionnaires were sent to randomly selected respondents through email and postal services. The eight professional bodies include Association of Project Managers (APM), Chartered Institute of Buildings (CIOB), Chartered Institute of Waste Managers (CIWM), Royal Institute of British Architects (RIBA), Chartered Institute of Architectural Technologists (CIAT), Institution of Civil Engineers (ICE), Institution of Structural Engineers (IStructE) and Royal Institute of Chartered Surveyors (RICS).

In order to reach out to more respondents, snowballing sampling technique was also used to facilitate quantitative data collection. This sampling approach was facilitated by the network of contacts enjoyed. Other studies that have employed this sampling technique within the design and construction management include Akintoye et al. (1998), Oyedele (2013) and Hodgson et al. (2011), among others. The chain referral sampling process is a simple and efficient technique that provides an avenue to reach out to a population that are difficult to sample when using other techniques (Biernacki and Waldorf, 1981). The technique was quite possible in the study due to the ease of social mobility of experts within the construction industry. With this sampling technique, additional 147 contacts were contacted for data collection, resulting into 622 invitations for the quantitative data collection.

7.3 Questionnaire Design and Formulation

In a bid to test wider applicability and acceptability of the findings of this study, it is important that generalizability of the measures to the experts within the industry be established. As such, a further quantitative research was carried out. At this stage of the study, the major consideration for selecting a mode of data collection is the ability to reach out to large participants within a short period, using a standardised research instrument. As such, a questionnaire was chosen as a medium of data collection because of its objective approach to collecting data from a large number of participants within a short period (Walliman and Baiche, 2005).

The aim of using questionnaire survey is to determine the wider applicability of previously identified factors (descriptive) and to explain the reason why it takes certain form –analytical/explanatory (Buckingham and Saunders, 2004). Numbers of waste impacting factors identified through literature review and focus group discussions were integrated into a self-developed questionnaire, consisting of four major parts.

7.3.1 Sections of the Questionnaire

The first part of the questionnaire contains general information about the respondents. This consists of their job titles, which could be architects, civil/structural engineer, project manager and site waste manager, among others. This section also consists of the respondent's years of experience within the construction industry.

The second part (Part B) consists of 78 questions, eliciting experts' knowledge of design practices, strategies and competencies for construction waste minimisation. The focus of this section is to establish the key and underlying design strategies and competencies for engendering low waste. It is further divided into two sections; the first section addresses the strategies and processes for designing out waste, while the second section addresses the competencies required for driving the processes.

Part C consists of 39 questions addressing materials procurement measures for minimising waste generated by construction activities. The goal of the section is to elicit experts' opinion on the key and underlying measures for engendering construction waste minimisation through materials procurement processes.

Part D consists of 93 questions that address requisite construction measures for minimising waste generated by building projects. It consists of three major sections, with the first and second sections seeking to establish site management practices and construction strategies/techniques for reducing waste in construction projects. The third section seeks to elicit broader experts' knowledge of contractual provisions, legislative/policy measures and human resources management for waste-efficient projects. Part E and F asked general questions and requested additional comments from the participants.

7.3.2 Scale of Measurement

Likert scale has been used as the scale of measurement for the study. Named after its inventor, Rensis Likert, the Likert scale is developed to measure attitude, opinion and belief by requiring people to respond based on the extent to which they agree with a statement or topic (Bowling, 1997). The Likert scale is based on the principle that the strength of experience and belief is on a continuum from "strongly agree" to "strongly disagree". Nunnally and Bernstein (2007) opined that Likert scales are very helpful in research, as they could be used in summing average response for each participant or question. While using Likert scales, respondents could be offered a bipolar scale with a choice of three, five, seven or even nine pre-coded responses, having a neutral point between the scales (Bowling, 1997; Buckingham and Saunders, 2004). In this study, a Likert scale of 1 to 5 was used to represent the degree of importance of the identified set of measures, where 1 = Not important, 2 = Less important, 3 = moderately important, 4 = Important, 5 = Most important. This provides an avenue for summing up the participants' response for each of the measures, thereby establishing the overall significant of each measure.

7.3.3 Pilot Study and its Evaluation Techniques

As pre-coding ensures easy recording of questionnaire information and saves time on filling and analysis (Buckingham and Saunders, 2004), the questionnaire was pre-coded. Similarly, the research instrument was pilot tested to evaluate its content validity, predictive or concurrent validity and construct validity (Creswell, 2014; Buckingham and Saunders, 2004), which are all important for adequacy of information obtained through the research instrument (Tashakkori and Teddlie, 2010). Different numbers of participants have been recommended as required samples for pilot studies. For instance, Van Belle (2002) suggested 10 samples; Mooney and Duval (1993) recommended up to 30 participants in preliminary instrument development, while Isaac and Michael (1995) argue that sample size of between 10 and 30 could be adequate. In this study, adequacy of the questionnaire was pilot tested by 18 professionals that are deemed information-rich for the study. The purpose of the pilot study was to test the clarity of language, layout, the degree of depth, logic of the questions, and to perform a preliminary check of the proposed statistical analysis.

At this stage, basic descriptive statistics such as frequency test and crosstabs analysis were used to evaluate the construct validity of the research instrument. By doing this, the pattern by which closely related questions were answered was used to evaluate the efficacy of internal constructs (Creswell, 2014). Feedback from the pilot study further helped in improving the questionnaire design, as it resulted in inclusion, removal and rephrasing of some of the questions that were earlier included on the questionnaire. After the pilot studies, the total questions on the questionnaire were 69, 30 and 89 for design, procurement and construction measures respectively.

7.4 Data Collection

After improving the research instruments through comments obtained from the pilot study, the questionnaire was administered through both face-to-face, postage and online medium to reach wider participants. The face-to-face approach is particularly preferred as evidence shows that it is the most accurate and representative of research population (Szolnoki and Hoffmann, 2013). Using the interviewer administrated technique (face-to-face), copies of the questionnaires were given to the respondents who filled and returned them immediately or at a later period. In addition to this, copies of the questionnaire were also sent to the sampled participants through returned paid envelopes.

The face-to-face and postal medium of data collection were corroborated with an online system due to the ease of reaching out to wider participants and cheaper cost of implementation that characterised the online administration platform (Collins, 2010; Duffy et al., 2005). The online questionnaire was designed through Google forms, which is a free online platform for designing, distributing and analysing questionnaire. Link to the questionnaire was sent to the participants through their email addresses. Alternatively, Microsoft Word format of the questionnaire was emailed to some of the respondents, who filled the questionnaire by checking the options provided on the research instrument. In all, a total of 622 participants were invited for the quantitative data collection.

7.5 Statistical Analysis Techniques

The purpose of statistical analysis in this study is to establish patterns of response and ensure suitability of the collected data for further structural equation and system dynamics modelling analysis. At this stage of the study, different analyses were carried out for the purpose of data cleaning, validation and description. Reliability of the research instrument and various factors on the questionnaire was evaluated through Cronbach's alpha test. Approaches used for data screening include missing value analysis, detection of multicollinearity, skewness and kurtosis, and detection of multivariate outliers.

After data cleaning and replacement of missing data, other analyses were also carried out to establish patterns in the responses. Descriptive statistics was performed to determine the distribution of the respondents and the ranking of various factors and measures available on the questionnaire. A non-parametric test was also performed to evaluate whether there is variance in the response patterns based on job roles of the respondents. The test measured the extent to which a group’s average differs from the overall average of all respondents.

7.6 Response rate

After series of email reminders, 302 responses were received, representing a response rate of 48.6%. Out of these, 17 questionnaires failed preliminary analysis through incomplete information and unengaged responses, and they were removed from further analysis. Based on this, 285 questionnaires were used for statistical analysis and the structural equation modelling. A preliminary analysis was carried out on the respondents' information – section A of the questionnaire – to determine the distribution of the respondents, all of whom are from construction companies. Table 7.1 shows the distribution of the 285 respondents whose responses were used for data analysis.

As shown in Table 7.1, 25.3% of the respondents are architects or design managers, 19.6% are civil or structural engineers, 33.7% are project managers, 5.6% are site waste managers, while 15.8% belonged to others, which includes Lean practitioners, demolition specialists and sustainability experts, among others. The years of experience of the respondents also vary from a range of 1-5 to above 25years of industry experience, with 36.5% of respondents having between 11 and 15years of experience.

Table 7.1: Overview of the research respondents

Item/Variables	***Groups/Labels***	***Frequency***	***Percentage (%)***
Job roles/titles	*Architects/design managers*	*72*	*25.3*
	Civil/Structural Engineers	*56*	*19.6*
	Project managers	*96*	*33.7*
	Site waste managers	*16*	*5.6*
	Others	*45*	*15.8*
Years of experience (years)	*1-5*	*31*	*10.9*
	6-10	*54*	*18.9*
	11-15	*104*	*36.5*
	16-20	*64*	*22.5*
	21-25	*16*	*5.6*
	Above 25	*16*	*5.6*

7.7 Preliminary Data Analysis and Screening

In order to prepare the data for further statistical analysis, some preliminary data screening and cleaning were carried out. This involved missing value analysis, detection of unengaged respondents, detection of outliers, and determination of multicollinearity. A quick overview of the dataset and calculation of standard deviation for each of the respondents shows that six of the respondents were unengaged, as their standard deviation return a value close to zero. Hence, they were removed from further data analysis. As recommended by Kline (2010), Mahalanobis distance (D) statistic of the structural equation modelling was used to test for any influential outlier in the data. With no output having a P1 less than 0.05, the finding suggests that there is no any significant outlier in the dataset. Further data screening shows that neither multicollinearity nor outlier exists in the dataset.

7.7.1 Missing Value Analysis

Missing value analysis is a statistical process that helps in addressing concerns that are raised by incomplete data, which can affect the precision of statistical computation (Hill, 1997). In order to prevent complexities in assumptions and theories behind statistical analysis, missing value analysis provides a procedural approach for treating incomplete data. It performs three key functions, which are identification and description of the patterns of missing values, estimation of means and other descriptive statistics, and replacement of missing values with estimated values (Kang, 2013).

The missing value could be missing completely at random (MCAR), missing at random (MAR) or not missing at random (NMAR). Value is termed to be MCAR if the probability of having a missing value for a particular variable is related neither to the missing variable nor other observed variables in the data set. The statistical advantage of MCAR is that the analysis remained unbiased with the replacement of the missing value with an overall average for the variable (Kang, 2013). Missing value at random (MAR) describe a systematic nature of missing, where missing value could be explained by other variables in the dataset. In such case, the missing value could be determined by identifying the variable that could predict the value of the missing data. NMAR, on the other hand, occurs when the missing value is not at random, and it could not be predicted by another observed variable in the data set (Hill, 1997). The cases of NMAR are problematic, and the best approach to tackling such cases is either to delete the data set with the missing value or by modelling (Kang, 2013; Hill, 1997).

While handling missing value, some researchers may choose to perform ad hoc procedure of substituting the missing value or discard the survey with missing items using listwise, pairwise or case deletion technique (Kang, 2013). In this study, the listwise deletion has been used to remove survey responses with significant missing value. Through this process, 17 responses were completely removed from the data set, leaving 285 questionnaire responses for further analysis. Nonetheless, nine of the useful 285 responses have missing values ranging between 1 and 4 cases. SPSS missing value analysis with Expectation Maximization was carried out to test whether the data is considered MCAR. With the chi-square being statistically insignificant, the missing values are considered MCAR, and as such, they could be replaced by mean or median. Based on theoretical background that a mean is a reasonable estimate of an observation that is randomly selected from a normal distribution; mean substitution technique was used for the missing value. This is particularly suitable when less than 10% of data for a particular respondent are missing (Konanahalli et al., 2014). As such, the mean value of a variable is used to replace missing data for that variable. The approach ensures that the incomplete dataset is usable, without affecting the overall mean of each variable on the dataset. This according to Kang (2013) ensures that the data analysis remained unbiased with the replacement of the missing value.

7.7.2 Reliability analysis

Internal consistency of criteria contained in the questionnaire, as well as the suitability of the data for analysis, was evaluated using Cronbach's Alpha. It is one of the common tests of reliability that determines average correlation or internal consistency of objects in a research instrument (Santos, 1999). This is in line with the recommendation that it is important that Cronbach's alpha coefficient be determined, especially when using Likert scale on a questionnaire (Field, 2009; Nunnally and Bernstein, 2007). With Cronbach's alpha ranging from 0 to 1, a value of 0.7 represents an acceptable consistency, 0.8 indicates a good internal consistency, while a value of 0.9 demonstrates an excellent consistency of the scale of measurement (Nunnally and Bernstein, 2007; Tavakol and Dennick, 2011). In addition to the overall Cronbach's alpha for different categories of variables for design, procurement and construction, Cronbach's alpha if item deleted were also estimated for each category of the variable. In this case, any item with Cronbach's alpha above the overall value means that such item is not a good construct and should be deleted from the list of variables (Field, 2009). Results of the Cronbach's alpha for each category of variables are presented in Table 7.2 to 7.5. In addition to those shown in the

Tables 7.2 to 75, the overall Cronbach's alpha for design, procurement and construction measures were 0.831, 0.701 and 0.947 respectively.

The *Cronbach's alpha if item deleted* suggested that some of the factors were not contributing to the overall reliability of the dataset; and as such, they were deleted from the list. For the design factors, three factors have their Cronbach's alpha coefficients above the overall value. The factors were DF27, DF40 and DF42 with *Cronbach's alpha if item deleted* of 0.833, 0.838 and 0.835 respectively. After the three factors had been removed, standardised Cronbach's alpha coefficient for the design factor was 0.844, which indicates a good internal consistency of the scale. The overall Cronbach's alpha coefficient for design competencies was 0.881, with only one factor, DC25, having its *Cronbach's alpha if item deleted* above the value. After removing the DC25 with the value of 0.894, the Cronbach's alpha for the design competencies increased to 0.894. The *Cronbach's alpha if item deleted* shows that five variables were not contributing to the overall reliability of procurement factor as they have values of 0.709, 0.717, 0.745, 0.733 and 0.751, all of which are above the overall value of 0.701. The factors were PF19, PF20, PF22, PF25 and PF26 respectively. After the factors had been removed from the dataset, the overall Cronbach's alpha of the procurement factors increased to *0.803*, which indicates a good internal consistency according to Nunnally and Bernstein (2007). Similarly, the overall reliability of the construction factors increased from 0.947 to 0.949 after six factors were deleted. The factors were CF2, CF8, CF46, CF48, CF67 and CF69, which have their *Cronbach's alpha if item deleted* as 0.948 each.

Apart from the overall reliability for each of design, procurement and construction measures, the reliability analysis was performed for the group of factors contributing to each of design, procurement and construction measures. The analysis shows a good total correlation for most of the items, while all the groups have their Cronbach's alpha above 0.7. However, the analysis suggested that some of the items were not adequately contributing to the grouping, as they have their *Cronbach's alpha if item deleted* above the group Cronbach's alpha. The items that are meant to be deleted from further analysis are indicated in Tables 7.2 to 7.5.

7.8 Descriptive Statistics

Descriptive statistics is an approach to summarising data collected in graphical and numerical formats. The numerical analysis computes such statistical analyses as means, frequency distribution, standard deviation and range, among others, while the graphical analysis creates stem and leaf display. Descriptive statistics provides opportunity for comparing and ranking between and within groups. In this study, descriptive statistics was carried out to generate the means and standard deviation for various factors underlying each of design, procurement and construction measures for minimising construction waste. Mean was used to determine the top ranked factors, as parametric test is considered to be suitable with larger sample size and normally distributed data (Hozo et al., 2005; Norman, 2010).

According to Field (2009), mean testing is a measure of central tendency, usually employed by statisticians when there is need to determine the means and relative significance of a set of statistical variables. In order to establish the critical design, procurement and construction factors for engendering waste minimisation, the established measures were ranked based on their mean. Table 7.2 to 7.5 present the mean, standard deviation, overall ranking and ranking within group for the design, procurement and construction measures for engendering waste minimisation in construction projects.

7.8.1 Descriptive statistics for Design Measures

Descriptive statistics was carried out to determine the key design measures for engendering waste minimisation in construction projects. IBM SPSS version 23 was used to compute the mean and standard deviation for each category of variables underlying waste-efficient design. The factors were ranked across the overall design factors and within the six dimensions for designing out waste. Based on the mean ranking, the top-ranked design measures for engendering waste minimisation are:

1. Designs are free of error
2. Involvement of contractors at early design stage
3. Design for standard dimensions and units
4. Drawings and other details are coordinated between design disciplines

5. Design freeze at the end of design process.

Table 7.2 shows the six underlying dimensions for designing out waste. The mean, standard deviation, Cronbach's alpha and ranking of the factors contained under each dimension are presented in the tables. The six dimensions are waste-efficient documentation, Waste-efficient design process, design for standardisation and dimensional coordination, design for Modern Methods of construction, design for flexibility and organic design. All the six dimensions show a good to an excellent internal consistency ranging from Cronbach's alpha coefficient of 0.797 to 0.937. The significance of the measures contributing to each dimension is indicated by in-group rankings on the table.

7.8.2 Descriptive statistics for Design Competencies

In order to identify the key competencies that are essential for engendering low-waste design, descriptive statistics was carried out on previously identified designers' competencies. Mean and Standard Deviation were computed to determine the significance of all the competencies, which are further divided into four underlying competencies, which are design task proficiency, construction and materials related competency, waste behavioural competency and inter-professional competency. Based on the descriptive mean testing, the key competencies for designing out waste in order of their importance are as follows:

1. Ability to coordinate dimension of building elements and components
2. Ability to produce designs that are devoid of error
3. Ability to coordinate design from all trades
4. Ability to detect and prevent clash in design
5. Ability to produce coherent and comprehensive design information

Table 7.3 shows the four underlying competencies for designing out waste as well as the individual variables contributing to the underlying competencies. Apart from the overall ranking of the competencies, ranking of the variables within each group is presented in the table.

7.8.3 Descriptive statistics for Procurement Measures

Descriptive statistics was performed to determine the key procurement measures for reducing waste generated by construction activities. Based on the mean ranking, the top procurement measures for engendering construction waste minimisation are:

1. Effective materials take-off
2. Provision for unused materials to be taken away from site (take back scheme)
3. Optimisation of materials purchases to avoid over/under ordering
4. Materials purchase in adherence to materials specification
5. Modification to products size and shapes in conformity with design

Results of the descriptive statistics are presented in Table 7.4. In addition to the overall ranking of the measures, ranking of the factors within four identified dimensions of procurement measures are also presented in the table.

7.8.4 Descriptive statistics for Construction Measures

As a means of establishing the key construction measures for minimising waste in construction projects, descriptive statistics was carried out on the established measures. Findings of the descriptive statistics show that the top construction strategies for minimising waste are as follows:

1. Prefabricated construction method
2. Supply chain alliance with materials suppliers
3. Use of collaborative procurement routes such as IPD
4. Adequate knowledge of construction methods and sequence
5. Ensure fewer design changes during construction

Detailed results of the descriptive statistics, involving mean, group ranking, overall ranking and standard deviation are presented in Table 7.5.

7.9 Kruskal-Wallis Test for Significant Difference

Kruskal-Wallis test is a non-parametric test that is used to determine whether there is a significant statistical difference between more than two independent groups of respondents regarding a variable (Field, 2009). In this study, the non-parametric test was used to determine whether job positions of the respondents affect the pattern by which they ranked the variables at 95% confidence level. This means that the perception is deemed to be different if the Kruskal-Wallis coefficient is less than 0.05. The analysis was performed for the design, procurement and construction measures identified in the study.

7.9.1 Test for Significant Difference on Design Measures

The Kruskal-Wallis test for significant difference was carried out on design factors to determine whether job positions affect the perception of the design measures for waste minimisation. As such, respondents' job positions were used as grouping variables, while the design factors were used as testing variables. As presented in Table 7.2, the Kruskal-Wallis coefficient suggests that only one of the remaining 39 design factors was perceived differently by the respondents ($P<0.05$), representing 97.4% of agreement on the factors. Other factors have their P-Value greater than 0.05. This means that combining the responses for all the respondents will not affect overall reliability of the findings. Meanwhile, the only factor with differing perception is “involvement of contractors at early design stage” (DF4), which has a P-Value of 0.009. A further probe into the different groups' mean suggested that the factor was ranked high by project managers, site waste managers and civil/structural engineers, while architect/design managers posit that the factor is of less importance.

7.9.2 Test for Significant Difference on Design Competencies

Kruskal-Wallis test was carried out to check for significant difference in perception of design competencies based on job role. The result suggests that at 95% confidence level, there is no difference in the perception of the respondents based on their job positions, as $P > 0.05$ for all factors. Kruskal-Wallis coefficients are displayed in the last column of Table 7.3.

7.9.3 Test for Significant Difference on Procurement Measures

Kruskal-Wallis test for significant difference on procurement measures shows that there is no difference of perception among the research participants based on job roles, as $P > 0.05$ for all factors. This shows that the data could be combined and analysed to establish the key procurement measures for engendering low waste construction process. Kruskal-

Wallis coefficients for the procurement measures are displayed in the last column of Table 7.4.

7.9.4 Test for Significant Difference on Construction Measures

The Kruskal-Wallis test for significant difference was carried out on construction factors to evaluate whether job positions affect the perception of the construction strategies for waste minimisation. The null hypothesis was that the distribution of all the factors is the same across job titles of respondents. The result suggests that none of the factors was perceived differently at 95% confidence level, as $P > 0.05$ for all factors. This confirms the null hypothesis for all the factors. As an output of non-parametric test, Kruskal-Wallis coefficients for the construction factors are shown in the last column of Table 7.5.

Table 7.2: Descriptive and non-parametric analysis of design measures

Label	***Design factors for driving waste-efficient projects***	***Mean***	***SD***	***Rank within group***	***Overall Rank***	***Cronb. Alpha***	***Kruskal-Wallis coeff.***
A	***Waste-efficient design documentation***						
DF1	Design are free of error	4.4412	.56091	1	1	0.797	.574
**DF8*	*Include waste management into assessment of stakeholders*	*3.6176*	*1.01548*	*5*	*21*		.463
DF29	Produce disassembly and deconstruction plan	3.0000	.95346	9	35		.427
DF33	Specifications are detailed & devoid of under/over ordering	3.9412	.88561	3	10		.579
DF34	Waste management plan is prepared along with design	3.5882	.95719	6	22		.891
DF35	Drawings and other details are devoid of clash	4.1471	.78363	2	6		.573
**DF36*	*Bar bending list is prepared as part of documentations*	*3.000*	*1.12815*	*9*	*36*		*.262*
DF37	Drawing and specifications are written in conventional lang. understood by all	3.7353	1.05339	4	16		.186
DF38	Drawing documents are legible	3.2941	.90552	8	31		.552
**DF39*	*Waste scenario planning*	*3.3824*	*.98518*	*7*	*29*		.704
B	***Waste-efficient design Process***						
DF2	Completion of contract documents before construction process	3.9118	.93315	5	12	0.932	.605
DF3	Design freeze at the end of design process	4.2059	.76986	3	5		.764
DF4	Involvement of contractors at early design stage	4.2647	.79043	1	2		**.009*****
**DF5*	*Pre-design meetings of key stakeholders*	*3.5294*	*1.02204*	*8*	*25*		.169
DF6	Early collaborative agreement before design activities	3.7941	1.00843	6	14		.279
**DF7*	*Give economic incentives and enablers to designers*	*3.0882*	*1.13798*	*10*	*34*		.254
DF9	Adequate coordination of various specialities involved	3.7353	.93124	7	17		.496
DF11	Improved communication between various specialities	4.0588	.64860	4	8		.198
DF12	Implementation of sustainable building assessment procedure (such as BREEAM)	3.3235	1.24853	9	30		.761
DF13	Drawings and other details are coordinated between design disciplines	4.2647	.93124	2	4		.282
C	***Design for standardization and dimensional coordination***						
DF14	Detailing of the building elements is simple and clear	3.8824	.91336	4	13	*0.859*	.301
**DF15*	*Complex designs are adequately detailed*	*3.5294*	*1.10742*	*7*	*26*		.780
DF16	Building forms and layout are standardised	3.9412	.85071	3	11		.583
DF18	Coordinate dimensions of building elements	4.0882	.96508	2	7		.645
DF19	Tiles layout is optimised in conformity with design shape	3.4118	.95719	9	28		.480

Label	***Design factors for driving waste-efficient projects***	***Mean***	***SD***	***Rank within group***	***Overall Rank***	***Cronb. Alpha***	***Kruskal-Wallis coeff.***
DF20	Specify the use of full height door or doors with fanlight	2.8529	1.10460	11	37		.141
DF21	Standardise doors, windows and glazing areas	3.6765	.87803	5	18		.176
DF22	Avoid overly complex design	3.2059	1.47257	10	32		.958
_*DF31_	*Carefully integrate building sub-system*	*3.4706*	*.92884*	*8*	*27*		.280
_*DF32_	*Coordination of structural grid and planning grid*	*3.5882*	*1.07640*	*6*	*23*		.412
DF41	Design for standard dimensions and units	4.2647	.66555	1	3		.365
D	***Design for Modern Methods of Construction***						
DF23	Specification of prefabricated structural materials	3.5588	1.02073	3	24	*0.801*	.803
DF24	Design for preassembled components e.g. bathroom pods	3.7647	.78079	2	15		.942
DF25	Employ volumetric modular design principles	4.0000	.77850	1	9		.343
DF26	Specify the use of drywall partitions (e.g. timber walling)	2.7647	.92307	4	39		.411
E	***Design for flexibility***						
DF28	Design for collapsible and easily demountable components	3.1176	1.06642	1	33	*0.937*	.703
DF30	Specify the use of joint system without glueing and nailing	2.8824	1.09447	2	37		.212
F	***Organic Design***						
DF10	Drawings consider and integrate existing site utilities	3.6765	.91189	1	19	*0.716*	.393
DF17	Drawings consider and integrate site topography	3.6471	1.06976	2	20		.784

Table 7.3: Descriptive and non-parametric analysis of design competencies

Label	***Design competencies for designing out waste***	***Mean***	***SD***	***Rank within group***	***Overall Rank***	***Cronb. Alpha***	***Kruskal-Wallis coeff.***
A	***Design task competencies***						
DC1	Ability to produce designs that are devoid of error	4.4412	0.56090	2	2	0.888	0.3038
DC2	Knowledge and ability to design for standard materials	4.3529	0.73370	5	6		0.0511
DC5	Ability to produce drawings in response to site shape and topography	3.9118	1.05507	7	14		0.0522

Label	***Design competencies for designing out waste***	***Mean***	***SD***	***Rank within group***	***Overall Rank***	***Cronb. Alpha***	***Kruskal-Wallis coeff.***
DC6	Ability to produce comprehensive design information	4.3824	0.69695	4	5		0.4722
DC9	Proficiency in detailing of design elements	3.6471	1.01152	10	22		0.0607
**DC12*	*Proficiency in design tools and vocabularies*	*3.3529*	*0.94971*	*11*	*25*		0.8689
**DC13*	*Proficiency in design flexibility and adaptability*	*3.8235*	*0.86936*	*9*	*16*		0.6859
DC14	Ability to coordinate dimension of building elements and components	4.4412	0.70458	1	1		0.4751
DC15	Ability to effectively design for preassembled components	3.8529	0.85749	8	15		0.7218
DC22	Ability to detect and prevent clash in design	4.3824	0.73915	3	4		0.9980
DC24	Awareness and use of standard detail and specification	4.1765	0.83377	6	11		0.7219
B	***Construction and materials related competencies***						
DC3	Knowledge of construction methods	4.264	0.9632	2	9	0.825	0.1036
DC4	Knowledge of construction sequence	4.029	0.8343	3	13		0.9487
DC7	Knowledge of materials durability that prevents early replacement of materials	3.764	0.9553	6	20		0.2350
DC10	Proficiency in materials specification	4.294	0.5788	1	7		0.2021
DC11	Ability to identify and integrate reusable elements into design	3.764	1.0461	5	19		0.6544
DC16	Knowledge and specification of secondary materials	3.529	0.8956	7	24		0.7788
**DC26*	*Awareness of materials quality and durability*	*3.794*	*0.6866*	*4*	*18*		0.4945
C	***Waste behavioural competencies***						
DC8	Ability to consider different design options based on their likely waste output	3.705	1.0307	3	21	*0.719*	0.7708
DC17	Awareness and belief in design causes of waste	4.264	0.8637	1	8		0.1143
DC27	Proficiency in waste scenario planning	4.205	0.5918	2	10		0.3818
D	***Inter-professional competency***						
DC18	Ability to coordinate design from all trades	4.441	0.6125	1	2	*0.754*	0.5949
DC19	Inter-professional conflict resolution	3.617	1.1013	4	23		0.3365

Label	***Design competencies for designing out waste***	***Mean***	***SD***	***Rank within group***	***Overall Rank***	***Cronb. Alpha***	***Kruskal-Wallis coeff.***
DC20	Knowledge of roles and responsibility of team members	3.823	1.1138	3	17		0.9659
DC21	Effective communication of design information	4.147	0.8574	2	12		0.0565
**DC23*	*Ability to collaborate with the project team*	*3.117*	*0.9133*	*5*	*27*		0.5404

Table 7.4: Descriptive and non-parametric analysis of procurement measures

Label	***Procurement measures for waste-efficient projects***	***Mean***	***SD***	***Rank within group***	***Overall Rank***	***Cronb. Alpha***	***Kruskal-Wallis coeff.***
A	***Delivery planning and scheduling***						
PF16	Protection of materials during loading and unloading	4.029412	0.7971	1	8	*0.756*	0.8644
PF17	Good site access for delivery vehicle	3.705882	1.1422	2	14		0.5337
PF18	Avoid loosely supplied materials	3.294118	1.1422	4	24		0.2928
**PF27*	*Planning for good delivery schedule onsite*	*3.294118*	*1.0307*	*4*	*23*		0.5163
PF30	Improved materials handling system	3.382353	0.8881	3	22		0.2810
B	***Suppliers' alliance and commitments***						
PF1	Procurement route that minimises packaging	3.764706	1.1297	4	13	0.802	0.8907
PF2	Supplier flexibility in providing small quantities of materials	3.676471	0.7675	5	15		0.7783
PF3	Modification to products size and shapes in conformity with design	4.147059	0.8574	2	4		0.2802
PF4	Collecting package materials back by suppliers	3.941176	0.9829	3	10		0.5427
**PF5*	*Collecting back recyclable materials*	*3.647059*	*1.2030*	*6*	*18*		0.2439
PF6	Provision for unused materials to be taken away from site (take back scheme)	4.176471	0.7576	1	2		0.4952
C	***Low waste materials purchase management***						
PF7	Procurement and use of preassembled components	4.117647	0.9133	1	5	0.746	0.4014
PF8	Purchase of pre-cut materials	3.970588	0.7581	3	9		0.3190
PF10	Purchase durable materials	3.558824	1.1062	7	19		0.7935
PF11	Buying materials with reusable packaging	3.823529	0.9991	4	12		0.9548
PF14	Order material with high content of recycled product	3.676471	1.1473	5	15		0.7682

Label	***Procurement measures for waste-efficient projects***	***Mean***	***SD***	***Rank within group***	***Overall Rank***	***Cronb. Alpha***	***Kruskal-Wallis coeff.***
PF15	Procure recycled aggregate instead of virgin aggregates	3.676471	1.0932	5	15		0.5170
PF23	Purchase of secondary materials	3.5	1.2370	8	20		0.1454
PF28	Use of Just-In-Time (JIT) procurement system	4.058824	0.7361	2	7		0.9011
***PF29**	*Reduced excess order to avoid breakage*	*3.235294*	*0.8548*	*9*	*25*		0.2855
D	***Waste-efficient bill of quantity***						
PF9	Optimisation of materials purchases to avoid over/under ordering	4.176471	0.7576	2	3	0.784	0.6233
PF12	Effective materials take-off	4.205882	0.9464	1	1		0.3089
PF13	Avoid frequent variation order	3.470588	1.0220	4	21		0.8803
PF21	Design freeze before materials procurement	3.882353	1.0376	3	10		0.9478

***Note for Tables 7.2, 7.3, 7.4 and 7.5:* ****denotes factors that have "Cronbach's Alpha if item deleted" above their individual groups' Cronbach's Alpha, suggesting that the factors should be deleted to enhance and standardise the groups' reliability.*

****denotes factors having significant Kruskal-Wallis coefficient at 95% confidence level. This means that respondents differ in their perception of the factor based on their job position. This affected only DF4 on Table 7.2.*

Table 7.4: Descriptive and non-parametric analysis of construction measures

Label	***Construction strategies for waste minimisation***	***Mean***	***SD***	***Rank within group***	***Overall Rank***	***Cronb. Alpha***	***Kruskal-Wallis coeff.***
A	***Site planning***						
CF12	Follow the project drawings/designs	4.2353	.923	3	8	0.872	.458
CF17	Ensure fewer design changes during construction	4.2941	.871	1	5		.618
CF29	Establishing task group for onsite CWM	3.0000	.953	9	74		.823
CF30	Development and implementation of waste management plan	4.1471	.857	6	13		.130
CF31	Effective communication of design change	4.1765	.673	4	10		.281
CF32	Thorough review of project specifications by contractors	3.8824	1.038	8	29		.261

Label	***Construction strategies for waste minimisation***	***Mean***	***SD***	***Rank within group***	***Overall Rank***	***Cronb. Alpha***	***Kruskal-Wallis coeff.***
***CF33*	*Effective communication and coordination of construction activities*	*4.0000*	*.853*	*7*	*20*		.889
CF34	Preparation of site layout planning before construction	4.1471	1.019	5	12		.160
CF39	Ensure conformity with design dimension	4.2647	.751	2	7		.130
B	***Waste segregation***						
CF11	Prefabrication space in the work site for correct management of C&D waste	3.4118	.957	7	61	0.901	.313
CF14	Preventing waste mixture with soil	3.9706	.870	3	25		.354
CF15	Providing bins for collecting wastes for each sub-contractor	3.3529	1.203	8	63		.966
CF16	Dedicated space for sorting of waste	3.7647	.923	4	42		.401
CF18	Setting up temporary bins at each building zone	3.6176	.739	6	50		.909
CF22	Provision of waste skips for specific materials (waste segregation)	4.2647	.618	1	6		.389
CF25	Sorting and reuse/recycling of waste	4.1471	.657	2	11		.766
CF35	Installation of information board to notice categories for waste separation	3.6765	.806	5	47		.895
C	***Logistic management***						
CF3	Use of safe materials storage facilities	3.8235	.968	2	32	0.888	.501
CF4	Onsite movement of materials through mechanical means	3.7059	1.001	5	46		.561
CF5	Prevention of double handling of materials	4.0294	.937	1	17		.441
CF19	Adequate site access for materials delivery and movement	3.7941	1.008	3	41		.393
CF20	Waste auditing to monitor and record environmental performance on-site	3.7059	1.001	4	45		.178
CF21	Central areas for cutting and storage	3.5294	.896	6	57		.585
**CF27*	*Mechanical movement of materials*	*2.8235*	*1.029*	*9*	*80*		.383
**CF28*	*Logistic management to prevent double handling*	*3.1471*	*1.234*	*8*	*71*		.096
**CF37*	*Adequate on-site materials control system*	*3.2647*	*.864*	*7*	*66*		.994
D	***Materials reuse***						
CF6	Use of reclaimed materials	3.8235	.936	3	33	0.849	.666
CF9	Reuse of off-cuts materials (such as wood)	3.6176	.922	6	50		.788
CF10	Use of demolition materials and excavation for landscape	3.7941	1.200	5	39		.598
CF13	Periodic checks on the use of C&D waste containers	3.4412	1.021	8	60		.889
CF23	Reuse material scraps from cutting stock-length material into shorter pieces	3.5882	.957	7	54		.947
CF24	Soil remains to be used on the same site	3.9706	1.114	2	23		.789
CF26	Maximisation of onsite reuse of materials	4.0588	.952	1	16		.377
CF36	Discussion with sub-contractors on the reuse of materials	3.8235	.999	4	38		.760

Label	***Construction strategies for waste minimisation***	***Mean***	***SD***	***Rank within group***	***Overall Rank***	***Cronb. Alpha***	***Kruskal-Wallis coeff.***
CF83	Educate clients about measures to reduce waste levels	3.2353	1.182	9	68		.759
E	***Deconstruct- ability and reusability enhanced technique***						
CF7	Construction with standard materials	3.8529	.958	2	31	0.749	.571
CF38	Reduced use of wet trades (such as cast in-situ)	3.2647	1.024	4	65		.961
CF44	Use of mechanical fixtures instead of glueing and nailing	2.8529	.892	7	78		.273
CF45	Use of lime mortar	2.3824	.888	8	83		.849
CF47	Use of demountable building techniques (such as collapsible partitions)	2.9118	1.138	6	77		.122
CF53	Construction with standard materials size	4.2059	.538	1	9		.880
**CF54*	*Consider replace-ability of building materials/components*	*3.1765*	*.936*	*5*	*70*		.298
CF55	Efficient framing techniques	3.6765	.768	3	47		.413
F	***Waste-efficient Formworks and falseworks***						
CF41	Use of reusable formwork and false work	3.8235	.904	1	36	0.800	.310
CF42	Use of Steel Scaffolds	2.9412	1.153	2	76		.674
CF43	Metal (non-timber) hoarding	2.6176	.954	3	81		.283
G	***Prefabrication and offsite technology***						
CF40	Use of Precast components such as bathroom and kitchen pods	3.8529	.989	5	30	0.874	.885
CF49	Adoption of modular construction technique	3.9706	.870	4	26		.483
CF50	Employment of offsite construction technology	4.1176	.880	2	14		.551
CF51	Use of precast cladding, units and modules	4.0294	.870	3	18		.292
**CF56*	*Prefabricated construction method*	*4.4706*	*.615*	*1*	*1*		.436
H	***Contractual provisions***						
CF57	Contractual clauses to penalise poor waste performance	4.0000	.921	1	20	0.993	.095
**CF58*	*Incentives for effective waste management practices*	*3.9118*	*.712*	*3*	*28*		.336
CF59	Incentive in bidding for a contractor having a plan about decreasing waste/increasing recycle	2.9706	1.029	7	75		.286
CF61	Making sub-contractors responsible for waste disposal	3.5882	1.209	6	55		.878
**CF64*	*Additional tender premium for implementing waste initiatives*	*2.8235*	*.968*	*8*	*79*		.670
CF65	Waste target set for sub-trades	3.8235	1.086	4	33		.695
CF70	Complete and resolve contract document before procurement	3.6176	.888	5	52		.553
CF77	Clear definition and communication of waste management strategies	4.0000	.816	2	20		.156
I	***Contractors' dedication and competencies***						

Label	***Construction strategies for waste minimisation***	***Mean***	***SD***	***Rank within group***	***Overall Rank***	***Cronb. Alpha***	***Kruskal-Wallis coeff.***
CF1	Detect the construction activities that can admit reusable materials from the construction	3.7647	.855	4	42	0.757	.989
CF52	Adoption of right work sequence	4.0294	.758	2	18		.853
CF60	Improved project stakeholders’ awareness of resource saving techniques	3.7647	.987	4	42		.105
CF62	Adequate knowledge of construction methods and sequence	4.2941	.760	1	4		.268
CF63	Cooperation of subcontractors	3.5294	.788	7	57		.486
_*CF66_	_Improved technical knowledge of construction professionals_	_3.2059_	_1.149_	_8_	_69_		.917
CF68	Carefully planned sequence of work to prevent damages to previously completed work	3.9118	.933	3	27		.740
_*CF71_	_Discuss methods of waste minimisation with suppliers/sub-contractors_	_3.5882_	_.701_	6	_53_		.754
J	***Cultural factors***						
_*CF73_	_Early completion of design documentation before constructn_	_3.8235_	_.758_	_3_	_33_	0.776	.334
CF74	Use of collaborative procurement routes such as IPD	4.3235	.535	2	3		.433
CF75	Use of common collaborative platform for information sharing	3.7941	.845	4	40		.307
CF76	Supply chain alliance with materials suppliers	4.3529	.646	1	2		.505
K	***Legislative and Policy Provisions***						
_*CF84_	_Government to develop market structure for recycled materials_	_3.6471_	_1.070_	4	_49_	0.729	.672
CF85	Reducing landfill tax for separated wastes and raising fees for mixed wastes	3.8235	.936	3	36		.451
CF86	Tax break for waste treatment equipment and secondary materials manufacturers/suppliers	3.5000	1.080	5	59		.441
CF87	Increased stringency of waste management regulations	3.9706	.870	2	24		.196
CF88	Integrate CWM into the assessment of construction contractor	3.2941	1.060	6	64		.454
CF89	Award of more points to waste management in sustainable design appraisal	4.0882	.712	1	15		.138
L	***Human Resources Management Measures***						
CF72	Improved stakeholders’ awareness of environmental protection	3.0882	.866	5	73	0.741	.263
CF78	Supervising waste management by a residential officer	3.2647	.931	3	66		.182
_*CF79_	_Little or no overtime for construction workers_	_2.4118_	_1.258_	6	_82_		.815
CF80	Employing workers/task group responsible for on-site waste management	3.4118	.957	2	62		.726
CF81	Waste management and materials handling vocational training for operatives	3.5882	.821	1	55		.869
CF82	Dedicated site team or specialist sub-contract package for on-site waste management	3.1176	1.008	4	72		.569

7.10 Validity and Reliability

The process of validating and ensuring credibility and reliability differ for both qualitative and quantitative data (Guba and Lincoln, 1994). In qualitative studies, trustworthiness features are usually used to address what quantitative research would address as credibility issues (Bloomberg and Volpe, 2012). Irrespective of terminologies, which might include credibility, confirmability, dependability, reliability and validity among others, a researcher must seek to prevent potential biases that could mar the design, implementation and analysis of data. The credibility of a study is an important phenomenon that determines how well the study is accurate from the standpoint of the researcher, participants and the readers (Merriam, 1998; Bloomberg and Volpe, 2012). According to Mason (1996), credibility of a study is concerned with methodological and interpretive validity. Methodological validity describes how well the adopted research procedural approach is suitable for the problem under evaluation as well as the nature of explanation the researcher seeks to pass across. A potential way of addressing this is to critically evaluate various components of research design and the adopted method (Bloomberg and Volpe, 2012).

In a quantitative study, reliability and validity of the research instrument are required for decreasing errors that could be due to measurement problems. Validity in a quantitative study, therefore, refers to accuracy and precision of both the research instrument and the measurement procedure (Buckingham and Saunders, 2004). In this study, stability of the research instrument regarding its face and content validity was ensured through pilot study, which was carried out with 18 participants before actual data collection. Internal (construct) validity particularly evaluates whether respondents' answer to closely related questions would be consistent (Buckingham and Saunders, 2004). It benchmarks the validity by evaluating the agreement between the measures and theoretical entity. Internal (construct) validity of the measurement taken on the Likert scale was also assessed from the results of the pilot study.

After collecting the data, reliability of the scale and the whole data was enhanced through preliminary analysis such as missing value analysis, Mahalanobis distance statistics, multicollinearity screening, detection of unengaged responses, and reliability analysis.

Deletion of factors that were negatively affecting reliability of the scale enhanced overall reliability of the data and findings of the study.

7.11 Chapter Summary

Quantitative approach was used as a means of data collection and analysis at the second stage of the study. Using findings from literature review and qualitative studies, a questionnaire was designed, pilot-tested and administered for data collection. Respondents were recruited through random sampling of databases of construction professional bodies and top UK construction companies, as well as through network of contacts within the UK construction industry. Pilot studies were used to improve the questionnaire, which was subsequently administered through face-to-face, postage and online platform. Out of 622 experts that were contacted, 302 respondents completed the questionnaire, representing a response rate of 48.6%. In order to ensure reliability of the findings, some preliminary data analyses were performed. These include missing value analysis, detection and removal of unengaged responses, Mahalanobis distance (D) statistics for detecting outliers, and reliability analysis.

Reliability analysis of the whole factors resulted in a deletion of three, five and six factors for each of design, procurement and construction measures respectively. After grouping the variables based on their underlying factors, standardisation of Cronbach's Alpha required deletion of some factors to enhance groups' reliability. This resulted into Cronbach's Alpha ranging from 0.719 to 0.993, with 53 out of 69, 22 out of 30 and 70 out of 89 factors established as being reliable for various groups of design and design competencies, procurement, and construction measures for waste minimisation respectively. Based on established groups with good value of Cronbach's Alpha, 10, 4 and 12 factors underlie each of design, procurement and construction measures respectively.

After achieving standardised Cronbach's Alpha, ranking of the factors was done using descriptive statistics. The factors were ranked within and across groups of design, procurement and construction measures, leading to an establishment of the key/critical design, procurement and construction strategies for minimising waste in construction projects.

In order to confirm whether the respondents perceived the factors in the same way, Kruskal-Wallis test was carried out on all the factors. Out of 69, 30 and 89 factors contained on the questionnaire for design, procurement and construction factors, only one design factor (DF4) was perceived differently. This represents less than 1% of all the factors, suggesting that job position of the respondents does not affect their perception of the factors. This means that combination of all the responses for further analysis would have no impact on the credibility and reliability of the finding.

CHAPTER 8: STRUCTURAL EQUATION MODELLING

8.1 Chapter Overview

In addition to descriptive statistics and non-parametric test, results of reliability analysis were presented in the previous chapter. The reliability analysis suggested that some factors were not contributing to the overall reliability of the groups; and as such, they were highlighted for removal from further analysis. In this chapter, structural equation models are developed to confirm the established factor structure, thereby testing the correlation and causal relationships between the observed variables and latent factors. The use of Structural Equation Modelling (SEM) is justified in the next section before discussion of various model fitness indices. This is followed by Confirmatory Factor Analysis (CFA) for second order factors of design, procurement and construction measures. Structural Model was developed to confirm relationship between design, procurement and construction measures, as well as their impacts on project waste output. The structural model helped to establish factor weighing, which is a significant input into System Dynamic Modelling that is presented in the next chapter.

8.2 Use of Structural Equation Modelling

Structural Equation Modelling (SEM) is a widely used multivariate technique for exploring and testing relationship between variables; and it encompasses regression analysis, factor analysis, multiple correlation and path analysis (Hair et al., 2006). Apart from its combination of these sets of analysis, SEM has an ability to estimate multiple interrelated relationships, while also taking care of measurement errors (Kline, 2010). It is also helpful in understanding model performance algorithms, as it provides visual representation of the complex relationships between constructs (Chen et al., 2011). Due to many benefits of SEM, it has been widely used in construction-related studies. For instance, Xiong et al. (2014) examine influence of participant performance factors on contractors’ satisfaction, using structural equation modelling. Mainul Islam and Faniran (2005) construct a SEM to investigate factors influencing project planning effectiveness, while Chen et al. (2012) employed SEM to investigate interrelationships among critical success factors of construction projects. More recently, Xiong et al. (2015) carry out a review of 84 construction-related studies that employed SEM between 1998 and 2012.

Modelling in SEM consists of two categories of variables, which are observed and latent variables. The former are the variables that are measured directly usually through item rating scale on questionnaires. The latter are dependent variables that cannot be observed directly, but they are constructed using some observed variables (Kline, 2010). Similarly, SEM consists of measurement model and structural model. While measurement model employs Confirmatory Factor Analysis (CFA) that evaluates how well the latent variables are represented by observed variables, structural model is the representation of the relationship between latent variables (Hoyle, 1995). Measurement models are valuable in establishing the reliability and validity of observed variables on the model, while structural models help in estimating relationship between latent (unobserved) variables (Kline, 2010).

In order to understand the key dimensions of measures for minimising waste in construction project, through design, procurement and construction stages of project delivery, SEM is used in the study. A key benefit of using SEM in this study is that its CFA helps in confirming the relationship between measured variables and independent variables. It also helps in establishing magnitude and significance of the latent variables, which is a valuable input into dynamic system modelling that is presented in Chapter 9.

8.3 Model Fitness

In SEM, model fitness refers to the extent to which the data reflects the theory or propositions underlying the model. Although there is wide disparity about most suitable model fit indices as well as the cut-offs for various indices, model fitness remains a key step and requisite in SEM (Hooper et al., 2008). Based on its importance, several criteria for goodness of fit have been developed. These are generally in three categories, which are absolute fit, incremental fit and parsimonious fit (Xiong et al., 2014). Predictive fit indices are the fourth index category introduced by Kline (2010), and they are population-based rather than being sample-based like others. It is important to use some fit indices across the three categories, especially as each index considers a unique aspect of the model (Crowley and Fan, 1997). Hair et al. (2010) suggests the use of alternative indices across the categories, especially the Chi Square (X^2) and assumed differences, Root Mean Square Error of Approximation (RMSEA) and Comparative Fit Indices (CFI). Similarly, Kline (2010) recommends the use of Chi-Square (X^2), RMSEA, Global Fit Index (GFI), CFI, PCLOSE and Standardized Root Mean Square Residual (SRMR). The categories of model fit indices are explained below.

8.3.1 Absolute Fit

Absolute fit indices explain the proportion of covariance in the sample data matrix that is explained by the model (Kline, 2010). It is similar to R^2 statistics except that it explains the relationship between model and data rather than the explanatory power that is explained by R^2 statistics. An absolute fit index of 0.75 suggests that 75% of covariance is explained by the model (Kline, 2010). Fitness indices in this category are Chi-Square ($\chi 2$), RMSEA, GFI, AGFI, SRMR and RMR.

Model Chi-Square ($\chi 2$) evaluates overall model fit, and it assesses the extent of discrepancy between the data and covariance matrices. A good fit model produces insignificant $\chi 2$ at 95% confidence level, and as such, Chi-Square ($\chi 2$), is usually referred to as badness of fit (Hooper et al., 2008). A major limitation of this test is its sensitivity to sample, meaning that it may reject model with large sample size while providing bad fit for model with small sample (Kenny and McCoach, 2003). An alternative approach to this limitation is the use of relative/normed Chi-Square ($\chi 2/df$), which have acceptable value ranging from 2.0 to 5.0 (Hooper et al., 2008).

RMSEA is another important fit index that evaluates the extent to which the model would fit the populations' covariance matrix with an unknown but optimally chosen parameter estimate. RMSEA in the range of 0.05 to 0.10 are acceptable, with 0.08 becoming an upper cut-off point (Hooper et al., 2008). The Goodness of Fit Index (GFI) is an alternative test to $\chi 2$ that evaluates the proportion of variance that the estimated population covariance accounted for (Tabachnick and Fidell, 2007). The index ranges from 0-1, and 0.9 is usually recommended as the lower cut-off point. Adjusted Good of Fit (AGFI), as the name implies, adjusts the GFI based on degree of freedom. Hooper et al. (2008) suggest that considering their sensitivity to sample size, GFI and AGFI are not reliable when used alone, but they remain important indices of model fit. Based on these, this study combines Normed Chi-Square, RMSEA, GFI and AGFI as measures of the absolute fit of the model.

8.3.2 Incremental Fit Indices

Incremental Fit Indices are a category of indices that do not use Chi-Square in its original form but compares the Chi-Square value to a baseline model (Kline, 2010). An assumption underlying indices in this category is that all variables in the model are not correlated (Hooper et al., 2008). Normed-Fit Index (NFI) and Comparative Fit Index (CFI) are the indices in this category. NFI compares the model's $\chi 2$ to that of a null model. Because of its sensitivity to sample size, it usually underestimates model with less than 200 samples (Bentler, 1990). Another variance of NFI is the Tucker-Lewis Index (NNFI), which prefers simpler model. A value of 0.80 is acceptable, and a value above 0.95 is recommended (Hooper et al., 2008). CFI is a revised form of NFI that performs better with a small sample. Like NFI, a CFI value above 0.90 within its range of 0-1 is recommended (Kline, 2010). This study evaluates its incremental model fitness using NFI, NNFI and CFI.

8.3.3 Parsimonious Test Indices

Parsimonious test builds in corrections for model complexity and it is measured through Parsimony Goodness of Fit (PGFI) and Parsimonious Normed Fit Index (PNFI). While PGFI is based on GFI with an adjustment for degree of freedom, PNFI is based on NFI with an adjustment for degree of freedom. While a value above 0.90 is expected, a value as low as 0.50 could be acceptable, provided the model satisfied other goodness of fit indices (Hooper et al., 2008). In this study, models were evaluated for Parsimonious fit through PGFI and PNFI. Table 8.1 summarises the benchmark for each of the model fit indices.

Table 8.1: Thresholds for model fit indices

Goodness of fit measures	***Recommended level of GOF measures[a]***
X^2 ⁄degree of freedom	<5 (preferably 1 to 2)
RMSEA	<0.10 (preferably <0.08)
Goodness of Fit Index (GFI)	0(no fit) – 1 (perfect fit)
Adjusted Goodness of Fit Index (AGFI)	0(no fit) – 1 (perfect fit)
Comparative Fit Index (CFI)	0(no fit) – 1 (perfect fit)
Normed Fit Index (NFI)	0(no fit) – 1 (perfect fit)
Tucker-Lewis Index (TLI)	0(no fit) – 1 (perfect fit)
Parsimonious Goodness of Fit Index (PGFI)	0(no fit) – 1 (perfect fit)
Parsimonious Normed of Fit Index (PNFI)	0(no fit) – 1 (perfect fit)

a: Thresholds adapted from Doloi et al. (2012); Kline (2010); Hair et al. (2010) and Chen et al. (2012).

8.4 Validity and Reliability of Constructs

In order to evaluate adequacy of the model regarding the relationship established between latent and observed (measured) variables, tests of validity and reliability are usually performed. These include face validity, discriminant validity of the measurement model and convergent validity of the measures associated with latent variables (Doloi et al., 2012; Kline, 2010). These set of evaluation are used to assess the accuracy of the model, thereby determining the extent to which the measured variables reflect the latent construct (Hair et al., 2010).

Through extensive literature review, focus group discussion and pilot studies reported in Chapters 4, 6 and 7 respectively, face/content validity of the constructs has been achieved. Convergent validity of the model seeks to test that measures that are theoretically expected to be related are actually related (Kline, 2010). It is a degree of confidence that a latent variable is well measured by its indicators. It is examined through standardised factor loading, and it is believed to be satisfied in a measurement model when factor loading is significant at appropriate level (Anderson and Gerbing, 1988). Other measures of convergent validity include Average Variance Extracted (AVE), which estimates the degree of shared variance between latent variables in a model (Hair et al., 2010). It estimates the level of variance captured by a construct as well as those due to error. A model with convergent issue will have variables that do not correlate well with latent factor. An acceptable value of AVE is 0.5, with a value above 0.7 being considered as good value. According to Fornell & Larker (1981), Average Variance Extracted (AVE) for a latent variable X, with indicators x_1. x_2, ….x_n, is calculated as:

$$\text{AVE} = \frac{\Sigma[\lambda_i^2]\text{Var}(X)}{\Sigma[\lambda_i^2]\text{Var}(X)+\Sigma[\text{Var}(\varepsilon_i)]}$$

Where λ_i is the loading of indicator x_i on X, Var represents variance, ε_i represent measurement error of x_i, and Σ means a sum. AVE is believed to be a more reliable measure of validity than Composite Reliability (Malhotra and Dash, 2011).

Discriminant validity is another measure of construct validity that evaluates the extent to which a measure diverges from what it is theoretically expected to diverge. It basically tests whether measures that are not expected to be related are in true sense unrelated (Sureshchandar et al., 2002). It is usually evaluated through Maximum Shared Squared Variance – MSV (Hair et al., 2010). The MSV of a latent factor is a measure of the extent to which it is better explained by other factors outside its construct (Malhotra and Dash, 2011). For a model to be reliable, AVE is expected to be greater than MSV, as the items (indicators) belonging to the factor should better explain it than the items belonging to another factor in the model (Hair et al., 2010). These sets of test are performed in addition to reliability analyses that were performed for all the dimensions of design, procurement and construction measures that are presented in Tables 7.2 to 7.5.

8.5 Confirmatory Factor Analysis

Confirmatory Factor Analysis were conducted to confirm the key underlying measures for mitigating waste through design, procurement and construction activities. The total sample size is above the N=200 threshold recommended by Kline (2010) for SEM, thus further buttressing the suitability of the data for measurement and structural models. Models were developed with AMOS 22 for structural equation modelling. For each of the CFAs, initial models were developed based on the factor established as presented in Tables 7.2 to 7.5. The factors that failed the initial reliability test were removed as indicated in the tables. As recommended by Ullman (2001), Kline (2010) and numerous other experts, Maximum Likelihood (ML) technique was used for the model estimation.

This is especially suitable as it yields maximum parameter estimate when used for normally distributed data of this nature (Ullman, 2001). Results of the covariance are assessed to test the appropriateness of the initial model, using some fit indices discussed in the previous section (8.3).

Based on evaluation of the initial model, improvements were required for adequate validity, reliability and model fitness with data. In order to improve model fit, two methods were used for model modification. As suggested by Kline (2010), modification indices of SPSS AMOS (version 22) were used to add covariance and causal relationships between error terms and measured variables respectively. This approach is widely used for refining SEM and for improving its model fit (Chen et al., 2012). It was ensured that all modifications made theoretical sense concerning interrelationship between waste mitigation measures. In addition to the modification indices, the path diagram was screened to check for variables that show no significant correlation with latent factor and to check for significant variable with low correlation coefficient. The hypothetical models went through some refinements before the desired model fit, reliability and validity were achieved in each case.

Based on the nature of constructs of this study, second-order factor analyses were performed for each of design, design competencies, procurement and construction measures for engendering waste minimisation. Apart from its preservation of multi-dimensional constructs as required in this study, an additional benefit of the second-order factor is that it reduces collinearity by allowing causality through a single second-order factor (Benson and Bandalos, 1992). In this case, design, procurement and construction became the second-order factors, while their underlying dimensions became the first-order factors that are estimated through observed variables.

8.5.1 Second Order CFA of Design Measures

In order to confirm the structure of factors underlying waste-efficient design, CFA was conducted on the design factors and its established dimensions. The six dimensions for designing out waste (as presented in Table 7.2) are design documentation, design process, design for standardisation, design for modern methods of construction, design for flexibility, and organic design. These dimensions for designing out waste were modelled as first-order latent variables, and they consist of seven, eight, eight, four, two and two indicator (measured/observed) variables respectively. Apart from confirming the main indicators contributing to each of the latent variables, an important aspect of this study is to establish the relationship between the six dimensions and waste-efficient design. This helped to establish the key dimensions for designing out waste. Based on this requirement, two-step approach that combined measurement and structural models were used as suggested by Anderson and Gerbing (1998). Thus, the model consists of both structural and measurement models. While the measurement model focuses on the relationship between indicators and first-order variables, the structural model confirmed the relationships between the first-order and second-order variables. Figure 8.1 show specification for initial model of relationship between indicators, first-order and second-order variables.

An evaluation of the model fit indices suggests the need to make some improvement on the model. Based on this, indicators with low factor loading and those with insignificant loadings were deleted from the model as suggested by Kline (2010). This affected one indicator (DF38) of design document, two indicators (DF3 and DF12) of design process and two indicators (DF16 and DF20) of design for modern methods of construction. After deleting the indicators, the model fit indices improved to satisfactory level and five of the six dimensions for designing out waste passed the convergent validity test with their AVE ranging between 0.62 and 0.79, which is above the 0.5 thresholds (Hair et al., 2008). All the loadings were also statistically significant. Design for flexibility with its two indicators was removed from the model as it is not contributing to the overall reliability of the model. Figure 8.2 shows the final model, while Table 8.1 shows the construct reliability and variance extracted for all constructs of designing out waste.

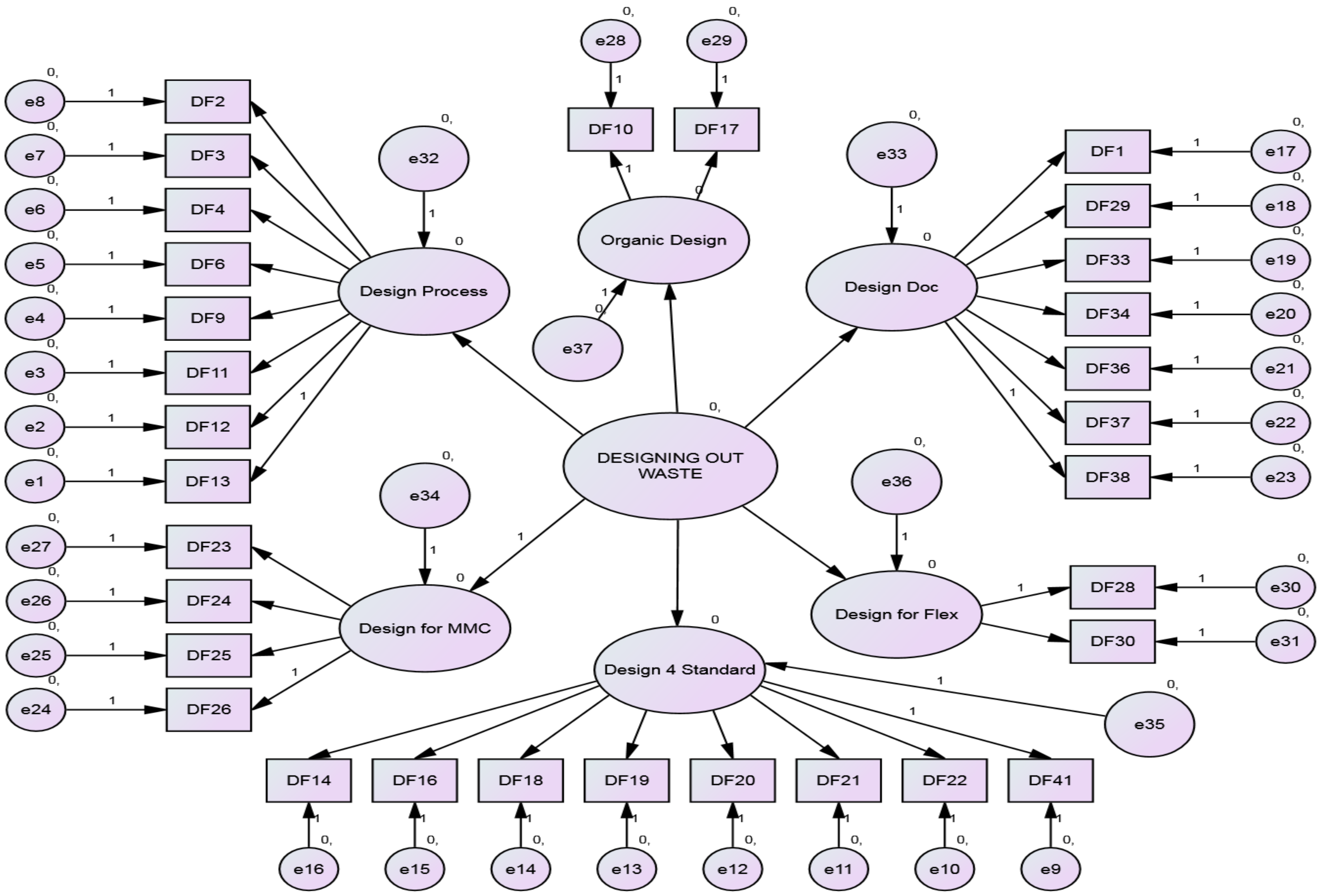


Figure 8.1: Initial/Hypothetical model of the design measures for waste minimisation

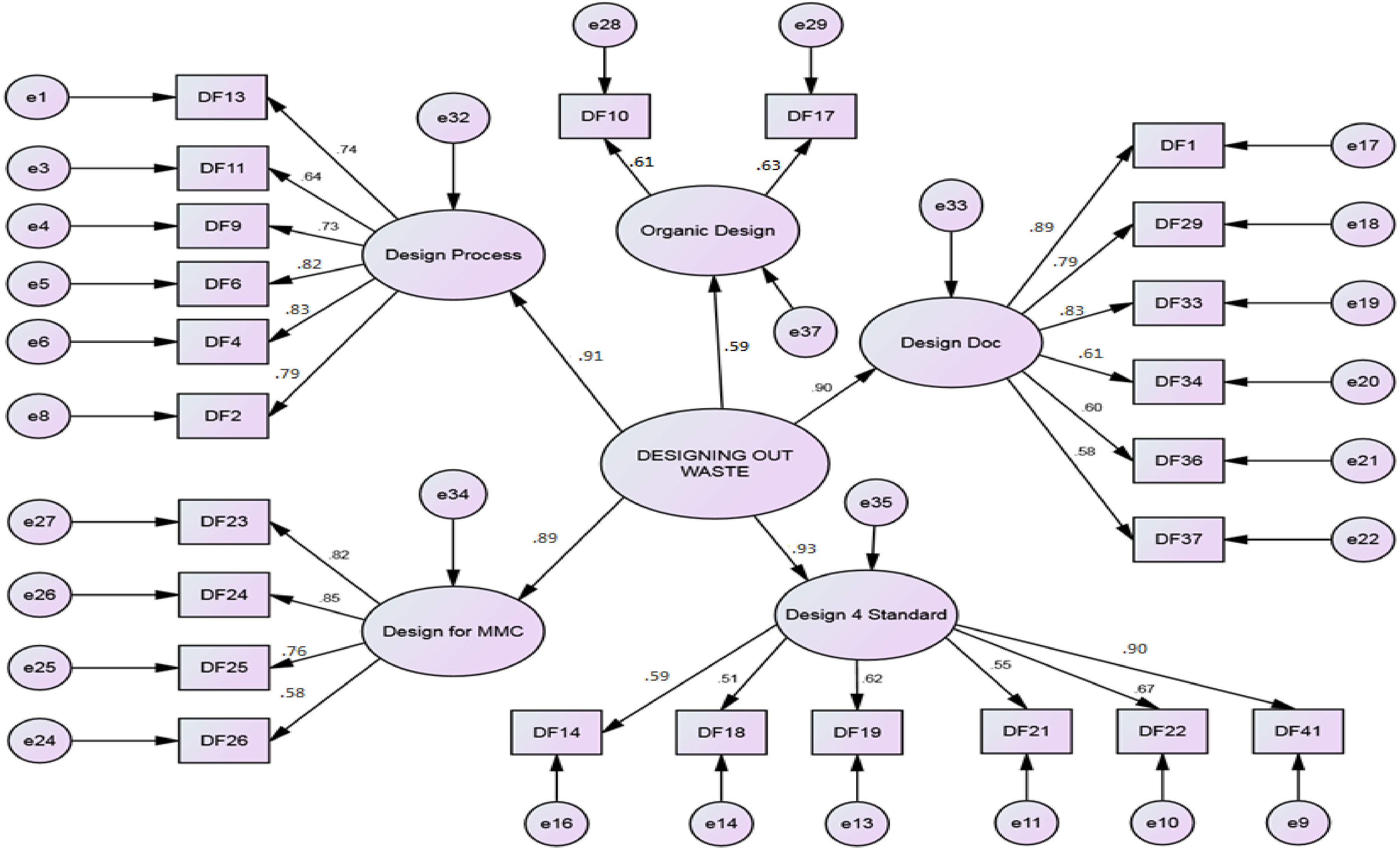


Figure 8.2: Final Model of design measures for construction waste minimisation

Table 8.2: Maximum Likelihood estimate and value of fit statistics for design measures

First-order CFA			
Relationship	***Estimate***	***AVE***	***CR***
DF1 <--- Design doc	0.89	0.62	0.84
DF29 <--- Design doc	0.79		
DF33 <--- Design doc	0.83		
DF34 <--- Design doc	0.61		
DF35 <--- Design doc	0.60		
DF37 <--- Design doc	0.58		
DF2<--- Design Pro	0.79	0.58	0.71
DF4<--- Design Pro	0.83		
DF6 <--- Design Pro	0.82		
DF9 <--- Design Pro	0.73		
DF11 <--- Design Pro	0.64		
DF13 <--- Design Pro	0.74		
DF23<--- Design for MMC	0.82	0.64	0.74
DF24<---Design for MMC	0.85		
DF25<---Design for MMC	0.76		
DF26<---Design for MMC	0.58		
DF14<---Design 4 standard	0.59	0.71	0.88
DF18<---Design 4 standard	0.51		
DF19<---Design 4 standard	0.62		
DF21<---Design 4 standard	0.55		
DF22<---Design 4 standard	0.67		
DF41<---Design 4 standard	0.90		
DF10<---Organic design	0.61	0.51	0.68
DF17<---Organic design	0.63		

Second-order CFA			
Relationship	***Estimate***	***AVE***	***CR***
Design document <--- DESIGN	0.90	0.83	0.92
Design Process<--- DESIGN	0.91		
Design for MMC<--- DESIGN	0.89		
Design 4 standard<--- DESIGN	0.93		
Organic design <--- DESIGN	0.59		

MODEL FIT INDICES		
Indices	***Initial Model***	***Final Model***
X^2⁄degree of freedom	6.165	2.791
RMSEA	0.073	0.052
GFI	0.930	0.987
AGFI	0.881	0.964
CFI	0.641	0.982
NFI	0.523	0.952
TLI	0.563	0.981
PGFI	0.819	0.977
PNFI	0.589	0.956
IFI	0.646	0.973
Cronbach's Alpha	0.831	

8.5.2 Second Order CFA of Design Competencies

Confirmatory Factor analysis was performed on the established competencies for designing out waste and its four dimensions as presented in Table 7.3. The aim of the CFA was to understand and confirm factor structure and underlying competencies for designing out waste. The four dimensions of competency, including design task competency, construction and materials related knowledge, waste behavioural competencies and inter-professional competencies, were modelled as first-order latent factor while design competency is the second-order variable. Figure 8.3 shows the initial model of design competencies for engendering waste-efficient design.

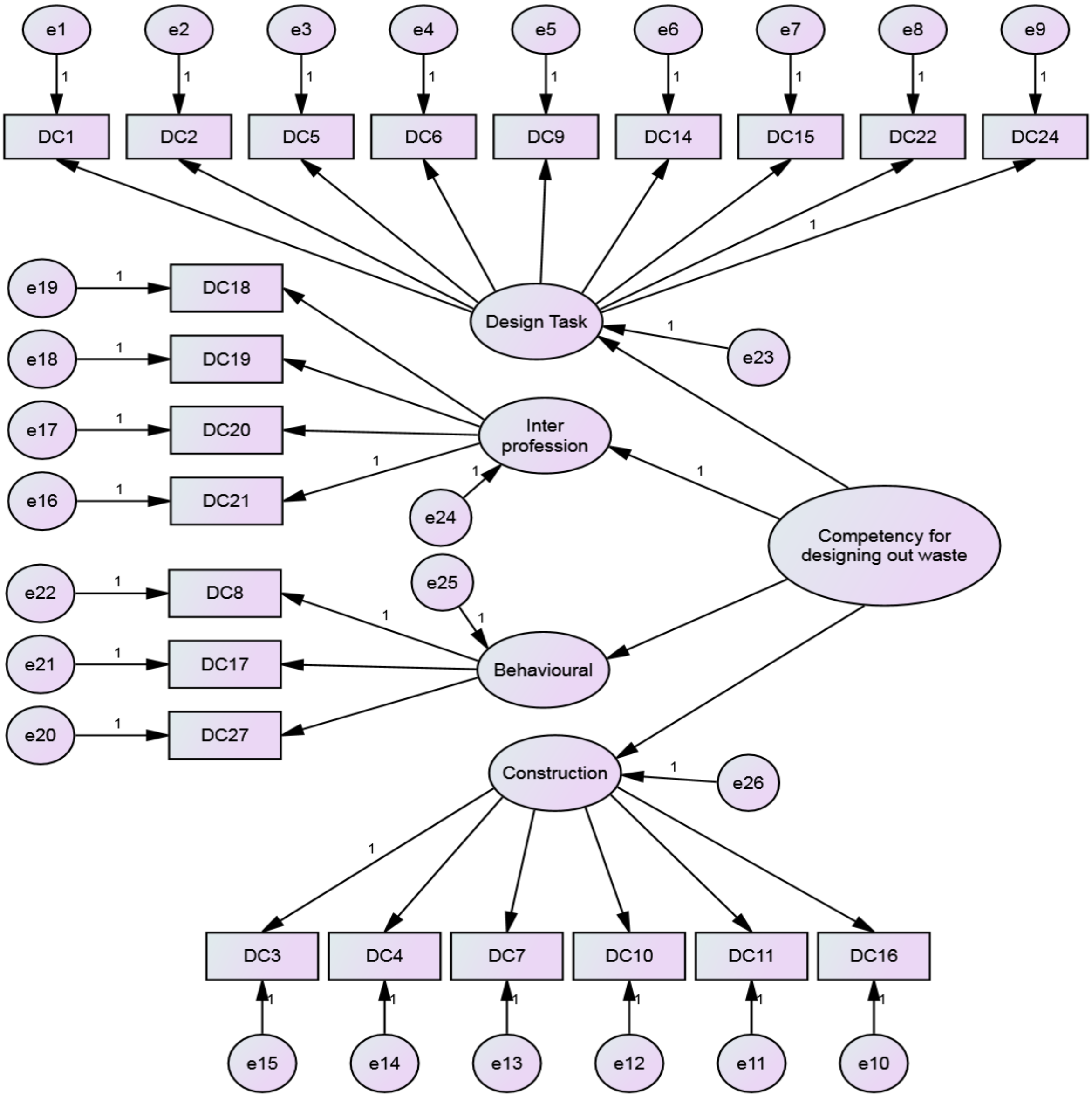


Figure 8.3: Initial model of competencies for designing out waste

The initial model was evaluated for validity, reliability and model fit to check fitness of the model with data. The fit statistics and reliability test suggests the need for further model improvement, which was done by deleting indicators with insignificant coefficient as well as those having low factor loading with their latent factors. This affected one indicator each of design task competencies (Design Task) and waste behavioural competencies (Behavioural). After some iteration and modifications, model fit indices were improved to expected standard. Both indicator and first-order factors loaded significantly onto their corresponding latent factor, with none of the value less than 0.53. Similarly, AVE and CR show that the model passed convergent validity and reliability. Figure 8.4 shows final model, while Table 8.3 shows the standardised estimate, model fit statistics and indices of validity.

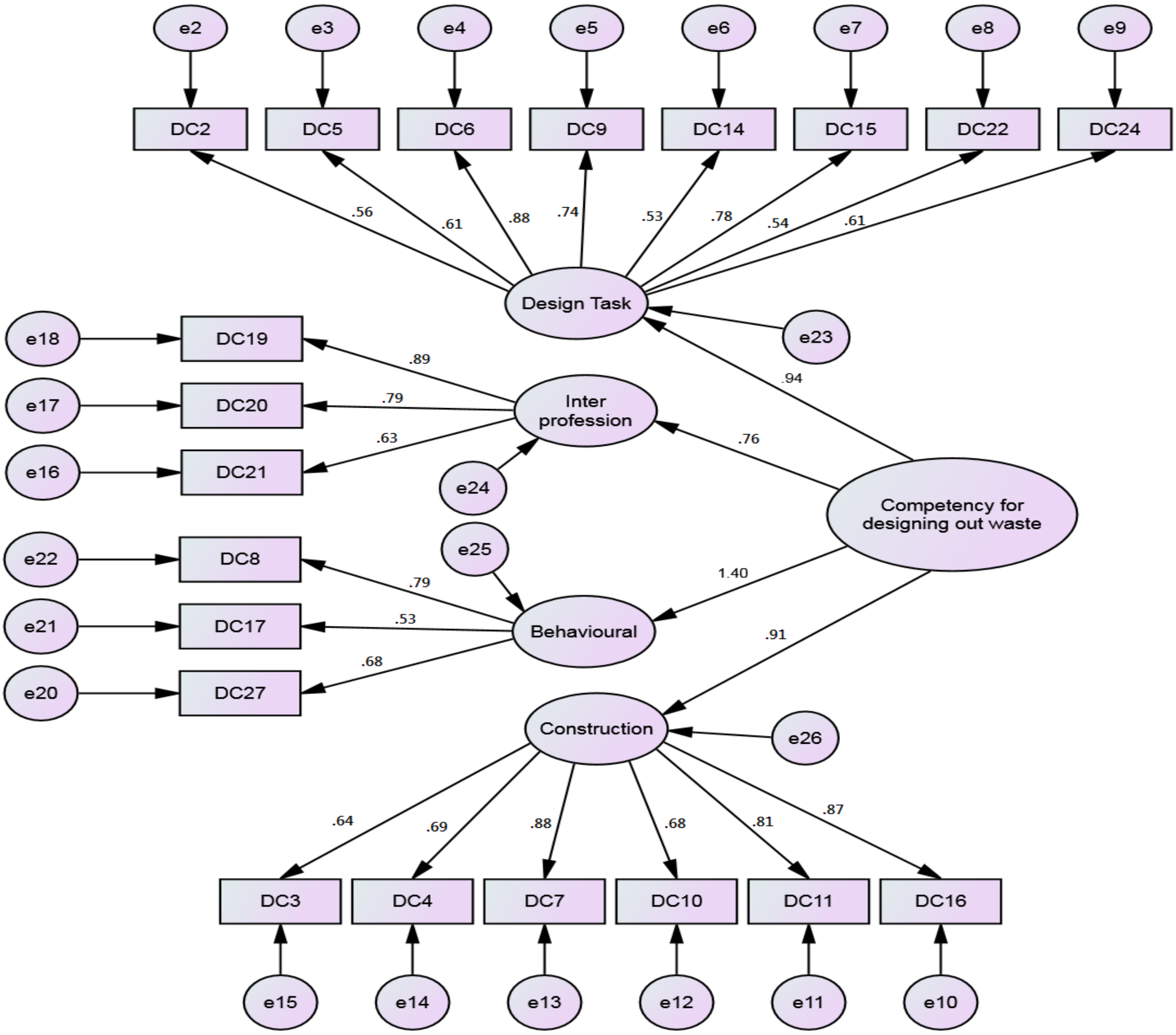


Figure 8.4: Final model of competencies for designing out construction waste

Table 8.3: Standardised estimate and value of fit statistics of design competencies

First-order CFA			
Relationship	***Estimate***	***AVE***	***CR***
DC2<--- Design Task	0.56	0.67	0.74
DC5<--- Design Task	0.61		
DC6<--- Design Task	0.88		
DC9<--- Design Task	0.74		
DC14<--- Design Task	0.53		
DC15<--- Design Task	0.78		
DC22<--- Design Task	0.54		
DC24<--- Design Task	0.61		
DC3<--- Construction	0.64	0.63	0.85
DC4<--- Construction	0.69		
DC7<--- Construction	0.88		
DC10<--- Construction	0.68		
DC11<--- Construction	0.81		
DC16<--- Construction	0.87		
DC19<--- Behavioural	0.89	0.62	0.72
DC20<--- Behavioural	0.79		
DC21<--- Behavioural	0.63		
DC8<---Inter_Pro	0.79	0.69	0.84
DC17<---Inter_Pro	0.53		
DC27<---Inter_Pro	0.68		

Second-order CFA			
Relationship	***Est.***	***AV***	***CR***
Design Task <--- COMPETENCY	0.94	0.76	0.89
Construction <-- COMPETENCY	0.91		
Behavioural <--- COMPETENCY	1.40		
Inter_Pro <--- COMPETENCY	0.76		

MODEL FIT INDICES		
Indices	***Initial Model***	***Final Model***
X^2/degree of freedom	3.997	1.062
RMSEA	0.062	0.042
GFI	0.947	0.992
AGFI	0.933	0.987
CFI	0.951	0.989
NFI	0.636	0.973
TLI	0.794	0.986
PGFI	0.895	0.985
PNFI	0.836	0.963
IFI	0.769	0.961
Cronbach's Alpha	0.894	

8.5.3 Second Order CFA of Procurement Measures

Like design measures, CFA was performed on procurement measures to confirm the factor structure of waste-efficient procurement. Waste-efficient procurement is the second-order latent factor that is predicted by the previously established dimensions of waste-efficient procurement (see Table 7.4), which are the first-order latent factors. The four first-order factors are delivery planning and scheduling, suppliers' alliance and commitments, low waste materials purchase management and waste-efficient bill of quantity, having four, five, eight and four indicators respectively. The initial model of waste-efficient procurement is presented in Figure 8.5.

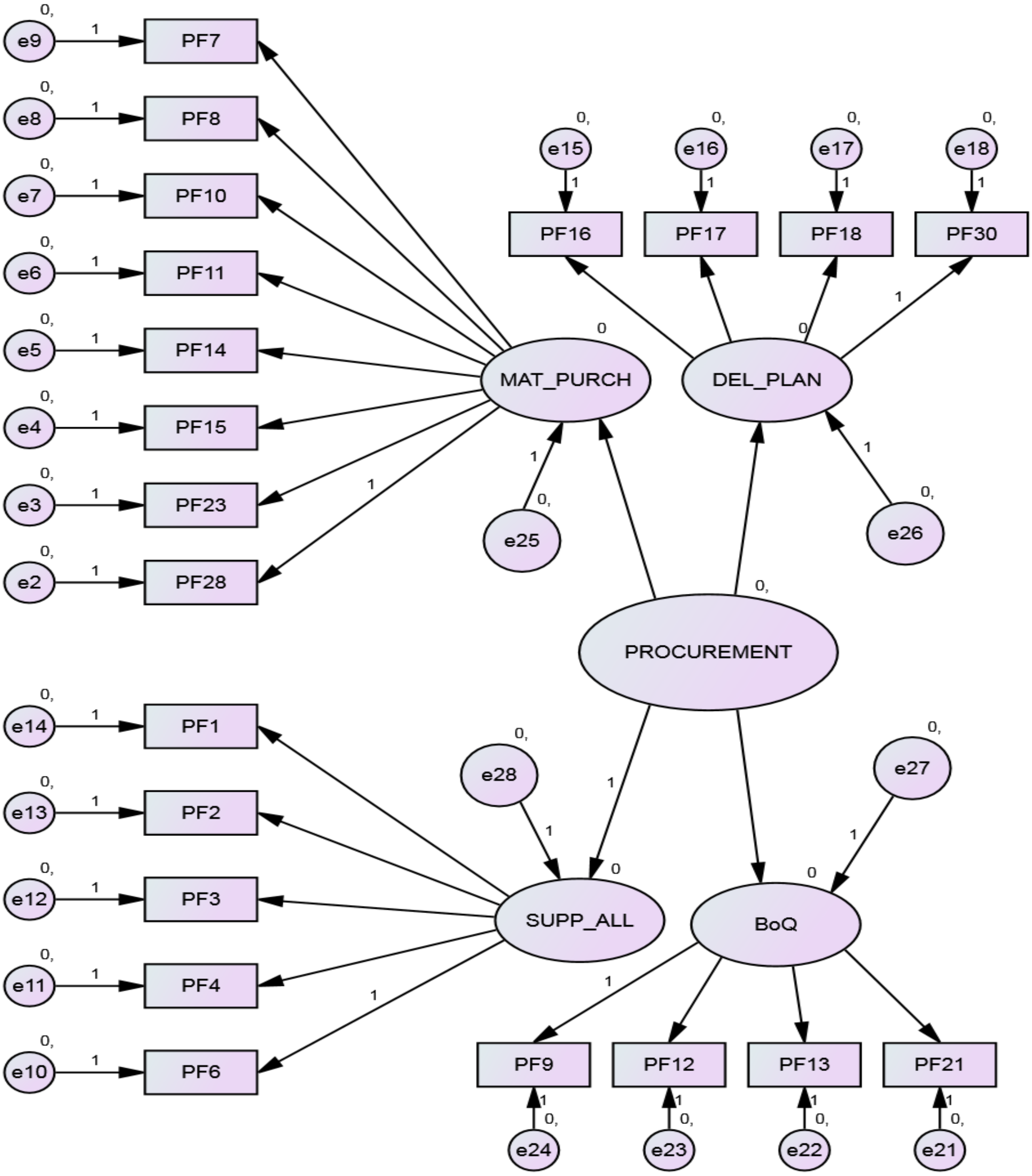


Figure 8.5: Initial model of waste-efficient procurement process

In order to enhance model fitness, reliability and convergent validity, the initial model went through model re-specification and refinement. Indicators with low factor loading and insignificant relationship were removed from the model. One of the first-order factors – delivery planning and scheduling (DEL_PLAN) – failed reliability and convergent validity tests. It also has an insignificant loading with the second-order factor. Also, two of its four indicators showed insignificant factor loadings. Hence, the first-order factor was deleted from the model. One indicator was deleted from each of low waste materials purchase management (MAT_PURCH) and waste-efficient bill of quantity (BoQ) due to insignificant and low loading with the first-order latent variables. In line with recommendation by Kline (2010) and Hair et al. (2008), covariance was introduced on error terms as suggested by AMOS modification indices. After model re-specification, the final model showed significant loading of factors at P<0.001 for both first and second-order latent factors. The model also demonstrated excellent fit as presented in Table 8.4. Figure 8.6 shows the final model and its standardised estimates.

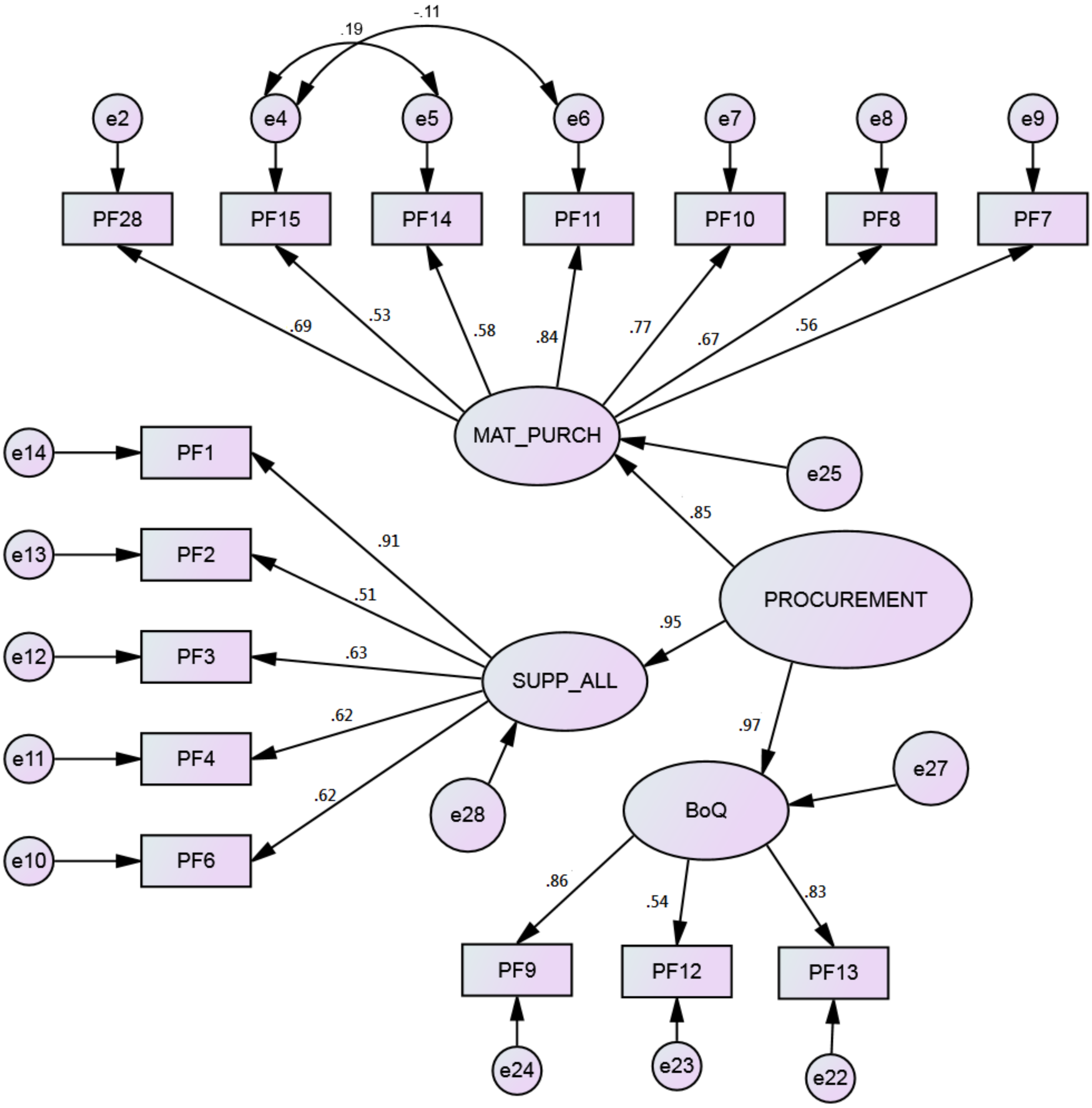


Figure 8.6: Final Model of waste-efficient procurement process

Table 8.4: Maximum Likelihood estimate and value of fit statistics of waste procurement

First-order CFA			
Relationship	***Estimate***	***AVE***	***CR***
PF7<--- Mat_Purch	0.56	0.60	0.72
PF8<--- Mat_Purch	0.67		
PF10<--- Mat_Purch	0.77		
PF11<--- Mat_Purch	0.84		
PF14<--- Mat_Purch	0.58		
PF15<--- Mat_Purch	0.53		
PF28<--- Mat_Purch	0.69		
PF1<--- Supp_All	0.91	0.63	0.77
PF2<--- Supp_All	0.51		
PF3<--- Supp_All	0.63		
PF4<--- Supp_All	0.62		
PF6<--- Supp_All	0.62		
PF9<--- BoQ	0.86	0.59	0.79
PF12<--- BoQ	0.54		
PF13<--- BoQ	0.83		

Second-order CFA			
Relationship	***Estimate***	***AVE***	***CR***
Mat_Purch<--- PROCUREMENT	0.85	0.58	0.73
Supp_All <-- PROCUREMENT	0.95		
BoQ<--- PROCUREMENT	0.95		

MODEL FIT INDICES		
Indices	***Initial Model***	***Final model***
X^2/degree of freedom	2.028	1.029
RMSEA	0.023	0.010
GFI	0.961	0.992
AGFI	0.945	0.952
CFI	0.973	0.979
NFI	0.756	0.951
TLI	0.967	0.989
PGFI	0.881	0.950
PNFI	0.650	0.906
IFI	0.978	0.982
Cronbach's Alpha	0.803	

8.5.4 Second Order CFA of Construction Measures

In order to establish the underlying dimensions of waste-efficient construction process, a second-order CFA was modelled. While waste-efficient construction is modelled as the second-order factor, other 12 latent factors presented in Table 7.4 were modelled as first-order latent factors. Figure 8.7 shows the initial model that was subjected to further modification and re-specification, which ultimately improved fit statistics, reliability and validity of the constructs.

The initial model shows poor fit statistics as well as insignificant loading of some of the first-order factors and their indicators. As such, the model was re-specified and modified to improve fit statistics and reliability of the constructs. This led to deletion of four latent factors, which are waste-efficient formwork (WEForm), Human resources management measures (HRMan), Waste segregation (WSeg) and Logistic Management (LogMan). Although two of the latent factors (WSeg and LogMan) have good Composite Reliability (CR ≥ 0.87) and Average Variance Extracted (AVE ≥ 0.61), they show low factor loading to the second-order variable at 0.18 and 0.21 respectively. What this suggests is that although the two factors have impacts on construction waste, they are of less significance. The other two latent factors (WEForm and HRMan) have poor CR and AVE, with insignificant impacts on the second-order factor (Waste-efficient Construction).

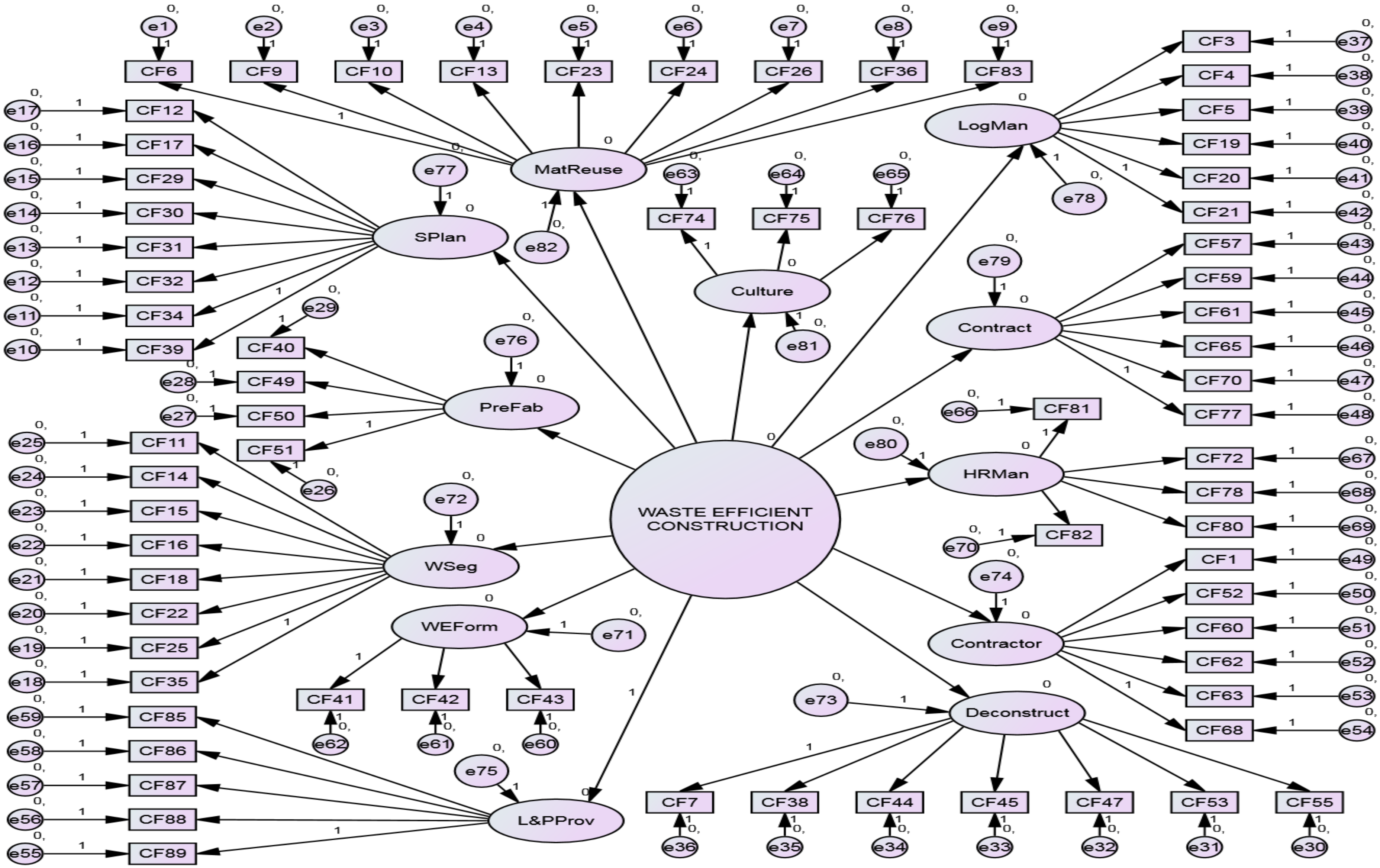


Figure 8.7: Initial model of waste-efficient construction indices

Apart from deletion of first-order latent factors and their indicators, some indicators were also deleted from other latent factors to enhance model fit and validity. Rather than being an indicator of waste-efficient construction, legislative and policy provisions (L&PProv) was remodified as a formative construct that is contributing to waste effective decisions. The final model with good fit statistics, reliability and validity, are presented in Figure 8.8. Table 8.5 shows estimate, fit indices and reliability index of waste-efficient construction model.

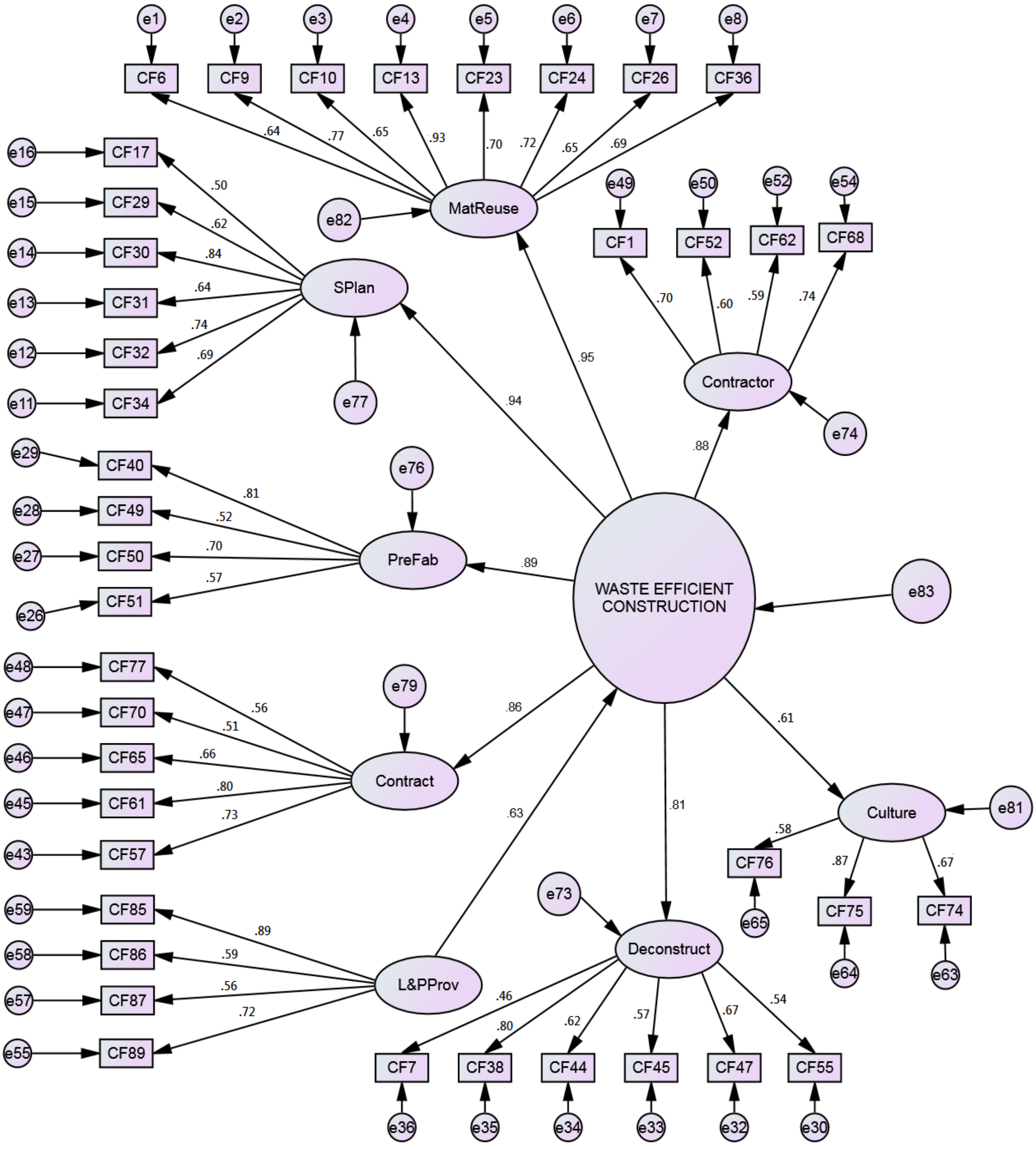


Figure 8.8: Final Model of waste-efficient construction indices

Table 8.5: Maximum Likelihood estimate and value of fit statistics of construction strategies

First-order CFA

Relationship	***Estimate***	***AVE***	***CR***
CF17<--- SPlan	0.50	0.57	0.84
CF29<--- SPlan	0.62		
CF30<--- SPlan	0.84		
CF31<--- SPlan	0.64		
CF32<--- SPlan	0.74		
CF34<--- SPlan	0.69		
CF6<--- MatReuse	0.64	0.63	0.85
CF9<--- MatReuse	0.77		
CF10<--- MatReuse	0.65		
CF13<--- MatReuse	0.93		
CF23<--- MatReuse	0.70		
CF24<--- MatReuse	0.72		
CF26<--- MatReuse	0.65		
CF36<--- MatReuse	0.69		
CF7<--- Deconstuct	0.46	0.62	0.77
CF38<--- Deconstuct	0.80		
CF44<--- Deconstuct	0.62		
CF45<--- Deconstuct	0.57		
CF47<--- Deconstuct	0.67		
CF55<--- Deconstuct	0.54		
CF40<---PreFab	0.81	0.67	0.89
CF49<---PreFab	0.52		
CF50<---PreFab	0.70		
CF51<---PreFab	0.57		
CF57<---Contract	0.73	0.70	0.86
CF61<---Contract	0.80		
CF65<---Contract	0.66		
CF70<---Contract	0.51		
CF77<---Contract	0.56		
CF1<---Contractor	0.70	0.59	0.82
CF52<---Contractor	0.60		
CF62<---Contractor	0.59		
CF68<---Contractor	0.74		
CF74<---Culture	0.67	0.51	0.72
CF75<---Culture	0.87		
CF76<---Culture	0.58		
CF85<---L&PProv	0.89	0.63	0.79
CF86<---L&PProv	0.59		
CF87<---L&PProv	0.56		
CF89<---L&PProv	0.72		

Second-order CFA

Relationship	***Est***	***AV***	***CR***
SPlan <--- CONSTRUCTION	0.94	0.73	0.86
MatReuse <--- CONSTRUCTION	0.95		
Deconstuct<--- CONSTRUCTION	0.81		
PreFab <--- CONSTRUCTION	0.89		
Contract<--- CONSTRUCTION	0.86		
Contractor<--- CONSTRUCTION	0.88		
Culture<--- CONSTRUCTION	*0.61*		
CONSTRUCTION <--- L&PProv	0.63		

MODEL FIT INDICES

Indices	***Initial Model***	***Final model***
X^2/degree of freedom	1.582	1.299
RMSEA	0.032	0.027
GFI	0.855	0.961
AGFI	0.839	0.952
CFI	0.682	0.948
NFI	0.469	0.906
TLI	0.556	0.953
PGFI	0.766	0.953
PNFI	0.554	0.957
IFI	0.616	0.971
Cronbach's Alpha	0.949	

8.6 Structural Model of Design, Procurement and Construction Strategies

After establishing model fit indices and validity of construct for each of design, procurement and construction measures for a waste-efficient project, the models were combined as a structural model. This helped to confirm the model structure of interrelationship between the three stages of project delivery processes, as well as to estimate impacts of each of the second order factors on project waste minimisation. In order to draw the final model as a second-order structural model, AMOS data imputation was used to generate values for the first-order factors of design, procurement and construction. This helped to prevent the use of third-order composite and reflective factors, which have been largely criticised for invalidity (Lee and Cadogan, 2013).

The overall model was evaluated through value of fit statistics, Maximum Shared Squared Variance (MSV) and Average Variance Extracted (AVE). As presented in Tables 8.6 and 8.7, the model shows excellent validity, reliability and fit statistics above the thresholds recommended by Hair et al. (2010) and Kline (2010), among other experts. For instance, AVE value was above the threshold of 0.5 for all the constructs as required (Hair et al., 2010). Similarly, lower value of MSV than AVE indicated that the item belonging to each factor explained it better than items belonging to another factor in the model. The overall structural model indicated that most of the variables loaded significantly onto their latent variables (at $P \leq 0.001$), which in turn have significant impacts on overall waste effectiveness of construction projects. For the overall model, only one item with low but significant correlation with its latent factor was "organic design", which is an indicator of waste-efficient design. As the measure also has a squared multiple correlation (R^2) of 28%, which is below the recommended threshold of 50% (Jöreskog and Sörbom, 1993), it is not confirmed to be a good reflection of waste-efficient design. The combined model is as presented in Figure 8.9.

Table 8.6: Standardised estimate and validity of the overall model

Constructs	***Items***	***Estimate***	***P-Value***	***AVE***	***MSV***
LOW WASTE OUTPUT	Waste-efficient design	0.90	≤0.001	0.792	0.217
	Waste-efficient Procurement	0.60	≤0.001		
	Waste-efficient Construction	1.45	≤0.001		
WASTE-EFFICIENT DESIGN	Design document	0.65	≤0.001	0.81	0.396
	Design process	0.75	≤0.001		
	Design for MMC	0.68	≤0.001		
	Design for standard supplies	0.73	≤0.001		
	Organic Design	0.31	≤0.01		
WASTE-EFFICIENT PROCUREMENT	Material purchase management	0.59	≤0.001	0.62	0.429
	Bill of Quantity	0.57	≤0.001		
	Suppliers' alliance	0.82	≤0.001		
WASTE-EFFICIENT CONSTRUCTION	Site Planning	0.63	≤0.001	0.79	0.121
	Materials reuse	0.91	≤0.001		
	Deconstructability	0.59	≤0.01		
	Prefabrication	0.97	≤0.001		
	Contractual Provision	0.94	≤0.001		
	Contractors' competency	0.71	≤0.001		
	Cultural change	0.51	≤0.001		
	Legislation and policy	0.53	≤0.001		

Table 8.7: Value of fit statistics for the overall model

Goodness of fit measures	***Recommended indices***	***Final model fit***
X^2/degree of freedom	<5 (preferably 1 to 2)	1.49
RMSEA	<0.10 (preferably <0.08)	0.04
Goodness of Fit Index (GFI)	0(no fit) – 1 (perfect fit)	0.97
Adjusted Goodness of Fit Index (AGFI)	0(no fit) – 1 (perfect fit)	0.98
Comparative Fit Index (CFI)	0(no fit) – 1 (perfect fit)	0.98
Normed Fit Index (NFI)	0(no fit) – 1 (perfect fit)	0.98
Tucker-Lewis Index (TLI)	0(no fit) – 1 (perfect fit)	0.96
Parsimonious Goodness of Fit Index (PGFI)	0(no fit) – 1 (perfect fit)	0.97
Parsimonious Normed of Fit Index (PNFI)	0(no fit) – 1 (perfect fit)	0.96

A further evaluation of Squared Multiple Correlation (R^2) for all the constructs on the model suggests that this model accounts for 72% of variance in waste-efficient construction, 68% in waste-efficient materials procurement and 81% of variance in waste-efficient design. The R^2 also indicated that one dimension of construction had a squared multiple correlation of 43%, which is slightly below the threshold of 50%. This means that less than 50% of variance in de-constructability is explained by waste-efficient construction; and as such it is recommended to be dropped from the model (Jöreskog and Sörbom, 1993; Kline, 2010).

Apart from significant relationship between overall waste efficiency and the three stage/processes considered in the study (design, procurement and construction), significant relationships were estimated between the three stages. The standardised estimate relating design to procurement was statistically significant at $\beta=0.50$, $P\leq0.001$, while those of design to construction and procurement to construction are also significant at $P\leq0.001$ with values of $\beta=1.30$ and $\beta = 0.63$ respectively. The percentage of variance in waste-efficient design, waste-efficient procurement and waste-efficient construction process explained by low waste output are 81%, 68% and 72%. In line with Falk and Miller (1992), the mean R^2 computed for the three key endogenous variables is 73.7%, indicating that the model could account for significant process of construction waste minimisation. Based on the established factor loading, validity, reliability and model fit indices, the underlying dimensions for low waste project are as represented in Figure 8.10.

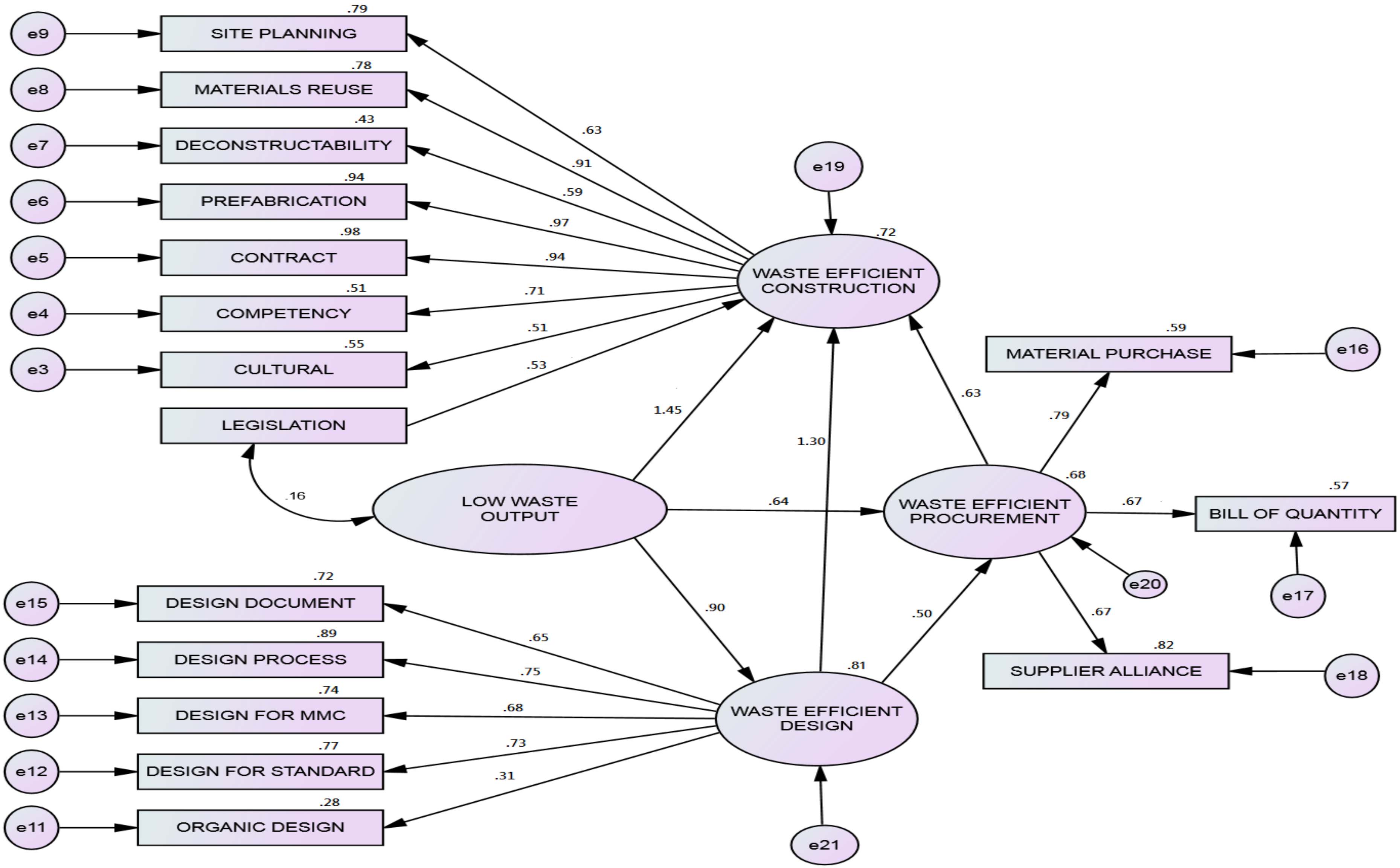


Figure 8.9: Overall Structural Equation Modelling for low waste construction project

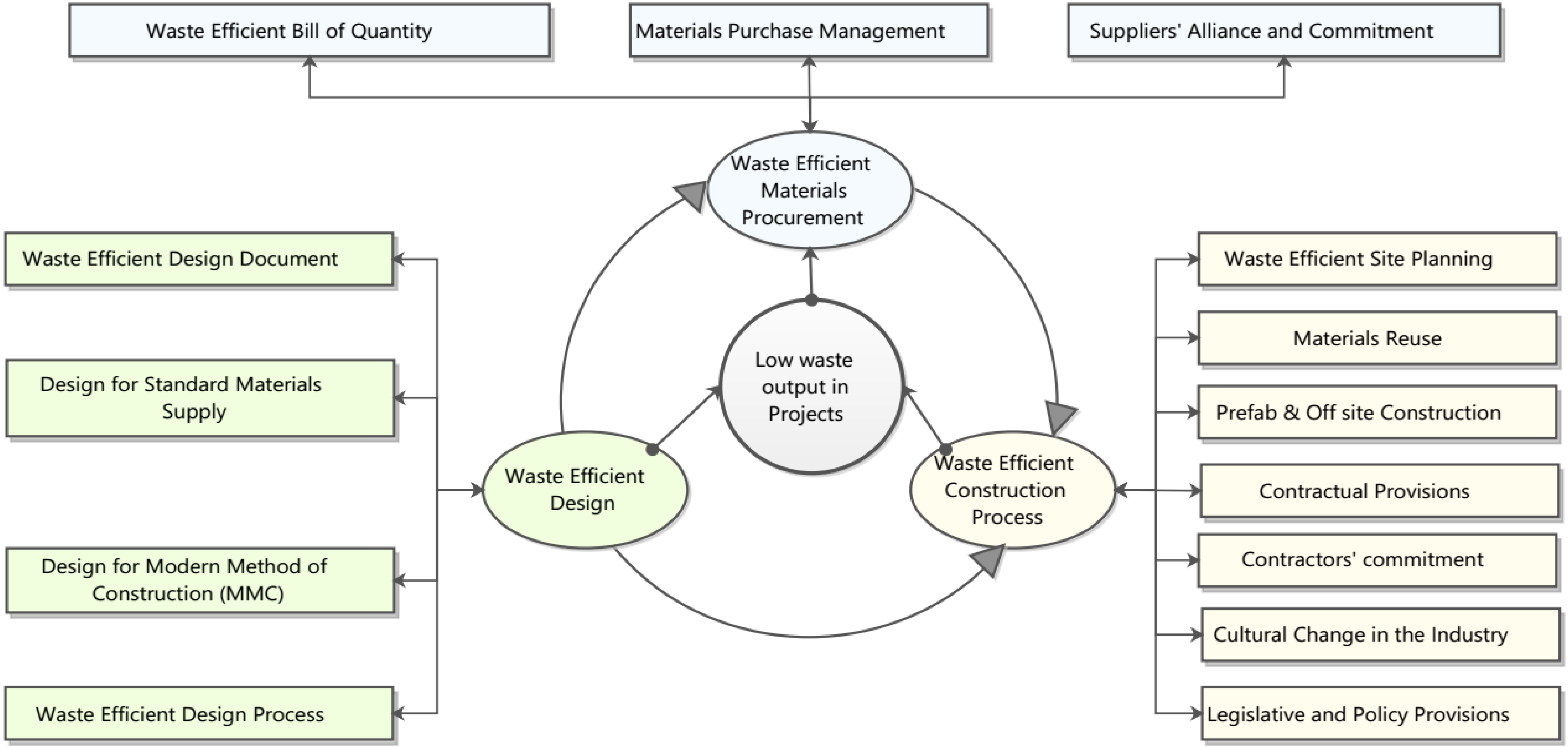


Figure 8.10: Framework of relationship between indices of low waste construction projects

8.7 Chapter Summary

In order to understand the key dimensions of measures for minimising waste in construction project, through design, procurement and construction stages of project delivery, Confirmatory Factor Analyses (CFA) were performed. The analyses involved two stages; the first stage confirmed the factor structure for each of design, design competencies, procurement and construction measures for engendering waste-efficient projects. The second stage confirmed the impacts of design, procurement and construction measures on overall waste efficiency of construction projects. Using AMOS Structural Equation Modelling (SEM) tool, model estimation was performed through Maximum Likelihood technique. Based on output of qualitative and statistical analyses, initial SEM was performed on 6, 4 and 12 latent factors for each of design, procurement and construction strategies respectively. The design model consisted of 31 indicators, which were confirmed to reliably measure the four different dimensions of design through reliability analysis. The procurement and construction model consisted of 22 and 70 indicators respectively. Competency for designing out waste was also modelled based on initial findings of statistical analysis. The competency model consisted of 22 factors, with four underlying variables/dimensions of competency for designing out waste.

In order to ensure that the model measures what it is supposed to measure, the model was evaluated for fitness, reliability and validity using a number established indices. These include value of fit statistics, Composite Reliability (CR), Average Variance Extracted (AVE) and Maximum Shared Squared Variance (MSV). The model went through series of modifications, re-specifications and adjustments, which required deletion of insignificant and poorly fit variables from the model. In each case, the final model showed a good reliability, validity and value of fit indices. Also, significant positive relationships were established between waste minimisation and the three main dimensions, which are design, procurement and construction measures. The model confirmed that four key strategies underlying Waste-efficient design are waste-efficient documentation, Waste-efficient design process, design for standard materials supply and design for modern method of construction, all of which consisted of 24 reliable and valid indicators. The other two previously established dimensions showed insignificant impacts on waste-efficient design. In order to design out waste in construction projects, four key competencies were confirmed to be required of design professionals. These include design task proficiency, inter-professional collaborative competencies, behavioural competencies and construction-related knowledge, all of which are based on 20 valid and reliable indicators.

The model confirmed that three key factors underlying waste-efficient materials procurement are materials purchase management, suppliers' alliance and waste-efficient Bill of Quantity, all of which are based on 15 measured variables. Excellently fitted and reliable model suggests that delivery planning and schedule have insignificant impacts on waste efficiency of materials procurement process. Similarly, results of the SEM suggest that eight key factors determine waste effectiveness of construction process. These include waste effective site planning, materials reuse, prefabrication and offsite technique, contractual provisions, contractors' commitment and competencies, cultural change as well as legislative provisions. 40 measured variables were established as the main indicators of underlying measures for waste effectiveness of building construction process. The mean and overall percentage of variance extracted by the model shows that the measures on the model are fit and significant enough to account for waste effectiveness of construction projects.

CHAPTER 9: SYSTEM DYNAMIC MODELLING

9.1 Chapter Overview

This chapter presents the system dynamic approach used for simulating dynamic impacts of various categories of measures on the overall waste efficiency of construction projects. The chapter starts with a review of the use of dynamic system approach in construction management research, which is followed by a brief explanation of the methodological approach of SDM as well as its relevance to this study. The approach used in model development, model simulation and validation were then justified and explained. Before a brief culminating section, various scenarios were modelled to determine the dynamic impacts of each waste management strategy on the overall waste efficiency of construction projects.

9.2 SDM in Construction Management Research

Dynamic models have helped in overcoming several complex problems, such as multiple interdependent components and non-linear relationships that are associated with construction activities (Sterman, 1992). The SDM was developed by Professor Jay Forrester, using a computer simulation technology as means of providing quantitative analysis on multifaceted real-world systems (Zhao et al., 2011; Yuan and Wang, 2014; Yuan et al., 2011; Li et al., 2014). It is capable of simultaneously correlating several factors, and it has a tendency of being simulated under controlled situations that allow experimentation (Love et al., 2000). In order to gain methodological insights from the studies, the overall aim of this section is to review construction management studies that have adopted SDM in their approach, and how it has been successfully channelled to enrich the studies.

A search for construction management studies with dynamic system approach shows that SDM has become increasingly important in construction research community in the recent years. Existing studies (e.g. Love et al., 2000; Ogunlana et al., 1998; Mohamed and Chinda, 2011; Dangerfield et al., 2003) show that the SDM has strong impacts in understanding, predicting and solving complex issues in design and construction management. Examples of construction management studies that used dynamic system approach are presented in Table 9.1. While each of the categories of the studies offers good insights into how dynamic system theory has been used, application of the approach in waste management research is further evaluated.

Table 9.1: Construction Management Studies that used SDM

	Area of Application in Construction Management	*Examples of Studies in the Category*
1.	Project management	Ogunlana et al., 1998; Xu et al., 2012; Rodrigues et al., 1998
2.	Waste management	Hao et al., 2008; Love et al., 2000; Ye et al., 2012; Sudhir et al., Kollikkathara et al., 2010
3.	Competitiveness of construction industry	Dangerfield et al., 2010; Ogunlana et al., 2003; Kim and Reinschmidt, 2006.
4.	Risk and Safety Management	Mohamed and Chinda, 2011; Shin et al., 2014; Han et al., 2010; Nasirzadeh et al., 2014
5.	Labour Productivity	Chapman, 1998; Nasirzadeh & Nojedehi, 2013; Liao et al., 2012

9.2.1 Application of SDM in Urban Solid Waste Management

Few studies have channelled the dynamism of SDM to investigate how various measures could be incorporated to ensure effective solid waste management approach. Sudhir et al. (1997) employed SDM to capture the dynamic interaction of various critical success factors (such as environment, cost, and health impacts) in solid waste management, with an intent of policy improvement. The model incorporated all processes involved in waste generation, collection and recycling system. Based on the dynamic simulation, the study recommended a solid waste management called "Structure Hard-Equivalent" and recovery of cost, by imposing a user fee, as a better policy that is capable of supporting more waste pickers, reducing management fees, and enhancing environment and health.

Kollikkathara et al. (2010) also adopted SDM in evaluating the dynamic interaction between various interrelated issues such as environmental impacts, landfill capacity and cost, which are all important for solid waste management. The study shows that waste preventive measures are central to long-term success of solid waste management. Similarly, Anghinolfi et al. (2013) investigated the dynamic interaction of solid waste collection and recycling management using SDM. Apart from developing an optimised model for solid waste management, the study shows that substantial cost of waste management could be reduced through the use of SDM.

9.2.2 Application of SDM in C&D Waste Management

Dynamism of construction waste generation and its management approaches have been investigated through SDM. For instance, Tam et al. (2014) and Ye et al. (2012) developed SDM to investigate effects of different policies on waste management strategies, such as landfilling, prevention, reuse and recycling. Having simulated the effects of different legislative and strategic measures on waste management, optimal strategic and policy measures for effective waste management were recommended. Li et al. (2014) also adopt SDM in measuring impacts of prefabrication on waste reduction. Yuan and Wang (2014) proposed a dynamic model that is suitable for determining cost of waste disposal in China, by integrating various waste predictive factors, while Yuan et al. (2011) used SDM to carry out cost-benefit analysis of different waste management approaches.

Hao et al. (2008) developed a simulation model that established interconnection between various onsite activities, towards determining ultimate waste management strategy. The model provides avenue for fine-tuning input parameters in order to predict suitable management strategy for onsite waste. While arguing for a need to study waste at dynamic level, Yuan et al. (2012) developed a dynamic model for determining impacts of waste management strategies on waste generation. Although their study left out non-construction stages of building process, it provides decision support model for projecting likely waste based on adopted waste management strategies. Love et al. (2000) also applied SDM to design management. Reworks caused by design errors was modelled and simulated to unravel complex problems and interrelated factors that lead to design errors, cost overrun and time overrun. Factors influencing design errors were identified, and model was developed to give a proper understanding of how project documentation could be effectively carried out.

Based on the review of the use of SDM in waste management studies, it is clear that SDM approach is suitable for unravelling dynamism of factors contributing to waste occurrence, as well as strategies for its management. However, existing studies show that despite the relevance of the dynamic system approach, no study has properly channelled the tool in a comprehensive manner to incorporate design, procurement and construction stages. Also, its capacity to identify interconnections between the stages and overall waste efficiency of projects is yet to be studied. Hence, in order to proffer a holistic construction waste management approach, there is need for understanding dynamic relationship between all waste management strategies at design, procurement and construction stage. This would help in proposing effective design, procurement and construction strategies and guidelines for waste minimisation.

9.3 Use of Dynamic Approach in this Study

Dynamic analysis of complex system usually involves four stages, which are representation of the phenomenon, generation of solution, exploration of structural relations, and modification and control (Luenberger, 1976). The sole purpose of using mathematical equation/approach is to represent the relationship between various components of the system, usually through mathematical modelling. The generation of solution is arguably the most direct reason for using dynamic system. This involves generation of system specific solution, which could be further studied for several purposes, such as to determine reasonableness of a hypothesis or for various prediction and planning purposes (Luenberger, 1976). It is usually achieved through the use of computer simulation known as System Dynamic Modelling or various mathematical equations. It is, however, notable that most models represent calculation of solutions that are determined by the nature of its study condition, parameter value and inputs (Maria and Thaler, 2005).

Apart from pattern prediction or generating solution to an identified problem, richness of dynamic system outspread to establishment and explanation of structural relations as to how different parameters could influence one another and how they can influence the whole system or the solutions it offers. This gives an opportunity to accept or reject a system not only based on its structure, but also regarding its system behaviour patterns (Luenberger, 1976). In the same vein, complex analysis involves modification and control of the whole system to comprehensively understand and improve its behaviour patterns. Through several simulation and control strategies, a dynamic system could help in proposing a modification to existing system so as to find solution to complex problems or to improve the system in generality (Luenberger, 1976; Ursem et al., 2002). Determination of appropriate control and modification strategy is the last stage of dynamic system analysis which marks the conclusion of a complete system analysis. It is held that if the system behaviour is fully understood though dynamic system process, behaviour of solution to a whole system or any of its input could be perfectly predicted (Maria and Thaler, 2005; Ursem et al., 2002; Luenberger, 1976)

Dynamic system modelling has successfully transformed several scientific paradigms (Spencer-Wood, 2013; Lerner, 2006; Lowie, 2012) so much that application of its concepts to construction waste has been widely advocated (Yuan et al., 2012; Hao et al., 2008; Love et al., 2000; Ye et al., 2012). Detail recognition and critical understanding of the way waste is generated remains a seemingly insurmountable task partly because many solutions often focus only on regular, recurring and static pattern (Yuan et al., 2012), thereby disregarding irregular and dynamic patterns, which are capable of proffering holistic waste management solutions. Sterman (1992) argues that multidimensional activities, such as construction operations, usually involve complex processes that stress beyond shallow and fallible capacity of both mental and static models. It requires the use of dynamic based models to compile the logical sequence, and incorporate various interrelated activities usually involved in construction operations.

Design, procurement and construction activities are in such a way that causes and effects are interrelated, lacking close and direct relationship as could be seen in other systems (Sterman, 1992). A flaw in one aspect of design could, unfortunately, results in errors in procurement and construction process, which would ultimately result in waste. As it would be difficult to trace the real cause and effect on static and direct basis, in this case, application of dynamic model is required to trace causal loops and feedback system of such interdependent system (Love et al., 2000). It is deemed that by modelling every possible waste mitigating strategy on construction projects using System Dynamic Modelling, efficient waste management solutions could be achieved. This is due to its ability to propose solutions to identified problems, predicts likely problems with certain parameters and identify dynamic cause and effects, which are required in construction management in general (Sterman, 1992), and waste management in particular (Kollikkathara et al., 2010).

Based on its relevance, a basic System Dynamic Model (SDM) identifying dynamic relationship between each of the critical factors and KPIs was modelled through VENSIM modelling software. The SDM was used in identifying dynamic relationship in this study most especially as it incorporates feedback, capture non-linear relationship and possess a functional capacity to distinguish between causality and correlation (Luna-Reyes and Andersen, 2003). As a result, the SDM furnished the study with causal-impact loop that relates all stages of construction process as a single entity, thereby identifying impact of taking one action over the entire processes and overall waste efficiency of projects.

9.4 Model Development

As confirmed in Chapter 8, design, procurement and construction processes contribute to overall waste efficiency of construction projects. Each of the three components consists of various other underlying dimensions that determine their overall effectiveness. In line with the relationships established through SEM, relationships between the measures were modelled through the use of VENSIM SDM tool.

9.4.1 Causal Loop Diagram

Causal loop diagram is a visual representation of cause and effect relationships between variables in a model. It aids in articulating and visualising the interconnectedness of various elements that make up a system (Kim, 1992). A causal loop diagram consists of various nodes and edges. While nodes refer to the variables, edge represents the relationship between the variables. A positively marked causal link connotes that increasing in the first element "A" leads to an increase in the other element "B". A negatively marked link depicts that an increase in the first element "B" will result in a decrease in the second element "C", and vice versa. Examples of positive and negative links are shown in Figure 9.1.

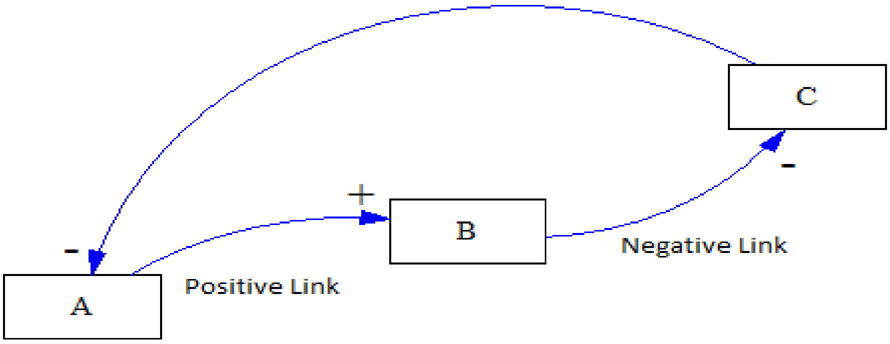


Figure 9.1: Polarity in Causal loop diagram

Based on the established relationship between various strategies for mitigating waste at design, procurement and construction stages of project delivery processes, a causal loop diagram was drawn. The diagram represents the relationship between all variables in the model. It is as represented in Figure 9.2. Cause tree diagrams that show causal relationship between the variables are presented in Appendices 3 to 6.

9.4.2 Stock and Flow Diagram

Stock and Flow diagram is another approach for representing causal relationships between elements in system dynamics models (Coyle, 1996). It is an algebraic representation of the model, which could be run on a computer. The main difference between causal loop and stock and flow diagram is that the latter is written in equation and computer coding, while the former is written in words and arrows. The causal loop diagrams facilitate understanding of problems under evaluation as well as tracing of the causal and use trees, while the stock and flow diagrams enhance mathematical simulation and quantitative analysis of the relationships between elements in the model (Wang et al., 2015).

In order to simulate the dynamic relationship between various strategies for minimising construction waste, the causal loop diagram was converted into a stock and flow diagram using VENSIM software tool. The stock and flow diagram is presented in Figure 9.3. Description of all variables included in the model is detailed in Table 9.2. The diagram allows imputation of mathematical equations and weighing to compute latent variables in the model. It provides an avenue for simulating impact of one variable on different sections of the model as well as on the overall model. Through this, impacts of adopting different strategies on overall waste effectiveness of construction projects were simulated.

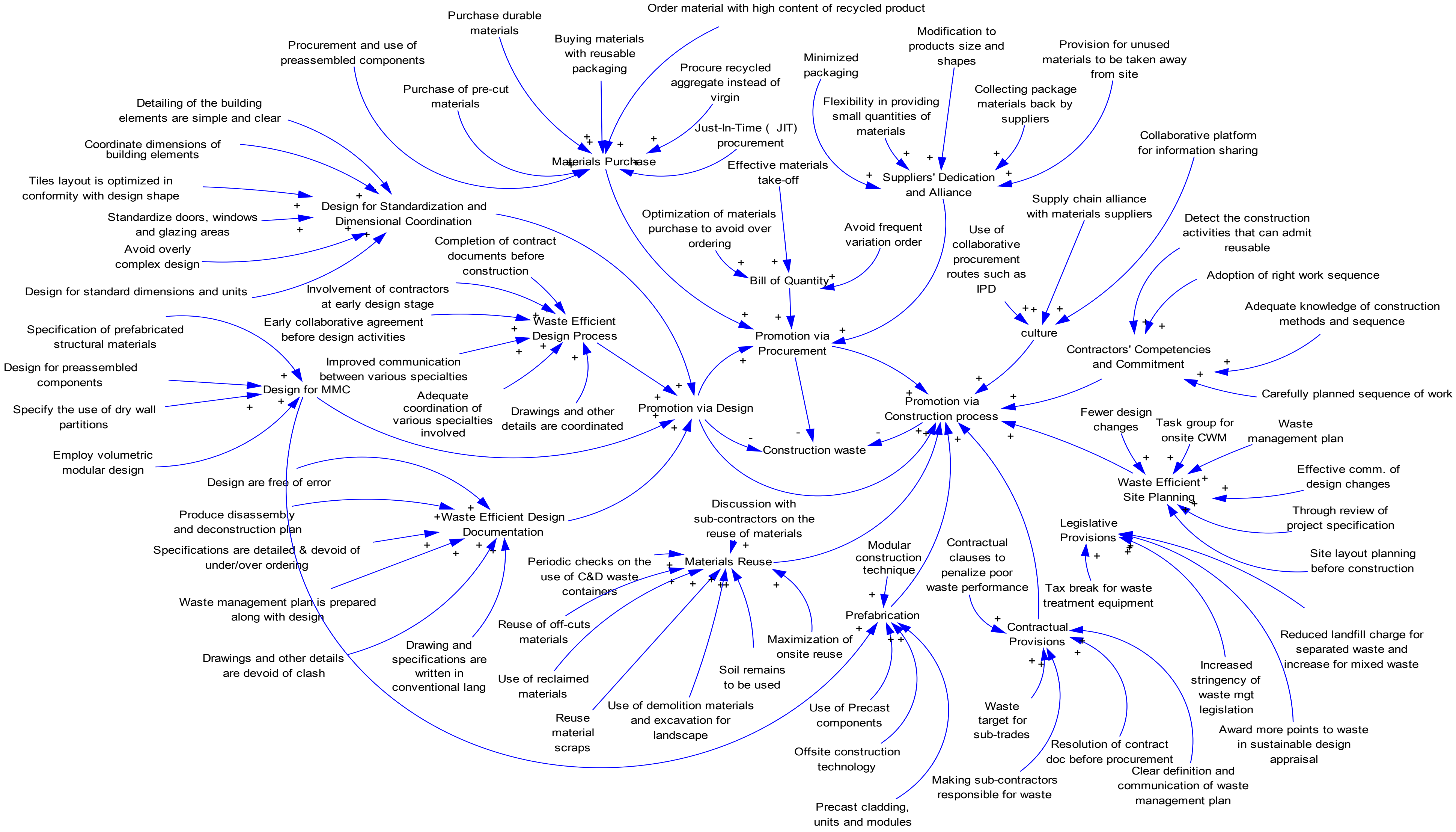


Figure 9.2: The Causal Loop Diagram of Waste Minimisation Strategies

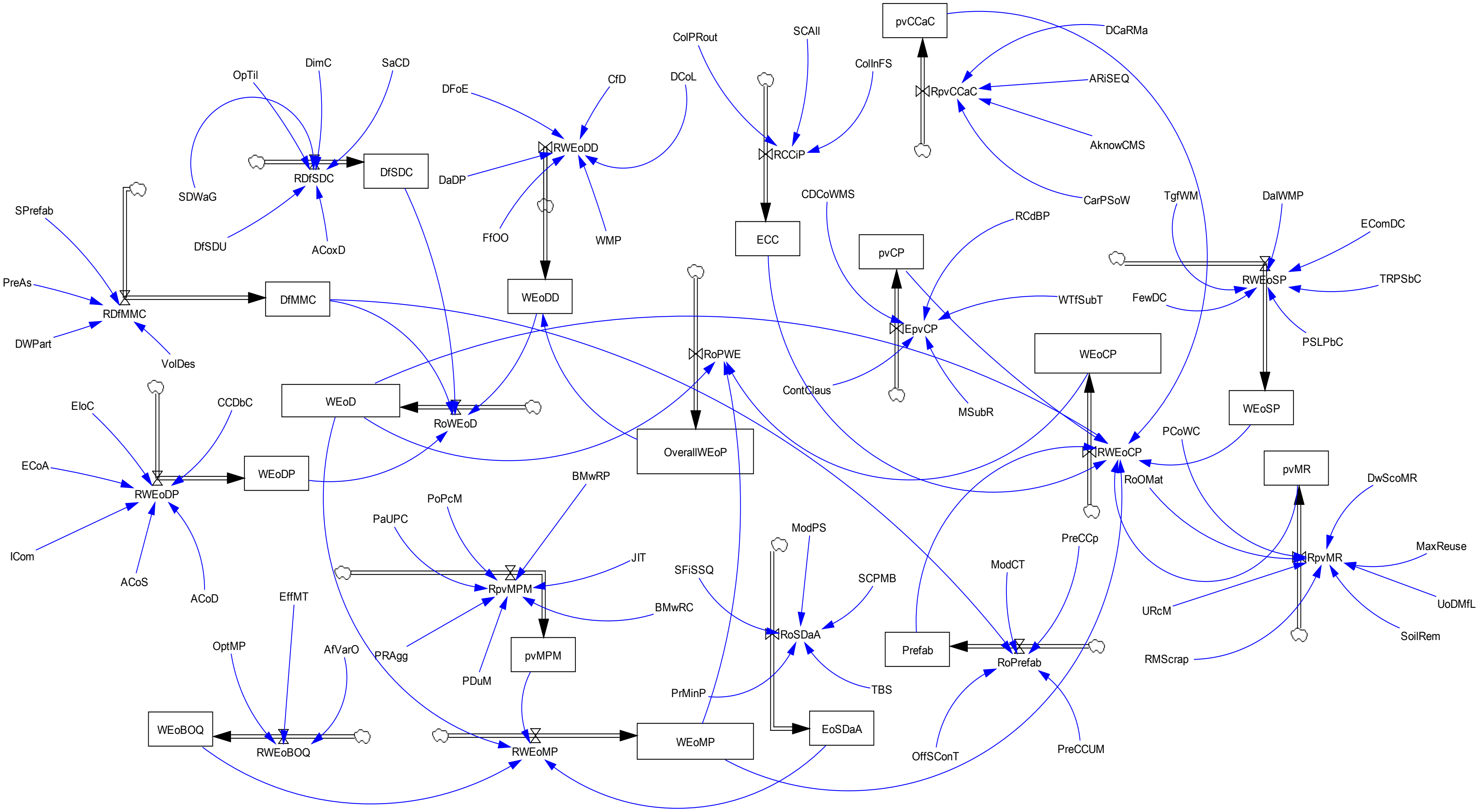


Figure 9.3: Stock and Flow Diagram of Waste Minimisation Strategies

Table 9.2: Description of the Model Variables

No	Abbreviations	Variable Name
1	ACoD	Drawings and other details are coordinated between design disciplines
2	ACoS	Adequate coordination of various specialities involved
3	ACoxD	Avoid overly complex design
4	AfVarO	Avoid frequent variation order
5	AknowCMS	Adequate knowledge of construction methods and sequence
6	ARiSEQ	Adoption of right work sequence
7	BMwRC	Order material with high content of recycled product
8	BMwRP	Buying materials with reusable packaging
9	CarPSoW	Carefully planned sequence of work to prevent damages to completed work
10	CCDbC	Completion of contract documents before construction process
11	CDCoWMS	Clear definition and communication of waste management strategies
12	CfD	Drawings and other details are devoid of clash
13	CioCON	Combined impacts of construction
14	CioDes	Combined Impacts of design
15	CioPRO	Combined impacts of procurement
16	CoL	Drawing and specifications are written in conventional lang. understood by all
17	ColInFS	Use of common collaborative platform for information sharing
18	ColPRout	Use of collaborative procurement routes such as IPD
19	ContClaus	Contractual clauses to penalise poor waste performance
20	DaDP	Produce disassembly and deconstruction plan
21	DaIWMP	Development and implementation of waste management plan
22	DCaRMat	Detect the construction activities that can admit reusable materials
23	DfMMC	Design for Modern Methods of Construction
24	DFoE	Design are free of error
25	DfSDC	Design for Standardization and dimensional coordination
26	DfSDU	Design for standard dimensions and units
27	DimC	Coordinate dimensions of building elements
28	DWPart	Specify the use of drywall partitions (e.g. timber walling)
29	DwScoMR	Discussion with sub-contractors on the reuse of materials
30	ECC	Cultural factors
31	ECoA	Early collaborative agreement before design activities
32	EComDC	Effective communication of design change
33	EffMT	Effective materials take-off
34	EIoC	Involvement of contractors at early design stage
35	EoSDaA	Suppliers' alliance and commitments
36	FewDC	Ensure fewer design changes during construction
37	FfOO	Specifications are detailed & devoid of under/over ordering
38	ICom	Improved communication between various specialities
39	JIT	Use of Just-In-Time (JIT) procurement system
40	MaxReuse	Maximisation of onsite reuse of materials
41	ModCT	Adoption of modular construction technique
42	ModPS	Modification to products size and shapes in conformity with design
43	MSubR	Making sub-contractors responsible for waste disposal
44	OffSConT	Employment of offsite construction technology
45	OpTil	Tiles layout is optimised in conformity with design shape
46	OptMP	Optimisation of materials purchases to avoid over/under ordering

No	Abbreviations	Variable Name
47	OverallWEoP	Overall waste efficiency of project
48	PaUPC	Procurement and use of preassembled components
49	PCoWC	Periodic checks on the use of C&D waste containers
50	PDuM	Purchase durable materials
51	PoPcM	Purchase of pre-cut materials
52	PRAgg	Procure recycled aggregate instead of virgin aggregates
53	PreAss	Design for preassembled components e.g. bathroom pods
54	PreCCp	Use of Precast components such as bathroom and kitchen pods
55	PreCCUM	Use of precast cladding, units and modules
56	Prefab	Prefabrication and offsite technology
57	PrMinP	Procurement route that minimises packaging
58	PSLPbC	Preparation of site layout planning before construction
59	pvCCaC	Contractors' dedication and competencies
60	pvCP	Contractual provisions
61	pvMPM	Low waste materials purchase management
62	pvMR	Materials reuse
63	RCdBP	Complete and resolve contract document before procurement
64	RMScrap	Reuse material scraps from cutting stock-length material into shorter pieces
65	RoOMat	Reuse of off-cuts materials (such as wood)
66	SaCD	Detailing of the building elements is simple and clear
67	SCAll	Supply chain alliance with materials suppliers
68	SCPMB	Collecting package materials back by suppliers
69	SDWaGa	Standardise doors, windows and glazing areas
70	SFiSSQ	Supplier flexibility in providing small quantities of materials
71	SoilRem	Soil remains to be used on the same site
72	SPrefab	Specification of prefabricated structural materials
73	TBS	Provision for unused materials to be taken away from site (take back scheme)
74	TgfWM	Establishing task group for onsite CWM
75	TRPSbC	Thorough review of project specifications by contractors
76	UoDMfL	Use of demolition materials and excavation for landscape
77	URcM	Use of reclaimed materials
78	VolDes	Employ volumetric modular design principles
79	WEoBOQ	Waste-efficient bill of quantity
80	WEoC	Waste efficiency of construction
81	WEoD	Waste efficiency of design
82	WEoDD	Waste-efficient design documentation
83	WEoDD	Waste-efficient design documentation
84	WEoDP	Waste-efficient design Process
85	WEoP	Waste efficiency of procurement
86	WEoSP)	Site Planning
87	WMP	Waste management plan is prepared along with design
88	WTfSubT	Waste target set for sub-trades

9.5 Data Collection and Analysis for Model Simulation

After developing the stock and flow diagram, a case study of construction project is required to generate values for the measured variables. In order to achieve this, a case study of residential project was selected based on access to project information and key stakeholders involved in the project. Detail information about the case study is available in Table 9.3.

Table 9.3: Specific characteristics of case study project

Features	**Project Description**
Project Type	New built residential units
Usage	Flats/Apartments
Cost	£11m
Start Date	June 2013
End Date	May 2015
Project Duration	24 months
Building Types	Load bearing masonry
Gross Floor Area	5578.36m^2
Waste Output	8912.54 tonnes

Data was collected through formal meetings with five key members of project team, including the project manager, site manager, project architect, site waste manager and a representative of sub-contractors. All the five participants were involved from inception to completion of the design and build project, and they are all experienced in construction waste minimisation. A questionnaire was designed to determine the extent of adoption of the established waste management strategies in the case study project. Only measures that were previously confirmed through SEM were included on the questionnaire. The project team were asked to rank the adoption of each of the strategies on a range of 0 to 100%, with 0 indicating narrowly adopted and 100 representing widely adopted. A copy of the questionnaire used for the project data collection is available in Appendix 2.

9.5.1 Mathematical Modelling for Model Simulation

In order to compute relative adoption value for each of the strategies, mathematical models were developed for various latent variables included in the model. This involved a number of steps, some of which are as explained below.

1. Computation of significance index for each measured variable

Based on the factor weight established for each element in the SEM, relative weights were computed for the elements using:

$$R(a_i) = \frac{w(a_i)}{w_{a_1}+w_{a_2}+w_{a_3}+\cdots+w_{a_n}} \tag{1}$$

Accordingly, Equation (1) could be generalised as:

$$R(a_i) = \frac{w(a_i)}{\sum_{j=1}^{n} w_{a_j}} \tag{2}$$

$R(a_i)$ is the significance index of element "a_i" that measures the extent to which "a_i" contributes to its latent variable, $w(a_i)$ is the factor weight of element "a" taken from the structural equation models. $\sum_{j=1}^{n} w_{a_j}$ is the sum of factor loadings for all elements a_1, a_2, a_3….a_n in the same category as a_j, contributing to a latent factor.

Taking for instance, a latent factor "Waste Efficiency of Design Document" represented as *WEoDD* where a_1= *DFoE*, a_2 = *DaDP*, a_3 = *FfOO*, a_4 = *WMP*, a_5 = *CFD*, a_6 = *CoL*, $W_{a1} = 0.89$, $w_{a2} = 0.79$, $w_{a3} = 0.83$, $w_{a4} = 0.61$, $w_{a5} = 0.60$ and $w_{a6} = 0.58$ *(see figure 8.2).* Then, from Equation (2), the relative weight of *DFoE*, i.e. *R(DFoE) = 0.89/4.3 = 0.21.*

2. Computation of adoption level for the underlying strategies – first-order variables in the SEM

Adoption levels were computed for first-order latent variables (such as WEoDD, WEoD, PpvMR, etc.) using:

$$AL(S) = K(a_1) \times R(a_1) + K(a_2) \times R(a_2) + K(a_3) \times R(a_3) + \cdots + K(a_n) \times R(a_n) \tag{3}$$

$$AL(S) = \sum_{i=1}^{n} K(a_i) \times R(a_i) \tag{4}$$

Where *AL(S)* is the adoption level of a strategy *S.* $K(a_i)$ is the level of adoption of sub-element a_1 contributing to strategy *S.* $R(a_i)$ is the significance index of sub-element a_1 as calculated through Equation (2).

3. Computation of the relative weight for the underlying strategies

In order to understand the baseline efficiency for each of design, procurement and construction processes, it is important that their significance index is established. Significance index is calculated using:

$$R(S_i) = \frac{w(S_i)}{\sum_{j=1}^{n} w(S_j)} \quad (4)$$

Where $R(S_i)$ is the significance index of strategy S_i contributing to design, procurement or construction, $w(S_i)$ is the absolute weight of the strategy as extracted from the SEM, $\sum_{j=1}^{n} w(S_j)$ is the sum of absolute weights for all strategies at equal level as S_i contributing to design, procurement or construction.

4. Equation for combined impacts of design, procurement and construction

Impacts of each stage of project delivery were modelled through relative impacts of their contributing factors as well as their adoption levels. They were modelled using:

$$CioDES = AL(WEoDD) \times R(WEoDD) + AL(WEoDP) \times R(WEoDP) + AL(DfSDC) \times R(DfSDC) + AL(DfMMC) \times R(DfMMC) \quad (5)$$

$$CioPRO = AL(EoSDaA) \times R(EoSDaA) + AL(pvMPM) \times R(pvMPM) + AL(WEoBOQ) \times R(WEoBOQ) \quad (6)$$

$$CioCON = AL(WEoSP) \times R(WEoSP) + AL(pvMR) \times R(pvMR) + AL(prefab) \times R(prefab) + AL(pvCP) \times R(pvCP) + AL(pvCCaC) \times R(pvCCaC) + AL(ECC) \times R(ECC) \quad (7)$$

Where:

$CioDES$ is the combined impact of design strategies

CioPRO is the combined impacts of procurement strategies

CioCON is the combined impacts of construction strategies

AL(WEoDD) (for instance) is the adoption level for *WEoDD* calculated using Equation (3). *R(S)* is the significance index for each of the strategies *S*

Using similar approach, mathematical equations were computed for other variables in the model. As a result of the calculation, adoption values computed for each of the strategies are as presented in Table 9.4.

Table 9.4: Inputted data on adoption rate for key dimensions of waste-efficient projects

Strategies confirmed by SEM		**Values (Adoption level)%**
Abbreviations	**Strategies**	
WEoDD	Waste-efficient design documentation	53
DfMMC	Design for Modern Methods of Construction	45
WEoDP	Waste-efficient design Process	57
DFSDC	Design for Standardization and dimensional coordination	7
EoSDaA	Suppliers' alliance and commitments	10
pvMPM	Low waste materials purchase management	30
WEoBOQ	Waste-efficient bill of quantity	18
WEoSP	Site Planning	40
pvMR	Materials reuse	57
Prefab	Prefabrication and offsite technology	5
pvCP	Contractual provisions	35
pvCCaC	Contractors' dedication and competencies	70
ECC	Collaborative culture	4

Based on the mathematical approach and ability to compute values for the latent variables, the whole model could be simplified as presented in Figure 9.4

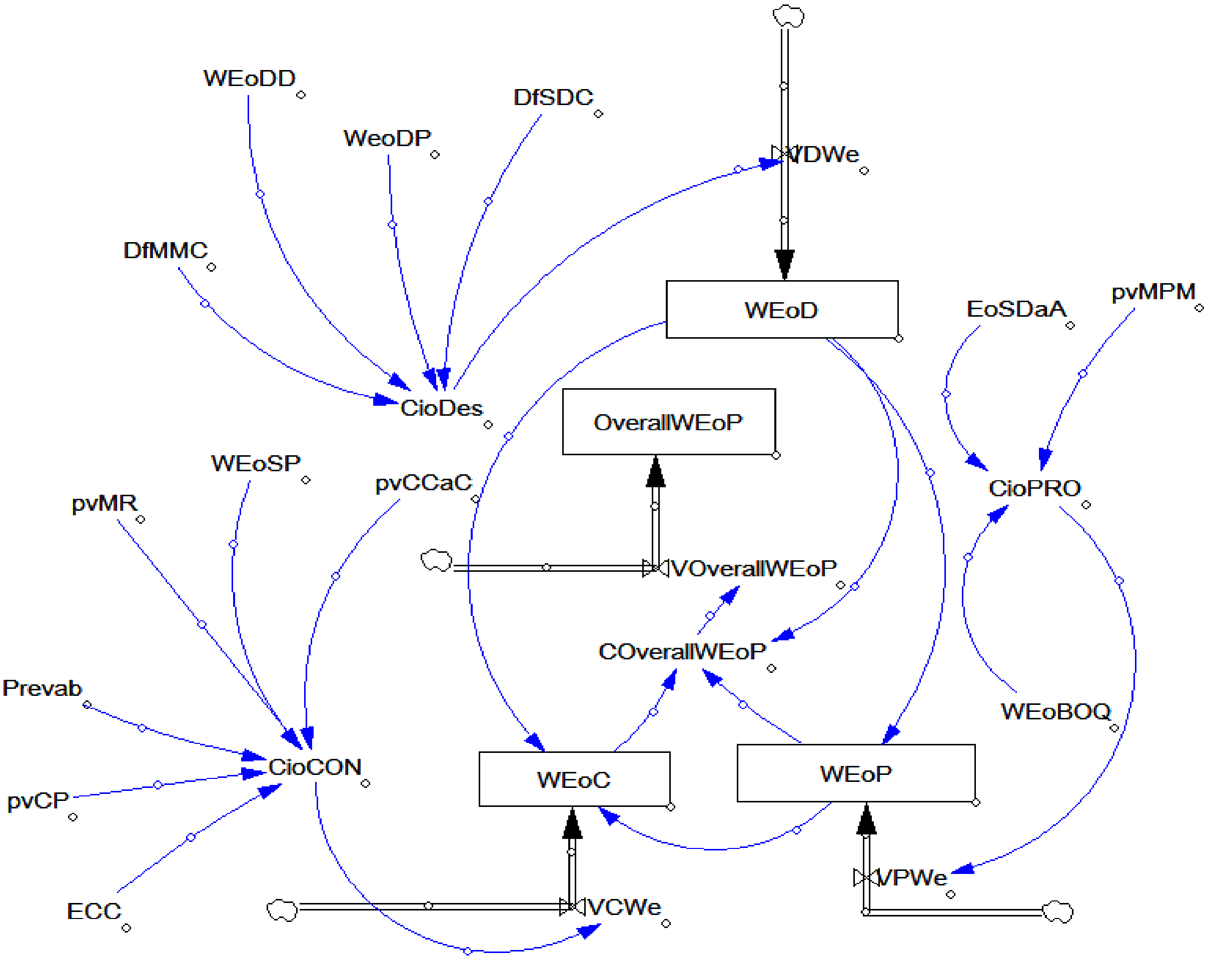


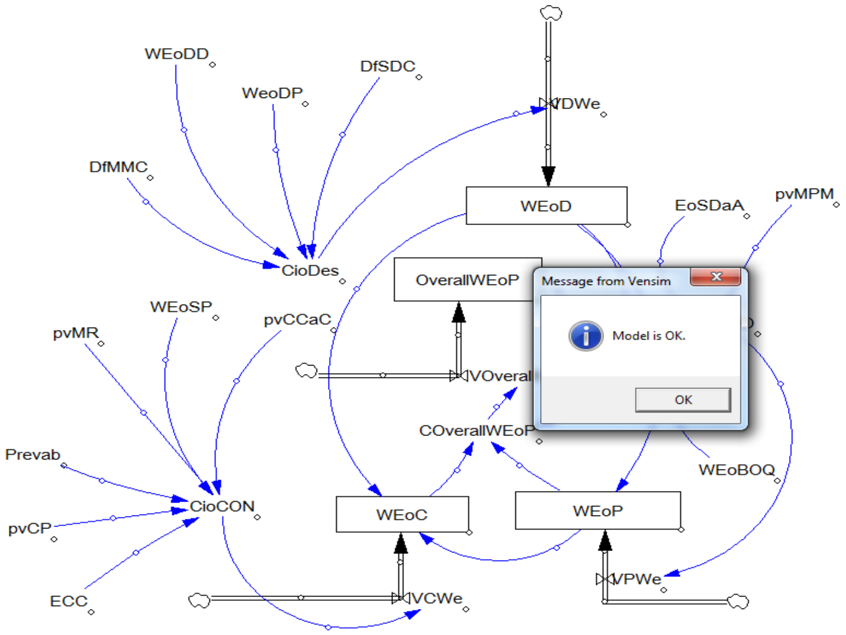
Figure 9.4: Simplified model of the overall system

9.6 Model Testing and Validation

Model validation is an essential part of modelling processes in system dynamic modelling (Sterman, 2000). It is used to ensure accuracy of the model in reflecting actual environment in a reasonable pattern (Richardson and Pugh, 1981). Various techniques are being used to confirm the behaviour and validity of model to establish confidence in the model. These include structure verification test, parameter verification test, dimensional consistency test and extreme condition test (Ding et al., 2016; Qudrat-Ullah and Seong, 2010). Model validation techniques used in this study are as discussed in the subsequent sections.

9.6.1 Structure Verification Test

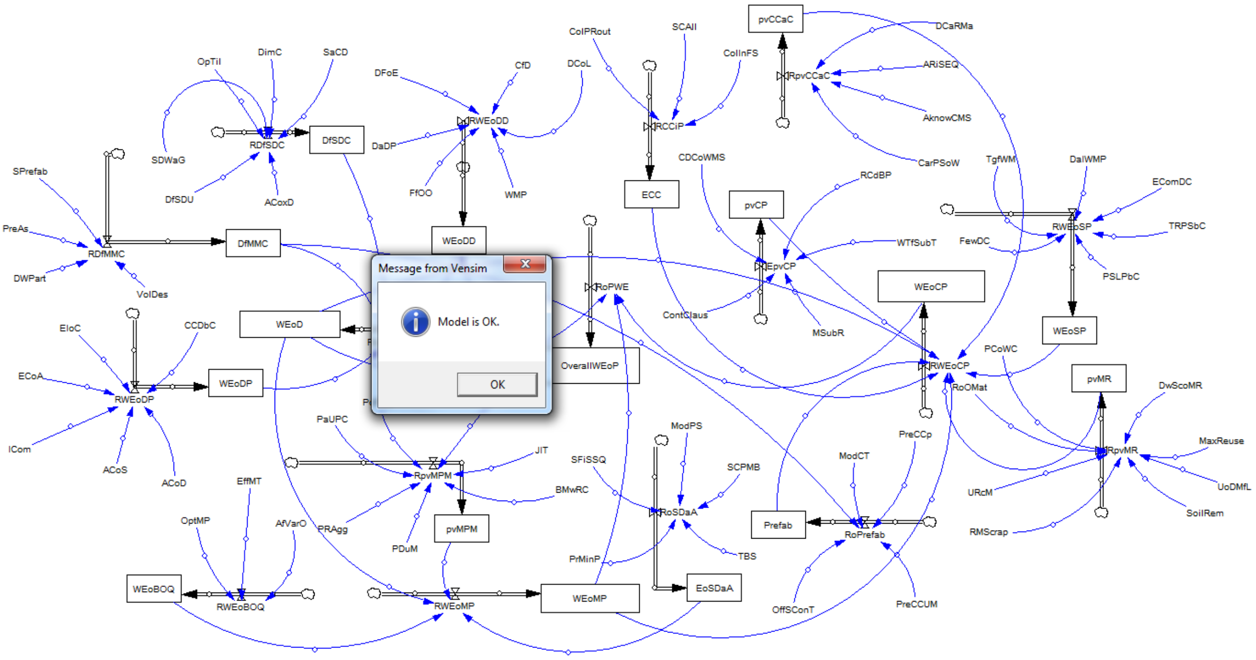
The essence of structure verification test is to ensure that the model represents the real-life relationship and interplay of various elements included in the model, as well as the actual description of the system being modelled (Ding et al., 2016). In order to ensure this, causal loop diagram and its subsequent stock and flow diagrams were based on the confirmed relationship between the variables as previously established through SEM. Variables with insignificant loadings to their latent factors were excluded from the SDM. In addition to this test, model check function of VENSIM confirmed that all the elements with causal influence on one another had been adequately considered. Figure 9.5 and 9.6 confirm the structural validity of the models.



Message from Vensim

Model is OK.

Figure 9.5: Structural validation of the simplified model



Model is OK.

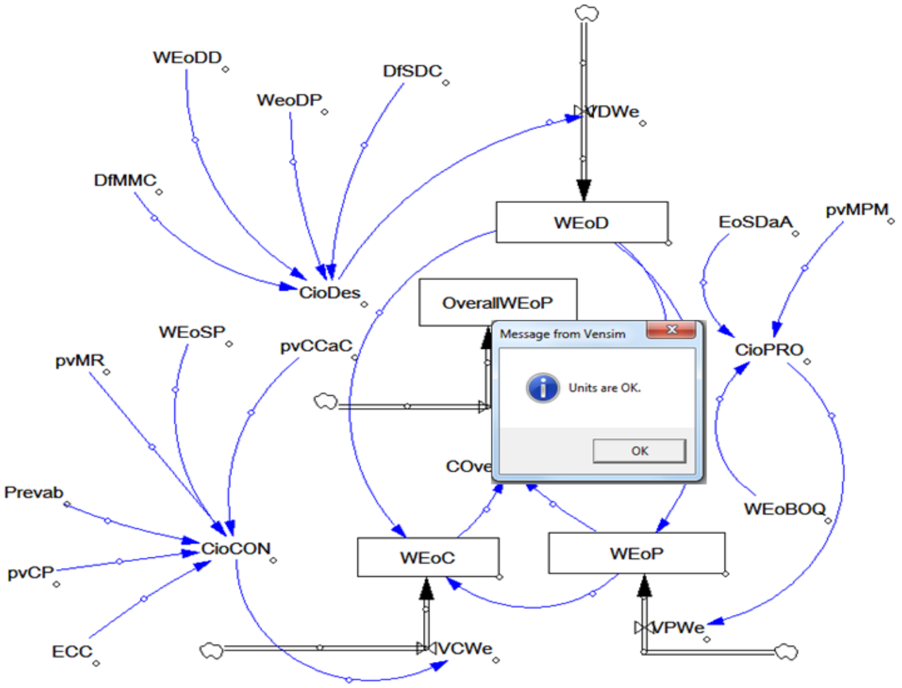
Figure 9.6: Structural validation of the main model

9.6.2 Parameter verification test

Parameter verification test is used to confirm whether the parameter value is numerically and descriptively consistent with the system knowledge (Sterman, 2000). In this model, the parameters used were based on rigorously confirmed factors that are grounded in literature and real-life practices.

9.6.3 Dimensional Consistency Test

In SDM, dimensional consistency test is performed to confirm that the unit of measure of variables on both sides of any equation is equal (Pejić-Bach and Čerić, 2007). The test ensures that the model is dimensionally consistent with its use of parameters (Sterman, 2000). The modelling tool, VENSIM has an inbuilt capacity to verify the dimensional consistency of the model. As shown in Figures 9.6 and 9.7, the two models were verified for dimensional consistency and the results indicate that the model is dimensionally consistent.



Units are OK.

Figure 9.7: Confirmation of Dimensional consistency for the simplified model

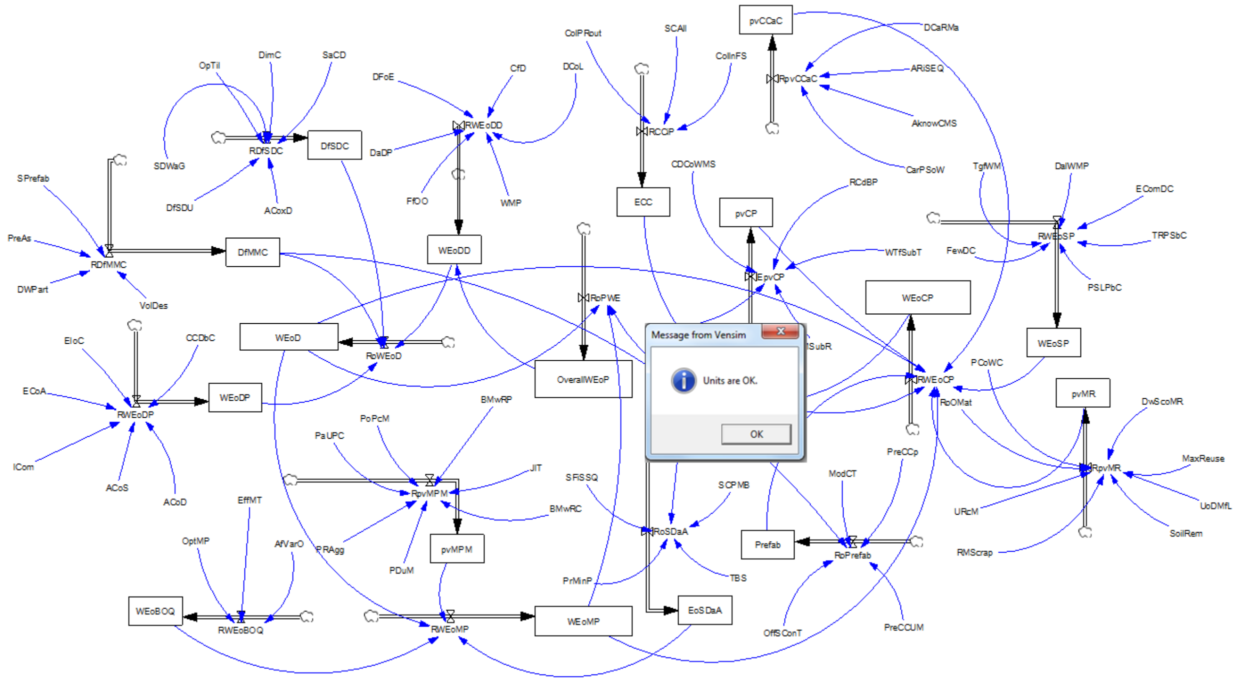


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Figure 9.8: Confirmation of dimensional consistency for the main model

9.6.4 Extreme Condition Test

Extreme condition test is used to evaluate model behaviour to extreme cases. It is used to simulate the behaviour of the system when its input is at extremely high or extremely low level (Sterman, 2000). According to Pejić-Bach and Čerić (2007), if the demand for a company's product is at zero during a simulation, it would be expected that sale and income from the product are at zero level. In this study, model behaviour at extreme cases was simulated with 0% implementation of all the strategies and at 100% implementation of all the strategy. As presented in Figures 9.9 and 9.10, the results indicated validity of the model. At 0% adoption of all the strategy, the overall waste efficiency of the project is about 0.4% and at 100% adoption of all the strategies, the overall waste efficiency of the project is 99.9%.

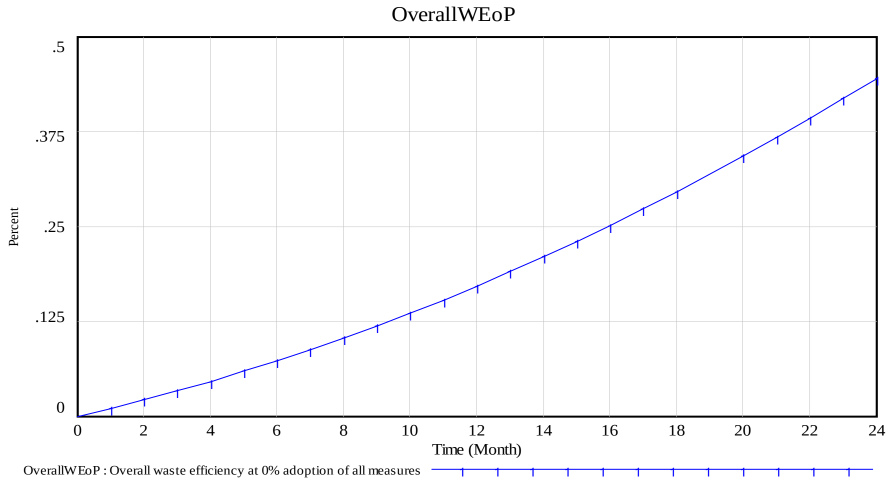

Figure 9.9: Model behaviour at 0% adoption of all the strategies

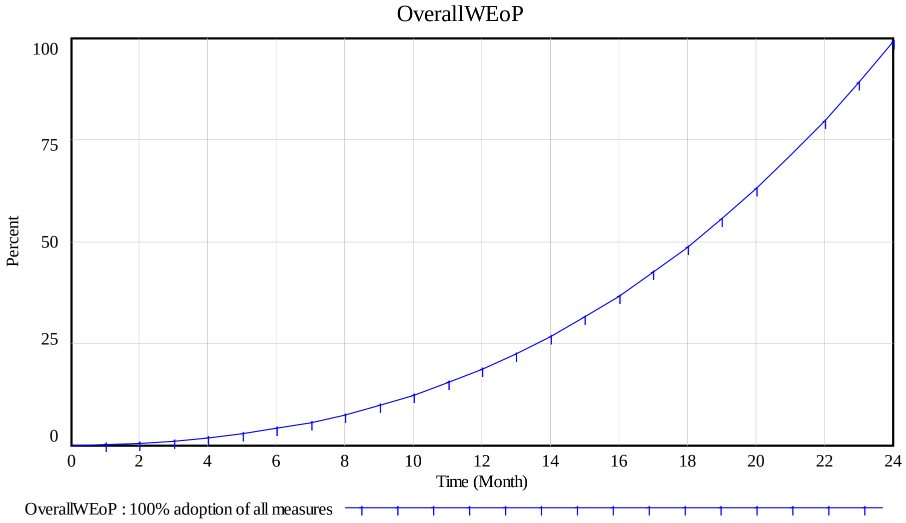

Figure 9.10: Model behaviour at 100% adoption of all the strategies

9.7 Scenario Testing

In order to understand optimal approach for mitigating waste generated by construction activities, various scenarios were modelled in two categories. The first scenario evaluated influence of design, procurement and construction processes on overall waste efficiency of projects. The second scenario evaluated impacts of various strategies on overall waste efficiency of construction projects.

9.7.1 Dynamic Impact of the three Stages

Scenario models were performed, using Simulate and Synthesim functionality of VENSIM, to investigate overall impacts of each of design, procurement and construction processes. For each of the stages, implementation levels were increased to 100% to evaluate their impacts on overall waste efficiency of construction projects, while leaving all other strategies at the baseline implementation as presented in Table 9.4. The "baseline implementation of all strategies" yielded approximately 40% efficiency as shown in Figure 10.11. Results of the scenario modelling are presented in Figure 9.11. The results suggest that design has the highest impacts on overall waste generated in construction projects. The graph indicates that at 100% implementation of design for modern methods of construction, collaborative design process, effective design documentation and design for standardisation and dimensional coordination, the project would achieve about 75% of waste efficiency. This is not only as a result of design from a unitary perspective; it is partly due to its ability to drive other activities at the procurement and construction stages.

Construction stage has the second highest impacts on overall waste efficiency of construction projects. This impact is driven by 100% adoption of other construction strategies on the model with 50% adoption of prefabricated elements. The result suggests that at 100% of promotion via materials reuse, adequate site planning, collaborative environment, contractual provisions and contractors' dedication, the project would achieve about 72.5% of waste efficiency, provided prefabrication is adopted for 50% of the project. However, at 100% adoption of prefabrication, which is the most significant construction driver of waste-efficient project, the project achieved about 82.5% of waste efficiency. This is an increase of 42.5% waste efficiency over the baseline waste performance of about 40%. This suggests that the construction stage is the most significant driver of construction waste minimisation for a fully prefabricated building. Otherwise, the design stage is the major driver of construction waste minimisation.

The dynamic simulation suggests that increasing use of procurement measures is capable of reducing waste generated by construction activities. As shown in the graph (Figure 9.11), the result indicated that waste-efficient procurement could drive overall waste-efficient of construction project to about 50%. With the baseline adoption of all measures being about 40%, this suggests that procurement process could improve project waste efficiency by around 10%, while design and construction could improve it by 35% and 32.5% respectively.

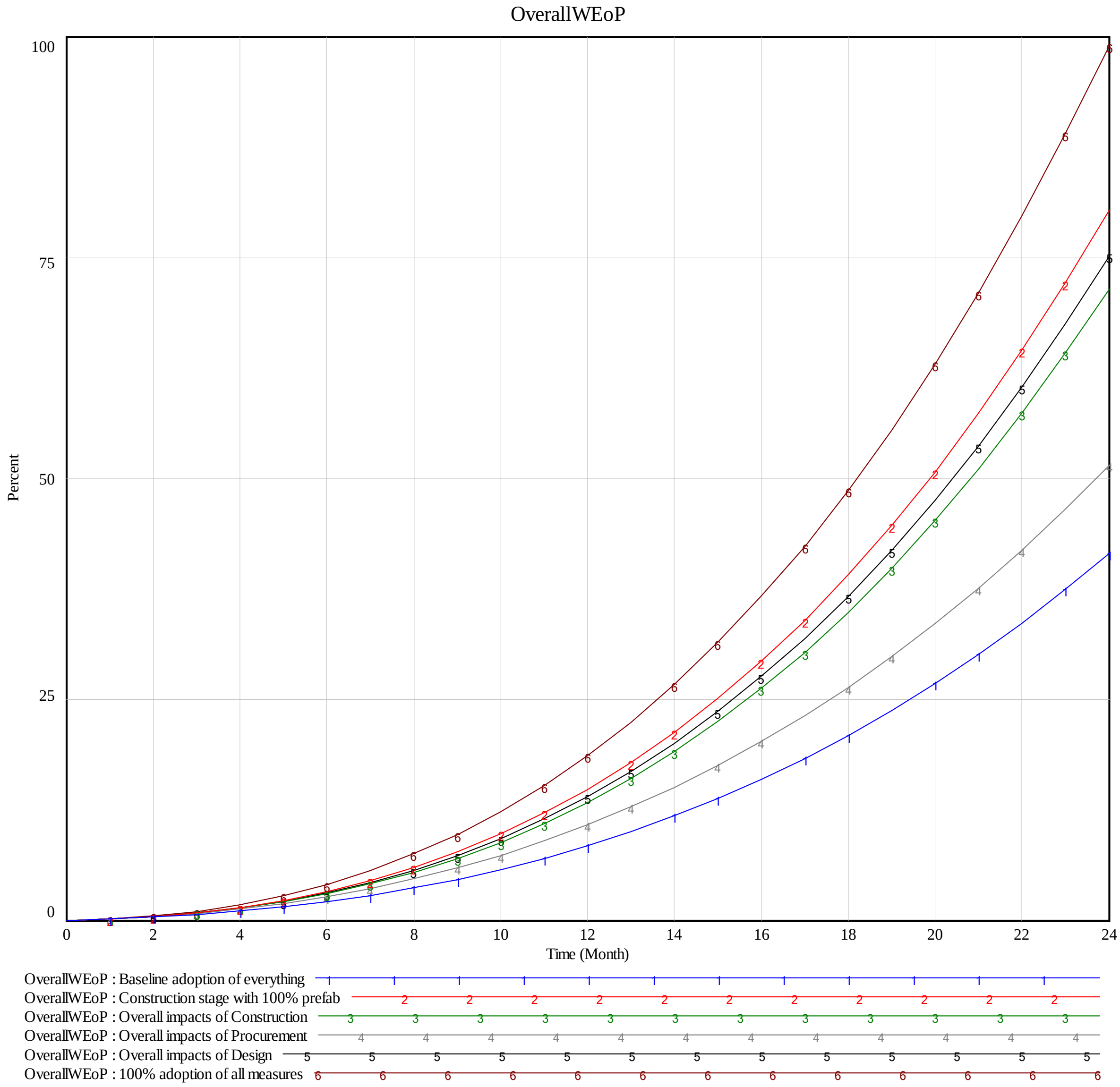

Figure 9.11: Dynamic impacts of different stages of project delivery process

9.7.2 Key Dynamic Drivers of Overall Waste Efficiency

Dynamic impacts of adopting individual strategies on overall waste efficiency were simulated by keeping other strategies at the baseline adoption level. The result extends beyond unitary impacts of the strategies, as it indicated dynamic impacts of adopting each strategy or group of related strategies at design, procurement and construction stages.

Among the design strategies, design for modern method of construction has the highest impacts on the overall waste minimisation in construction projects. This is followed by collaborative design process, which entails adequate communication, effective collaboration and involvement of construction team right from the design stage. As shown in Figure 9.12, design for standardisation and dimensional coordination has the third highest impact, while the impact of design document is ranked fourth.

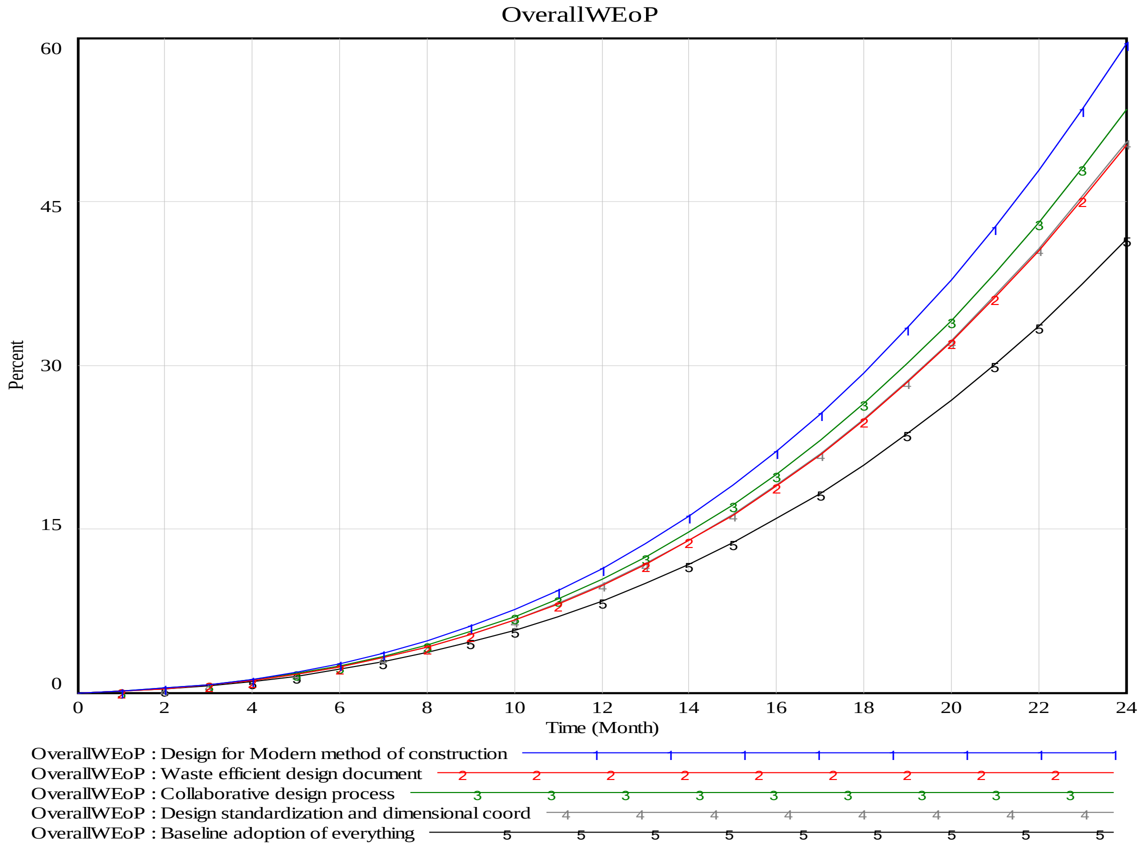

Figure 9.12: Dynamic impacts of different strategies for designing out waste

Relative impacts of different procurement strategies were also simulated to understand how they influence overall waste efficiency of construction projects. As shown in Figure 9.13, suppliers’ alliance has the highest impacts on overall waste efficiency of construction projects. Materials purchase management has the second highest impact, while bill of quantity has lowest relative impact.

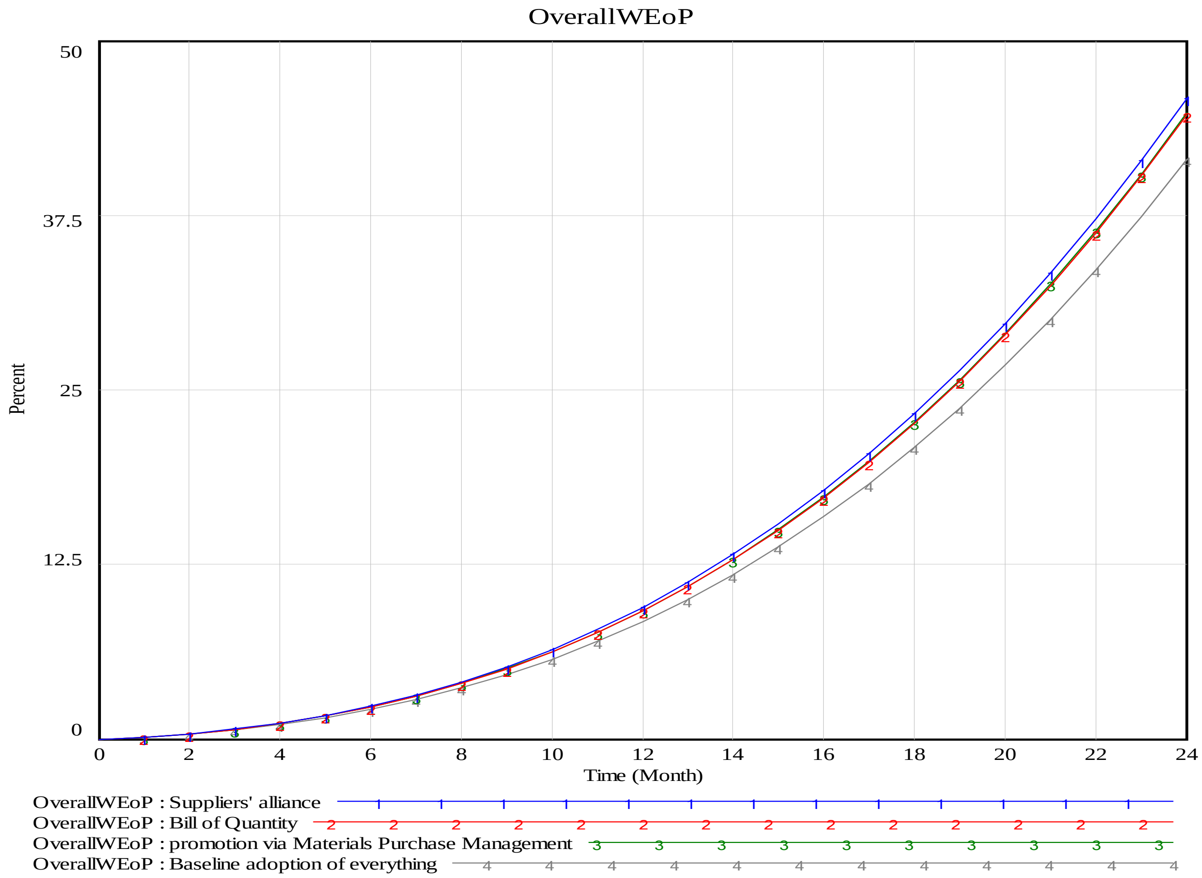

Figure 9.13: Dynamic impacts of different procurement strategies for waste mitigation

The construction strategies for waste minimisation were similarly simulated to understand relative impacts of various strategies on overall waste efficiency of construction projects. As presented in Figure 9.14, the result indicated that prefabrication construction method has the highest possibility of minimising waste generated by construction activities. Collaborative construction process such as the use of IPD and BIM has the second highest waste minimisation tendency, while contractual provision has the third highest tendency of mitigating waste generated by construction activities. Other strategies in order of their significance are materials reuse, site planning and contractors' dedication respectively.

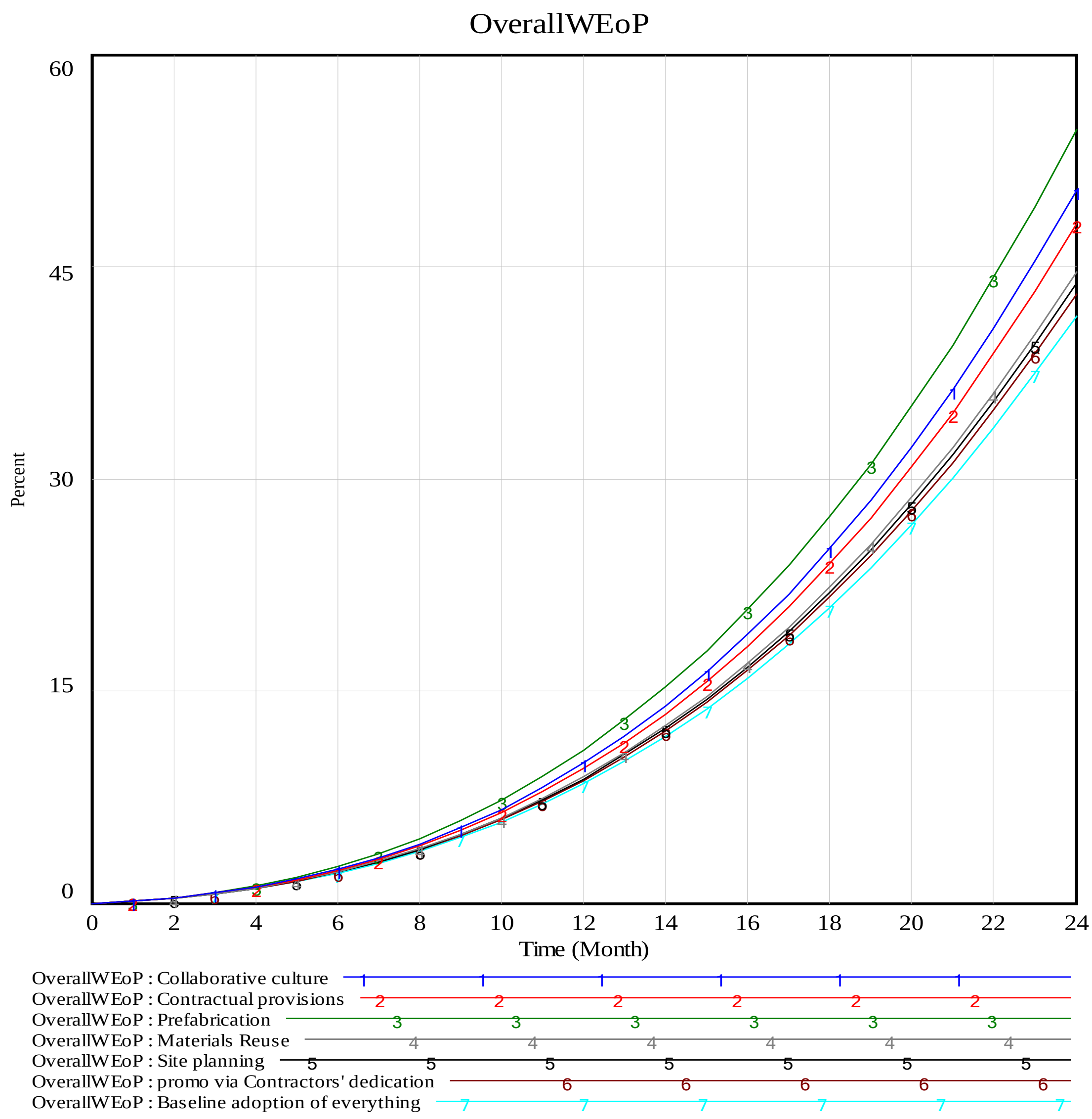

Figure 9.14: Dynamic impacts of different construction strategies for waste mitigation

In order to understand the top measures for engendering waste minimisation, irrespective of stage of its implementation, simulation results for the design, procurement and construction strategies were combined. The result indicates that designing for modern method of construction and its associated modern method of construction – prefabrication – have the highest tendency of reducing waste generated by construction activities. Other measures are collaborative design process, design standardisation and collaborative construction, among others. Order of their significance is presented in Figure 9.15.

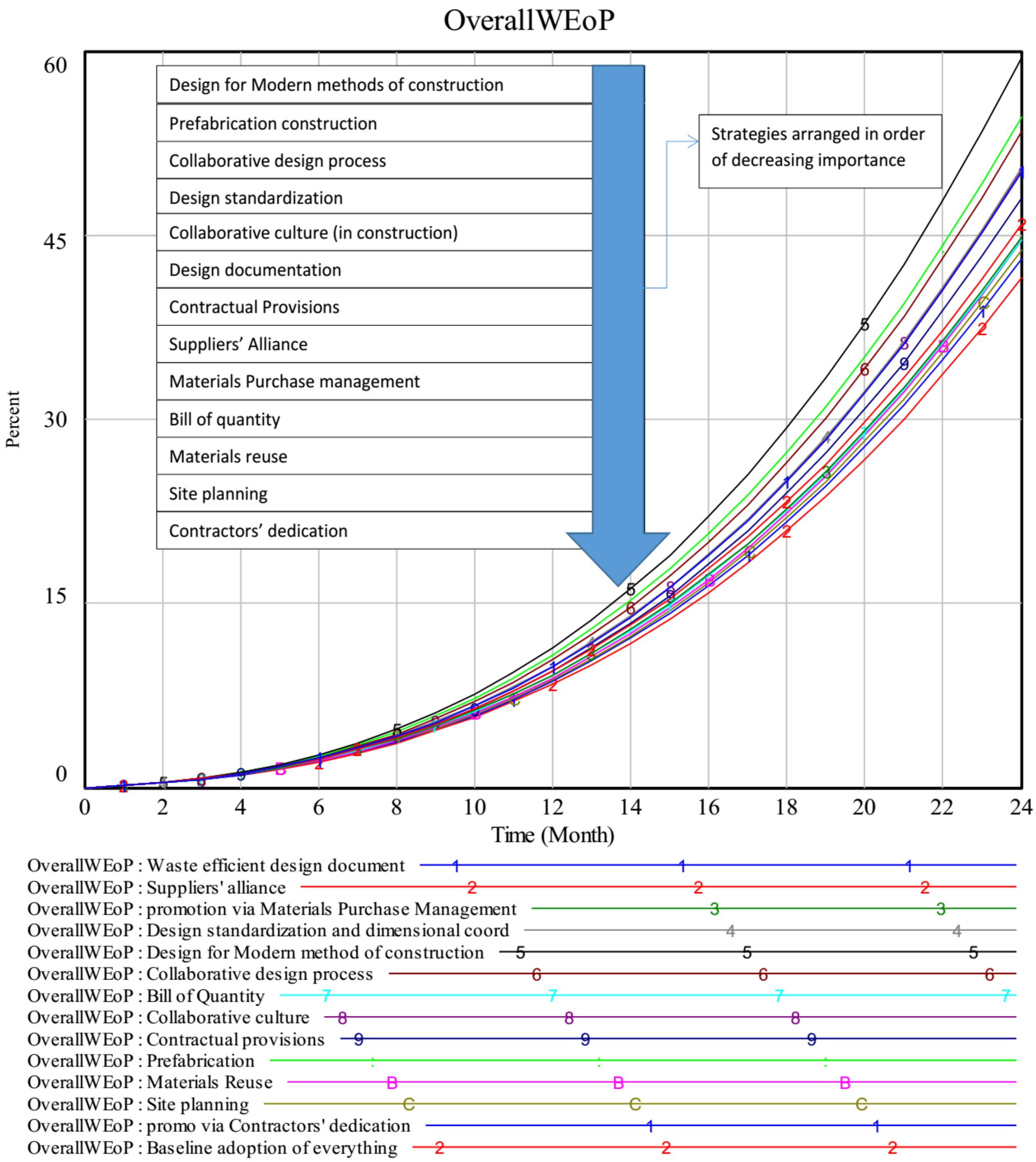

Figure 9.15: Dynamic impacts of design, procurement and construction measures

9.7.3 Underlying strategies for Holistic Waste Minimisation

Based on the dynamic impacts of different strategies for construction waste minimisation, related strategies were combined to develop key measures with highest impacts on waste mitigation. The top key measure for driving waste minimisation is the use of prefabrication technique, which is made up two components of designing for modern methods of construction and prefabrication construction technique. The design for modern methods of construction encompasses specification of prefabricated materials, volumetric design principles, design for preassembled components and the specification of dry walling system, while the prefabrication construction encompasses onsite implementation of the design for modern methods of construction. This includes the use of offsite construction, modular system, precast elements and prefabricated components. As shown in Figure 9.16, the use of this technique has tendency of significantly improving waste efficiency to about 73% from a baseline of about 40%.

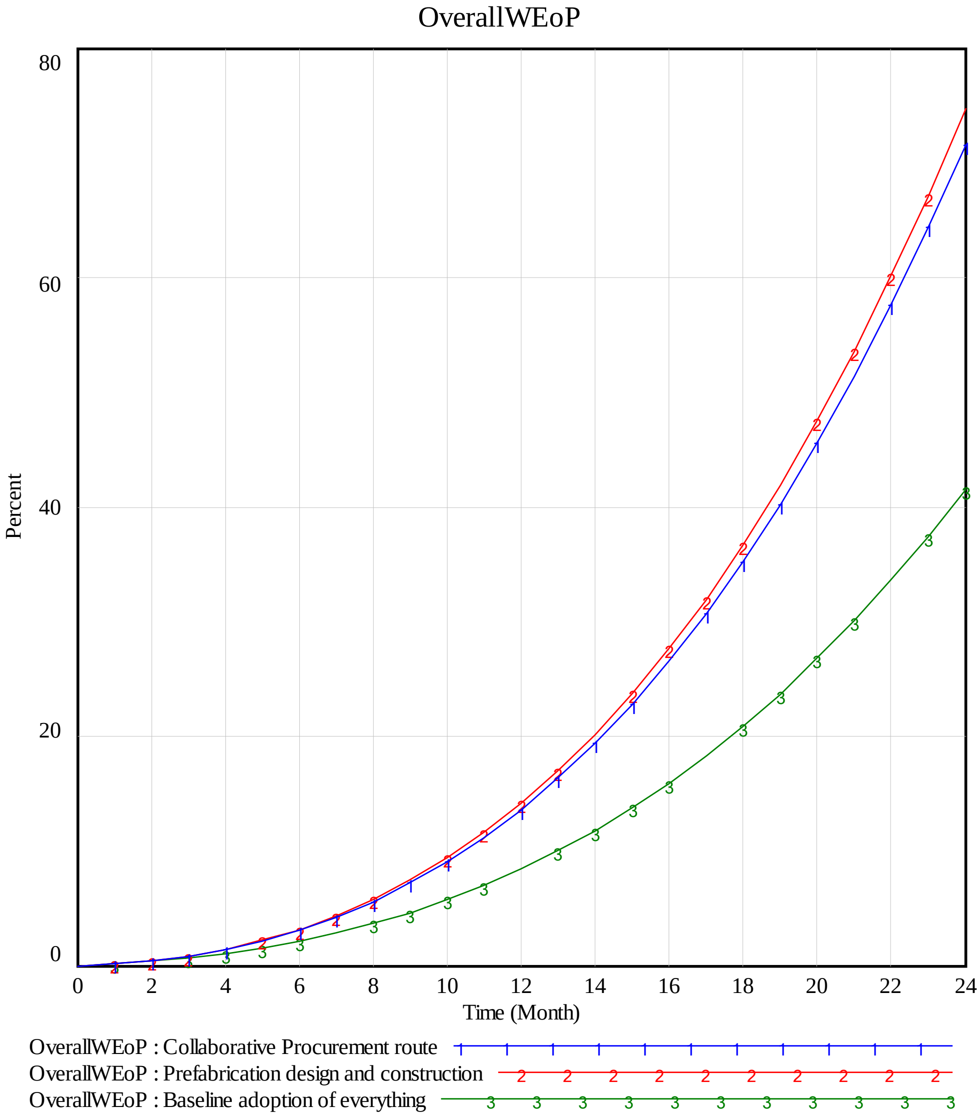

Figure 9.16: The two holistic drivers of construction waste minimisation

The second combined approach for driving waste minimisation is collaborative procurement route, which encompasses collaborative design process, collaborative culture in construction and suppliers’ alliance in materials procurement. Combining the effects of the three components, collaborative procurement routes have tendencies of improving construction waste efficiency up to 70% from the baseline of about 40%.

9.8 Chapter Summary

In this chapter, a system dynamic model was developed to simulate dynamic impacts of design, procurement and construction stages, as well as their associated strategy, on overall waste efficiency of construction projects. The model was developed using VENSIM system dynamic modelling tool, and it consists of cause and effect diagram, which was converted into stock and flow diagram with the aid of mathematical equations. In order to simulate impacts of adopting each strategy on overall waste efficiency of construction projects, a case study of a completed building construction project was used. In line with the recommended steps for system dynamic modelling and simulation, the model went through a number of testing and validation before various scenarios were modelled.

The result suggests that design stage has overall highest impacts on construction waste minimisation. This is followed by construction stage, with materials procurement processes having the least impacts. Effects of all design, procurement and construction measures were also evaluated. Through combination of related strategies over the entire lifecycle of construction projects, the results suggest that prefabricated design and construction has the highest significance in driving waste minimisation. Similarly, the result suggests that substantial construction waste could be reduced through collaborative procurement routes and collaborative techniques such as Integrated Project Delivery (IPD) and the use of Building Information Modelling (BIM).

CHAPTER 10: FINDINGS AND DISCUSSIONS

10.1 Chapter Overview

In this chapter, findings from the previous chapters are discussed and elaborated. The chapter is discussed under five broad headings. The first part addresses the difference in perception of waste minimisation strategies based on job role, which illuminates deep-rooted non-collaborative culture within the construction industry. Subsequent four sections discuss findings of design, design competencies, procurement and construction strategies for engendering waste minimisation. Preceding the culminating section is the discussion of dynamic relationship and interplay of design, procurement and construction strategies for engendering project waste efficiency. Table 10.1 summarises the findings that are discussed in this chapter.

10.2 Difference in Perception Based on Job Role

Results of non-parametric test confirmed null hypothesis that respondents agreed on all but one measure based on their job roles. The affected factor is DF4, which is “involvement of contractors at early design stage”. An evaluation of mean values for architect/design managers, project managers, civil/structural engineers and waste managers suggests an interesting trend in the construction industry. While other respondents ranked the measure as being requisite for designing out waste, architect/design managers posited that the strategy is of low importance. Designers believed that early involvement of contractors at design stage have less impact on the likelihood of designing out waste.

This finding suggests that while contractors and other site-based team believed that their input is invaluable at the design stage of project delivery process; designers believed that they independently possess skillsets required for designing out waste. However, evidence suggests that design could be responsible for about a third (33%) of construction waste (Innes, 2004). This means that despite the acclaimed ability of designers in designing out waste, the design remains a major factor responsible for waste intensiveness of the construction industry. Oyedele et al. (2014) suggest that inadequate use of recycled products in the UK construction industry is partly due to poor consideration of the materials at the design stage. This specifically called for increasing collaborative arrangement at the design stage, where contractors and other team members would have their input into the design. Apart from waste minimisation tendencies, evidence suggests that early involvement of contractors have positive impacts on drawing quality, information flow, materials supply and schedule performance (Song et al., 2009).

Considering the manufacturing industry where low waste is generated, there is more integration of design with manufacturing process (Koskela, 2004; Mohd Nawi et al., 2014). This prevents the likelihood of over-the-wall syndrome, a phenomenon that occurs due to poor collaboration among project participants (Chary, 1988). Notwithstanding the difference in experts' view of the early involvement of contractors, there is an agreement on several other factors requiring collaborative working system among project participants. For instance, there is a general agreement that the use of collaborative procurement route such as Integrated Project Delivery (IPD) is essential to reducing waste generated by the construction industry. Nonetheless, such collaborative system requires win-win approach rather than imposition and unequal commitment, which could offset the benefits (Rahman and Alhassan, 2012).

Based on this difference in perception, it could be inferred that unlike manufacturing industry, the construction is highly fragmented and each party prefers to work independently. This affects the ability of other parties to contribute their expertise, which in turns results in errors, reworks and subsequent waste generation. In line with this, Arain et al. (2014) suggest that non-involvement of the contractor at the design stage is responsible for errors in construction projects. Consequently, while designers are expected to collaborate with contractors during the construction stage, inputs from contractors is capable of enhancing waste effectiveness of the design. Thus, there is a need for cultural and behavioural change from fragmented to a collaborative approach to project delivery.

Figure 10.1: Summary of the key and underlying measures for design, procurement and construction processes

Stages of project delivery process	Critical Success Factors (CSF) for design, procurement & construction	Underlying Factors/Dimensions for preventing waste through design, procurement & construction	Ranking of stages based on their dynamic impacts	Ranking of the dimensions/drivers of waste minimisation based on their holistic impacts at project level	Two major practices for holistic waste minimisation in construction projects
Design stage	Designs are free of error		1		**Use of prefabrication technique**: This encompasses *design for modern method of construction*, *prefabricated construction method* and elements of *design standardisation*
	Involvement of contractors at early design stage	Design for modern methods of construction		1. Design for Modern Method of Construction	
	Design for standard dimensions and units	Waste-efficient design process		2. Prefabricated construction method	
	Drawings are coordinated between design disciplines	Design for standardisation		3. Collaborative design process	
	Design freeze at the end of design process	Waste-efficient design document		4. Design standardization	
Materials procurement process	Effective materials take-off		3	5. Collaborative culture in project delivery	
	Take back Scheme			6. Waste-efficient design documentation	
	Optimisation of materials purchase	Waste-efficient bill of quantity		7. Contractual provisions	
	Materials purchase in line with specification	Waste-efficient Materials Purchase management		8. Suppliers' alliance and commitment	
	Modification to products size & shapes	Suppliers' alliance and commitment		9. Waste-efficient Materials Purchase management	**Collaborative procurement route**: This entails *collaborative design process, suppliers' alliance* and *collaborative culture in construction*
Construction stage	Prefabricated construction method	Prefabrication and offsite technology	2	10. Waste-efficient bill of quantity.	
	Supply chain alliance with materials suppliers	Contractual provisions		11. Maximisation of materials reuse	
	Use of collaborative procurement routes	Maximisation of materials reuse		12. Waste effective site planning	
	Knowledge of construction methods and sequence	Contractors' dedication and competencies		13. Contractors' dedication and competencies	
	Fewer design changes during construction	Waste effective site planning			
		Collaborative culture in project delivery			
		Legislative provisions as an external driver of waste minimisation			

10.3 Designing out Construction Waste

The widely referred McLeamy curve recognised design stage as being a decisive stage with multiple implications on project outcome (McLeamy, 2004). It has critical impacts on key project performance indicators such as cost, time and quality, among others (Isikdag and Underwood, 2010). In addition, the cost of change is cheaper if such change is made at the design stage of project delivery process (McLeamy, 2004). In line with these benefits, evidence suggests that waste could be significantly reduced by taking waste preventive measures at the design stage (Cf. Osmani et al., 2008; Faniran and Caban, 1998; Ekanayake and Ofori, 2004). With design stage widely reckoned as being decisive for construction waste minimisation, this section discusses the design measures for driving low waste construction projects. The discussions are in three sections, which are based on the results of statistical analysis and Structural Equation Modelling (SEM). The first section addresses the underlying dimensions for designing out waste based on final structural models of strategies for designing out waste. The second section discusses five key design strategies for designing out waste based on results of descriptive statistics.

10.3.1 Underlying Dimensions for Designing out Waste

Results of the Structural Equation Modelling shows that the 39 previously identified measures for designing out waste could be replaced by four key factors that were rigorously confirmed through Confirmatory Factor Analysis. These factors include:

- Design for modern methods of construction
- Waste-efficient design process
- Design for standardisation
- Waste-efficient design document

The four underlying factors have significant proportion of their variance explained by waste-efficient design, and they are discussed in the next subsequent sections.

10.3.1.1 Standardisation and dimensional coordination

A key measure that loaded significantly with Waste-efficient design is standardisation and dimensional coordination, which has 77% of its variance explained by waste-efficient design. It is constituted by six measures for designing out waste, which are clear detailing, dimensional coordination, optimised layout, standardised fixtures, simplicity and overall standardisation. Dimensional coordination of design refers to a scenario whereby standard materials supplies are considered and taken into consideration during design. Coordination of design dimensions and specification of standard materials would not only improve constructability of buildings, but it would also help in preventing avoidable off-cuts, which could lead to waste. Constructability of a building is a key factor that measures the extent to which efficient construction is factored into design and design processes (Mbamali et al., 2005). It has been reasoned that design teams are expected to take a leading role in ensuring buildability and constructability of their projects (Lam et al., 2006). Improved buildability of design is not only required for early project completion and resource efficiency (Lovell, 2012), it is a proven way through which construction waste could be reduced (Yeheyis et al., 2013; Yuan, 2013b).

Crawshaw (1976) suggests that a discrepancy of 10mm in one dimension would not only affect contractors' programmes, but it could also cost up to £3,000 in reworks. As such, it is important that while error is prevented in dimension, design should also be standardised to avoid unnecessary offcuts. In a similar note, WRAP (2009) recommends standardisation of building forms and layout and the use of full height doors as a means of reducing construction waste. This is in line with this study, which posits that apart from preventing errors in design, individual elements of the buildings are to be standardised based on market size of the materials. For instance, window and glazing area, as well as door openings, should be appropriately sized.

In line with this study, other authors have also recommended dimensional coordination and standardisation of building elements as an optimal means of reducing construction waste (Dainty and Brookes, 2004; Ekanayake and Ofori, 2004; Baldwin et al., 2007; Alshboul and Ghazaleh, 2014). It is expected that buildings are designed in response to site topography to avoid excavation waste (Yuan, 2013b), complex designs are adequately detailed to improve buildability (Negapan et al., 2013) and structural grid and planning grid are properly coordinated (WRAP, 2009). Thus, it is not only important that designers address dimensional coordination of the building elements, spaces and elements need to be standardised in design. This would result in reduction of both construction and end of life waste.

Another benefit of dimensional coordination and standard materials supplies is ability to reuse the materials at the end of buildings' life cycle. In order to reduce waste generated by the construction industry, designers' waste management measures should go beyond immediate construction activities and current use to which the building is put. It is important that buildings be designed for flexibility and change, in a way that building modification and change in spatial configuration will result in minimal waste. This is particularly necessary as evidence suggests that substantial proportion of waste generated by the construction industry is as a result of renovation works (Esin and Cosgun, 2007).

10.3.1.2 Collaborative Design Process

Early collaboration and improved communication during the design process is confirmed as a key approach for designing out waste in construction projects. The SEM of design strategies in Figure 8.2 shows that design process is a key dimension for designing out waste, with a β value of 0.91 at 99.9% confidence level. The five key contributing factors that were confirmed in the final model pointed towards collaborative design arrangement that engenders adequate information sharing and communication among the project team.

Due to its fragmented and dynamic nature, construction activities usually involve series of errors capable of influencing project success. When error occurs, it leads to reworks, which in turns affect project cost and results into waste. Although cost of reworks has significantly reduced from 30% around 1970s (Crawshaw, 1976), it could still account for about 5% of project costs (Hwang et al., 2012). Rework is one of the major activities that contribute to waste intensiveness of the construction industry (Faniran and Caban, 1998; Ekanayake and Ofori, 2004). Although design change might not be totally prevented in construction, increasing collaborative working has tendency of preventing error-induced design change and reworks (Osmani, 2012). This could be achieved by involving the contractors at early design stage to contribute to design decisions, materials specification and technology. Dainty and Brooke (2004) suggests that most error at construction stage is usually due to contractors' poor knowledge of the design and its documentation. This results in insufficient understanding of design, and as such, results in error. Thus, involving contractor in the design process would not only benefit the design, but it would also equally enhance contractors' understanding of project requirements and design documents.

The SEM suggests that a key factor that defines Waste-efficient design process is adequate communication between various specialities involved in design. Typically, design input is made by various professionals within the built environment, involving architects, civil/structural engineers and M&E engineers among others. In order to ensure adequate coordination of design from various specialities involved, as well as to prevent design clash, there is need for effective communication among the parties (Domingo et al., 2009). This further buttresses the importance of collaboration right from design stage, as collaborative procurement routes are characterised by improved communication and adequate information sharing (Cicmil and Marshall, 2005).

Meanwhile, the need to improve collaboration in the construction industry has engendered various procurement route and digital platforms, among which BIM and Integrated Project Delivery are becoming increasingly required (Ilozor and Kelly, 2011). While IPD is underpinned by integration of people and every aspect of project to harness insights and inputs for project optimisation (AIA, 2007), BIM is a technologically driven collaborative platform for enhancing digital representation, collaboration, production, storage and sharing of building information (Eastman et al., 2011). Thus, apart from likelihood of preventing immediate clash and other causes of waste, increased collaboration would enhance information sharing and early collaboration among project stakeholders, thereby foreseeing and preventing likely causes of waste.

10.3.1.3 Design for Modern Methods of Construction (MMC)

Design for Modern Method of Construction (MMC) is confirmed as a key dimension for designing out waste, with a β value of 0.68 at 99.9% confidence level. It also has 74% of its variance explained by waste efficiency in design, suggesting that it is a good reflector of the extent by which waste is designed out in a construction project. MMC usually refers to building construction technique whereby buildings are factory manufactured and site assembled (Lovell, 2012). It involves a situation whereby various components of buildings are manufactured in controlled factory environment and are transported to the site, where the components are assembly. Innovative onsite building technologies are also sometimes referred to as MMC (Mohd Nawi et al., 2014). The result of SEM shows that designing for MMC is a key dimension for designing out waste. These measures include designing for modular construction, prefabrication and preassembled components as well as the use of modern low waste techniques such as drywall partitions (Baldwin et al., 2007; Yuan, 2013).

This finding is also buttressed by earlier studies, which posit that adoption of modern methods of construction, such as offsite construction and prefabrication of building components, significantly reduces construction waste (Cf. Dainty and Brooke, 2004; Al-Hajj and Hamani, 2011).

In addition to its tendencies for waste minimisation during construction, MMC supports constructability and de-constructability of buildings (Formoso et al., 2002; Oyedele et al., 2013). This could ensure that building elements are reused after the end of its lifecycle, as the elements are appropriately sized to conventional standards. For instance, bathroom or kitchen pods could be diligently removed and reused in another building. It is, therefore, important that designers consider the MMC while designing, as the methods are proven waste-efficient (Yuan, 2013; Kozlovska and Splsacova, 2013).

10.3.1.4 Waste-efficient design Documentation

Another reflector of Waste-efficient design is the quality and comprehensiveness of design document, which has a β value of 0.65 at 99.9% confidence level, with 72% of its variance explained by the latent factor. The quality of design documents has great impacts the on overall effectiveness of the build process (Andi and Minato, 2003; Gann et al., 2003). It is a key requisite for preventing waste generated by construction activities. For instance, design errors and wrong detailing have tendency of resulting in construction errors, which will in turns lead to reworks (Faniran and Caban, 1998). As such, completeness and accuracy of design documents is important for reducing waste generated by construction activities. This is because; design documents do not only affect buildability of the project, its comprehensiveness and accuracy would go a long way in preventing errors that could lead to reworks (Formoso et al., 2002). Therefore, it is not only important that design documents provide adequate information, but it is also required that it employs conventional language and incorporates all features that are site specific. It is vital that design documents are legibly presented in a consistent detailing language and format, easily understood by all trades involved in the project lifecycle.

Specification as an important document has a decisive influence on the waste output of construction project. Oyedele et al. (2003) and Osmani (2013) considered inadequate specification as a major cause of waste in construction projects. If over-ordering, under-ordering and over-allowance were well addressed in schedule and specification document, less waste would be generated on construction sites. It is, therefore, important that design and specification documents be accurately prepared in order to prevent waste that could arise from deficiencies in design documentation. In addition, evidence suggests that design document usually lack some essential details required for successful construction exercise, thereby leaving the contractors with guesswork and subsequent waste generation (Begum et al., 2009). It is expected that adequate design information is provided in the design document to ensure that subsequent businesses are carried out with less waste (Khanh and Kim, 2014).

Similarly, current industry practices lack provision for preparation of deconstruction plan, which in itself would not reduce waste generation during construction but become a vital document for demolition and end of life waste diversion from landfill. The deconstruction plan is an important document for reducing waste intensiveness of the construction industry, as building demolition waste constitutes a larger portion of total waste generated by the construction industry. Designing for deconstruction is recognised as one of the five spectrums through which waste could be designed out in construction projects (WRAP, 2009). It involves careful planning, designing and selection of building materials in such a way that buildings support selective demolition of its elements (Saghafi and Teshnizi, 2011). Careful planning for buildings to support deconstruction at the end of its lifecycle, and subsequent availability of deconstruction plan, would reduce waste generated by the industry. This finding buttressed earlier studies by Oyedele et al. (2013) which suggests that in order to reduce landfill waste, there is a need for deconstruction plan to become part of design documentation. Thus, a major attribute of Waste-efficient design is the extent to which deconstruction has been factored into it.

10.3.2 Key Strategies for Designing out Waste

Results of statistical analyses suggest that error free design, early involvement of contractors, design standardisation, adequate design coordination and design freeze are the top ranked measures for designing out waste. While the top four factors have been adequately addressed by the key dimensions for designing out waste as discussed in the previous section, the study suggests the need for design freeze at the end of the design process. Meanwhile, design change is one of the major activities that contribute to waste intensiveness of the construction industry (Faniran and Caban, 1998; Ekanayake and Ofori, 2004). This is usually as a result of errors that require amendment to the design, need to work within a realistic budget or as a result of owners' change in requirement. As such, a major feature of waste-efficient design is that it incorporates adequate measures capable of preventing design change. This means that efforts should be made to ensure that design is made for the targeted budget and should be devoid of errors, which could otherwise require amendments. The key strategy for mitigating such change and its subsequent waste generation is through design freeze, which is ranked as the fifth measure for designing out waste. This would ensure that construction activities are carried out with legally binding and completed design documents and adequate information, thereby preventing errors that could otherwise result in reworks and subsequent waste generation.

10.4 Competencies for Designing out Waste

The relationship between competencies and achievement of desired goals has become more noticeable in many project-based organisations within the construction industry (cf. Dainty et al., 2005; Zhang et al., 2013, Hardison et al., 2014, Lampel, 2001). Concomitantly, several studies have suggested adequate design competencies as key requisite for minimising waste generated by the construction industry (Cf. Wang et al., 2014; Oyedele et al., 2014). Based on this, designers' competencies for driving low waste projects have been investigated in this study. The underlying competencies for designing out waste as well as the top-ranked competencies are discussed based on results of statistical analyses and SEM.

10.4.1 Dimensions of Competencies for Designing out Waste

Four categories of competencies for designing out waste were established in the study. These include:

- Waste behavioural competency
- Design task proficiency
- Construction-related knowledge
- Inter-professional competency

The underlying competencies along with their overall impacts on designers' capability for driving waste minimisation are discussed in the subsequent sections.

10.4.1.1 Waste Behavioural Competency

Likelihood of designing out construction waste is not only determined by cognitive ability and knowledge of designers, behavioural competence and personal commitment is the underlying factors that determine whether the skill and knowledge would be applied. These sets of behavioural competencies have also been referred to as self-competence or contextual dimension of competency. Harter (1982) refers to self-competence as one's perceived ability and belief in a particular task. With respect to designing out waste, this study refers to self-competence as self-awareness and concept, ability, motivation, attitude and dedication to waste minimisation. Results of SEM indicate that behavioural competency is a key competency for designing out waste having a β value of 1.40. With the highest factor loading among all latent factors of design competency, this finding confirms that contextual competency is a key requisite for driving task competencies for designing out waste. This aligns with Motowildo's task-contextual model, which posits that contextual and behavioural traits are essential components of competency (Motowildo et al., 1997).

In order to design out waste, this study finds that designers should be dedicated to understanding waste causative influence of design in addition to their knowledge of design actions that result in waste. While investigating architects' perspectives to waste reduction by design, Osmani et al. (2008) similarly claimed that understanding underlying causes and origin of waste is a requisite knowledge for reducing waste by design. Asides basic understanding of design causes of waste, commitment on the part of designers determines attitudes to waste management, and whether their skill would be used for designing out. To raise self or behavioural competence for designing out waste, more dedication is needed from designers, some of who believe that waste is only site induced and that they have no professional responsibility for tackling it (Osmani, 2013). This commitment could be demonstrated by setting waste minimisation as priority, avoiding known waste-inducing activities, and engagement in training and development, among others (Lu and Yuan, 2010; Mckechnie and Brown, 2007). In addition, ability to prepare waste scenario plan that compares and improves design based on likely waste outcome is an essential part of competency for designing out waste.

10.4.1.2 Design Task Proficiency

This study suggests that design task competencies are indispensable to achieving low waste construction projects. The factor has a β value of 0.94 as a significant reflector of competency for designing out waste. This buttresses findings of earlier studies aiming at identifying design factors with causative influence on construction waste. For instance, design error, poor detailing and inadequate specification are known causes of construction waste (Faniran and Caban, 1998; Formoso et al., 2002). Results of SEM indicates that the extent to which a designer is capable of considering basic design quality indicators would reduce waste induced by design. These sets of design quality indicators include design functionality, detailing, specification as well as the quality of its documentation (Gann et al., 2003; Andi and Minato, 2003). As illegible or incorrectly detailed design leads to construction waste, ability to produce error-free design, correct materials specification and coherent documentation are key competencies for designing out waste.

In addition, the result suggests that competency of a designer in designing out waste is determined by the extent to which constructability thinking comes into his/her thought process. Constructability of a design refers to the extent to which it facilitates ease of construction (Lam et al., 2006). A construction project tends to be waste intensive if buildability/constructability, as basic design quality, is not thoroughly considered in the design process (Yuan, 2013b). It results in project delay, cost overrun and design change, which is a major cause of waste (Yeheyis et al., 2013). A similar competency that significantly reflects designers' overall competency is ability to design in response to the site topography as well as integration of existing facilities into the new design. This finding aligns with earlier suggestion that designers are not only to design in response to site topography (WRAP, 2009) but are also expected to identify and integrate reusable elements into design (Begum et al., 2009). This could range from materials from previous buildings, in case of redeveloped site, to excavation materials where new sites are being developed (Del Río Merino et al., 2009). Thus, in addition to adequate technical and cognitive design skills, constructability thinking and ability to design in conformity with site are basic task competencies required for designing out construction waste.

Certain design techniques and skills are potentially waste-effective. Improving proficiency of designers in such technique are agenda for Continuous Professional Development (CPD) with respect to waste management. Consequently, the result suggests that designers' competency for designing out waste is directly related to their proficiency in such skill as design for prefabrication, clash prevention and standard materials supply. While prefabrication is evident to reduce waste by up to 84% (Jaillon et al., 2009), design for standard materials supply is essential to preventing materials offcuts, which is a major source of construction waste (Formoso et al., 2002). In addition to this, Crawshaw (1976) points out that a little discrepancy of 10mm in dimension would result in reworks up to a cost of £3,000. Without necessarily considering waste output, it is essential that designers are versed enough to prevent clash, while also coordinating and standardising the dimensions of building elements, as these set of measures would in turns reduce waste output of construction projects.

10.4.1.3 Construction-related knowledge

Causative influence of design stage on construction outcome is well established across literature (Cornick, 1991). The extent to which designers consider actual construction process would determine the ease with which construction is carried out. In line with this, the study suggests that designers’ proficiency in construction-related knowledge is a measure of their competencies for designing out waste. This is as the study confirmed construction and materials related knowledge as key competency for designing out waste, having a β value of 0.91. In line with this finding, Alshboul and Ghazaleh (2014) suggest that knowledge of construction process and sequence would assist designers in preventing certain forms of error that could result in waste. For instance, adequate knowledge of which of wall tiles and floor rendering comes first could reduce offcuts or over ordering of tiling materials. In the same vein, understanding whether ceiling materials is fitted before wall rendering could assist in saving cost and preventing materials wastage. By understanding how construction site layout and activities are carried out, designers would be able to design in line with subsequent businesses.

Apart from awareness of construction operation sequence and real site activities, adequate knowledge of construction materials is required for designing out waste. This corroborates the position of Dainty and Brooke (2004) who argued that large percentage of building renovation waste is due to the use of less durable materials, which requires incessant replacement. Thus, designers are not only expected to be versed in standard materials supply and specification, their knowledge of materials quality and suitability for purpose is a key competency for preventing waste.

Balance theory for recycling suggests that by using secondary materials equivalent of waste generated, landfill sites would be freed (Wong and Yip, 2002). Notwithstanding this, Oyedele et al. (2014) found that recycled material is less acceptable in construction industry as designers lack adequate awareness of its durability, market availability and correct specification. As such, adequate knowledge of secondary materials, as well as their efficient specifications is an important competence for driving low waste culture within the construction industry.

10.4.1.4 Inter-professional Competency

Due to highly fragmented project-based nature of the construction industry, this study confirmed that inter-professional collaborative competency is essential to driving low waste projects. The measure has a β value of 0.76, and it is a significant reflection of designers' competency for designing out waste. Corroborating the need for inter-professional collaborative competencies, Osmani (2013) opines that although zero waste target was debated for construction industry, concerns regarding the industry's fragmentation and poor collaboration prevents its implementation. Meanwhile, Canadian National Inter-Professional Competency Framework (2010) suggests that achieving optimal outcome in a multi-professional engagement requires effective collaboration and role awareness between parties involved. All these point to the importance of inter-professional competencies in such a fragmented and multi-party setting as the construction industry.

Ability to coordinate design from various trades including architecture, M&E, and structural engineering is an important competency required of design managers, as it will assist in early detection and mitigation of design clash before construction. This aligns with argument by Crashaw (1976) who points out that poor coordination of designs is a major cause of waste and rework. In order to avoid make-do waste which occurs as a result of poor communication between design team (Koskela, 2004), this study suggests that designers are not only required to understand team functioning and role responsibility, they are expected to have competencies for effective communication within and across trades.

Apart from competencies required for managing project team works, interpersonal management, inter-professional conflict management skill and collaborative competencies are required for minimising waste in construction projects. This means that other than proficiency in design task, contextual job performance in terms of collaborative competency of designers is a good measure of their competency for designing out waste.

10.4.2 Top Ranked Competencies for Designing out Waste

Significance ranking for design competencies suggests that most of the key competencies for designing out waste are part of designers' core skills. For instance, the top-ranked factor is the designers' ability to coordinate dimension of building elements and components in line with standard materials supply, which is essential task proficiency. By coordinating dimension of building elements and components, there is likelihood of preventing offcuts, which is a major cause of construction waste (Formoso et al., 2002). It is as such important that designers are aware of standard materials supply so that dimensions could be adequately coordinated in line with the supplies.

The second, third and fifth ranked factors are ability to produce error-free design, ability to coordinate design from all trades and ability to ability to produce coherent and comprehensive design information respectively. These sets of competency felled within the task competencies that are required of designers, whether or not waste mitigation is of concern. As previously discussed, design errors, clash and inadequate information could result in rework, a major cause of waste in construction project (Love et al., 2000). The fourth-ranked factor is the ability to detect and prevent clash in design. This felled within both task and inter-professional competency, as design clash could occur at both individual and collaborative levels. Based on this requirement, it is essential that designers possess adequate skills needed for preventing design clash. An increasingly popular among such skill is the use of BIM tools such as Revit, which could help in coordinating design from all trades.

10.5 Procurement Strategies for Waste-efficient Projects

As materials could contribute up to 50% of project cost (Kong et al., 2001), success and profitability of a construction project largely depend on the extent to which its materials purchase is effectively managed. Notwithstanding the knowledge that wasted materials are purchased through the procurement process, relevance of the process in reducing construction waste has not been adequately considered. This is albeit the fact that substantial percentages of waste generated in construction activities have been traced to ineffective coordination of materials procurement activities (Greenwood, 2003; Lu et al., 2011; Wang et al., 2008). Based on the importance of materials procurement process in mitigating construction waste, this study has investigated procurement measures for waste-efficient projects. Underlying procurement measures for mitigating waste, as well as the top-ranked procurement strategies for construction waste minimisation, are discussed in this section.

10.5.1 Underlying Dimensions of Waste-efficient Procurement

Results of SEM confirmed that all the procurement strategies for mitigating construction waste could be substituted with three underlying factors, which are:

- Waste-efficient materials purchase management
- Suppliers’ alliance and commitment
- Waste-efficient bill of quantity.

The three factors are significant indicators of waste-efficient procurement, with none of the factor having its β value less than the benchmark of 0.50 (Kline, 2010). They are further discussed in subsequent sub-sections.

10.5.1.1 Waste-efficient Materials Purchase Management

The structural model confirmed that waste effectiveness of materials purchase management is essential to reducing overall waste generated by construction activities. It has a β value of 0.79 and waste-efficient procurement accounts for 59% of its variance. Materials purchase management entails management of materials purchase management and its related activities. It ensures that the right quantity and quality of materials are purchased and adequately transported at the right time. In line with this study, Tam (2008) identified purchase management as an effective measure for reducing waste in construction projects. Other studies have pointed out various measures through which materials purchase could be adequately used to reduce waste. It is important that activities that could lead to wrong materials purchase be addressed before actual materials ordering (Bernold et al., 1991; Muhwezi et al., 2012).

Key measures that significantly contribute to waste-efficient purchase management is the purchase of secondary materials such as recycled aggregate and materials with high content of recycled products. Although these sets of measures would not contribute to onsite minimisation of waste, they help in diverting waste from landfill thereby reducing overall waste generated by the construction industry. This is in agreement with earlier studies, which suggest that specification and subsequent use of recycled materials is indispensable to waste minimisation and the overall global sustainability agenda (Oyedele et al., 2014). Based on this, there is need to procure secondary materials and support reuse of existing materials (Begum et al., 2009). This, according to the study, is important for reducing waste output of the construction industry. In addition, reusability of packaging materials will reduce waste output of the project, especially as packaging waste constitutes substantial proportion of construction waste (Esin and Cosgun, 2007; Wang et al., 2008).

While materials optimisation should be carried out to avoid over ordering, under ordering and excess waste allowance (Begum et al., 2007), adequate considerations should also be given to the nature of materials purchased. This is because the quality and reusability of materials would ensure its longevity and conservation of mineral resources respectively. This corroborates earlier findings that the use of low-quality construction materials is a major cause of incessant renovation and its subsequent waste generation (Dainty and Brooke, 2004). As such, purchase of durable materials is a long-term strategy for reducing waste intensiveness of the construction industry.

A key procurement strategy that reflects waste efficiency of materials purchase management is the use of Just in Time delivery route, which ensures that materials are delivered to the site in batches when needed. This helps in reducing the length of time the materials are stored as well as eliminating the likelihood of over-ordering that could otherwise result in leftovers and breakages (Dainty and Brooke, 2004). Another key benefit of the use of JIT delivery system is its likelihood of preventing double handling of materials, which is a known cause of materials breakage and subsequent waste generation (Al-Hajj and Hamani, 2011). As it prevents waste due to double handling and materials leftover, the use of JIT delivery system is a key strategy for preventing waste generated by construction activities. Similar to JIT in preventing waste is purchase of pre-cut and preassembled materials and components. These would prevent waste due to offcut, which is a key source of construction waste (Formoso et al., 2002).

10.5.1.2 Suppliers' Alliance and Commitment

This study reinforces the significance of materials manufacturers/suppliers as an important stakeholder in the construction industry. The result of SEM confirmed that a major measure for ensuring waste-efficient procurement is alliance with materials suppliers in waste-efficient materials supply, which has a β value of 0.67 and 82% of variance. Owing to their contribution to the industry, most literature often places them at equal level as such stakeholders like designers, waste managers and contractors (Adams et al., 2011). Apart from their central role in the industry, this study confirmed their role in reducing waste intensiveness of the construction industry.

Meanwhile, a common cause of waste on construction site is excessive stocking of materials, which could result in breakage (Del Río Merino et al., 2009). In such instance, supplier that is flexible in providing small quantity of materials, when required, could assist in reducing waste. This confirms earlier suggestion by Dainty and Brooke (2004), who posit that flexibility of materials suppliers in providing small quantities is requisite to reducing waste generated by construction activities. It is as well important that measures be taken to modify materials in conformity with design, as it is capable of reducing offcut, which is a major source of waste landfilled by the industry (Bernold et al., 1991).

Similarly, another measure through which readiness of materials suppliers for waste mitigation could be ascertained is their commitment to take back scheme. This involves an agreement between project team and suppliers so that the latter would take back unused materials at the end of construction activities. This finding confirmed earlier studies, which suggest take back scheme as a means of reducing waste due to materials leftover (Osmani et al., 2008; Oyedele et al., 2013; Nagapan et al., 2013; Al-Hajj and Hamani, 2011; Bernold et al. 1991). As such, it is important that materials suppliers be committed to take back scheme as a means of getting the reusable materials back to the market. Overall, this study suggests that commitment and support of materials supplier is a key requisite for achieving waste minimisation through materials procurement process.

10.5.1.3 Waste-efficient Bill of Quantity

The third dimension of waste-efficient procurement is extent of waste effectiveness of Bill of Quantity, which has a β value of 0.67. The result suggests that a way of minimising waste generated by construction activities is to ensure that ordered materials are devoid of over/under ordering. Within the industry, it is a norm that a certain proportion of materials are added procuring as waste allowance while ordering materials. According to Buchan et al. (1991), this allowance is usually in the range of 2.5 to 10% of quantity purchased. The cost of this proportion that usually ends up as waste is normally factored into project cost, and the clients pay for it. As such, waste effectiveness of materials procurement process requires optimisation of materials purchase to avoid over-ordering, which is a major cause of materials leftover and subsequent waste generation (Greenwood, 2003). It is, therefore, important that materials take-off is accurately done in preparation for actual materials purchase (Muhwezi et al., 2012; Nagapan et al., 2013). This is then expected to be followed up by materials ordering that is devoid of over ordering.

10.5.2 Key Procurement Measures for Low Waste Projects

Effective materials take-off is considered as the most important step for waste-efficient procurement process. This is due to the understanding that volume of materials purchase is largely influenced by materials take-off. Based on its importance, accuracy of materials ordered and likelihood of materials leftover is determined by materials take-off (Nagapan et al., 2013). As it drives other materials procurement process, careful attention needs to be given to materials take-off so as to avoid over-ordering and its subsequent waste generation.

Similarly, findings suggest that the second-ranked procurement and materials logistics measures for preventing waste is the take-back scheme, which is a agreement between project team and suppliers so that the latter would take back unused materials from site. Through this agreement, waste due to materials leftover would be significantly reduced. According to Osmani et al. (2008) and Oyedele et al. (2013), materials leftover constitutes significant proportion of total waste generated by construction activities.

Prevention of over-ordering and adherence to carefully prepared specification are ranked as the fourth and fifth procurement strategies for engendering waste minimisation. As earlier evident, over-ordering is a major cause of materials leftover and subsequent waste generation in construction projects. This is usually due to mistakes made in quantity estimates, poor delivery schedule or as a result of deliberate waste allowance that is added to ordered materials (Begum et al., 2007; Hassan et al., 2012). In line with the established impacts of over ordering on materials waste, this study suggests the need for preventing over ordering as a requisite for mitigating waste generated by construction activities. Modification to products size and shapes in conformity with design is also a top ranked measure for engendering waste minimisation through materials procurement. By modifying materials supply in conformity with design, materials offcut would be eliminated. This finding conforms with Formoso et al. (2002) who argued that materials procurement that supports pre-cut and precast materials is indispensable to waste effectiveness of the construction industry.

10.6 Construction Strategies for Holistic Waste Minimisation

Effective management of construction processes is indispensable to overall performance of construction projects (Forster, 2014). It involves direction and supervision of operations on construction projects in order to ensure timely, safety, quality and cost-effectiveness of the projects, among other success indicators (Harlow, 1992). Apart from these sets of KPIs, certain construction techniques, strategies and processes could substantially reduce waste generated by construction activities. This section discusses the underlying measures and key strategies for mitigating waste at the construction stage of project delivery process.

10.6.1 Dimensions for Waste-efficient Construction

Results of SEM confirmed that in addition to legislative provisions that influence adoption of various strategies for construction waste mitigation, six factors are requisite for driving waste effectiveness of construction projects. These include:

- Prefabrication and offsite technology
- Contractual provisions for waste minimisation
- Maximisation of materials reuse
- Contractors' dedication and competencies
- Waste effective site planning
- Collaborative culture in project delivery

The seventh measure for driving waste minimisation is legislative provisions, which is an external driver of waste minimisation practices within the industry. All the confirmed factors significantly reflect waste-efficient construction, with 51-98% of their variance explained by waste-efficient construction. They are further discussed in the subsequent sections below.

10.6.1.1 Prefabrication and Offsite Technology

Prefabrication and offsite technology is confirmed as the key underlying measure for preventing waste generated by the construction industry. The key dimension of waste-efficient construction has a β value of 0.97 and 94% of its variance is explained by the latent factor. This makes the construction technique the underlying strategy with the highest factor loading to waste-efficient construction process. A key factor contributing to the measure is the use of precast components such as bathroom and kitchen pod in place of cast in-situ. This means that building elements are manufactured offsite, assembled onsite, while several factors that cause waste such as materials handling, poor storage as well as design changes have been entirely prevented. This would not only reduce construction waste due to in-situ and finishes (Poon et al., 2003), it would also support reusability of the components at the end of building lifecycle.

Modular construction is another technique that loaded significantly to prefabrication and offsite technology. It is a term that describes factory produced building units that are delivered and assembled on site as building elements or volumetric components. The use of precast units and modules, as well as all other offsite technologies, has been evident to reduce waste generated by construction activities (Lu and Yuan, 2013a). A study by Tam et al. (2007b) suggests that waste minimisation tendency of prefabrication construction is up to 84.7%. As such, the use of offsite techniques is requisite to reducing waste generated by construction activities.

10.6.1.2 Contractual Provisions for Waste Minimisation

Another measure that influences waste effectiveness of construction process is the contractual clauses and provision, which has a β value of 0.94, with 98% of its variance explained by the second-order latent factor. The factor name, “contractual provisions for waste minimisation”, was imposed on the factor grouping, as all measures that made up the group are suggesting what could only be achieved through contractual clauses. For instance, a key factor that contributes to the component is to penalise poor waste performance, which makes waste management a key performance indicator. This would mean that contractor would treat waste minimisation in similar as time performance, which is essential to project success (Sanvido et al., 1992).

Usually, construction waste minimisation receives little or no attention in several projects due to lack of its consideration in project contracts (Osmani, 2013). Time, cost and quality, among others, have become the top performance indicators for benchmarking success of construction projects (Sanvido et al., 1992). Because of this, site managers and other project stakeholders always give their priority to activities that could directly contribute to indices upon which their performance would be measured. This is rational from static point of view, as waste minimisation is not usually required of project stakeholders from benchmarking point of view. Nonetheless, this practice is albeit the understanding that waste minimisation has tendency of improving cost of construction projects (BRE, 2003). In addition, the use of project contracts to prevent some of the key causes of construction waste could significantly prevent cost and time overrun, which are rife in the construction industry (Assaf and Al-Hejji, 2006). A project that has clear communication of waste management strategy in contract document is more likely to have a good waste performance, as contractual provisions engender commitment. A project that sets waste and recycling target as part of contractual provision is more likely to divert substantial waste from landfill site (Marinelli et al., 2014). Thus, there is need for using contractual clauses as strategy for engendering waste minimisation on construction projects.

10.6.1.3 Maximisation of materials reuse

Material reuse is confirmed as another dimension for minimising waste generated by construction activities, and it has a β value of 0.91 with 78% of its variance explained by the second-order latent factor. It requires maximisation of on-site reuse of materials, and it includes reuse of such materials as off-cut, soil remains, as well as excavation and demolition materials. This factor incorporates various waste mitigating practices suggested by previous studies (Cf. Del Río Merino et al., 2009; Al-Hajj and Hamani, 2011; Cha et al., 2009; Lu and Yuan, 2010). As such, it is a key measure that combines various strategies that are capable of diverting substantial proportion of construction waste from landfill. Begum (2009) recommended that by reusing soil remains on site, substantial proportion of waste could be diverted from landfill. In line with this, WRAP (2009) identified that apart from using demolition and excavation materials for filling, it could as well be used for landscape mulch.

Apart from preventing landfilling, materials reuse, in this case, prevents the need for waste transportation and recycling, which is not without its negative environmental impacts (Oyedele et al., 2014). In addition to reuse of materials on-site, this factor requires the use of reclaimed materials for construction activities. This could be achieved by identifying the construction activities that could admit secondary materials, rather than using virgin materials that require substantial amount of energy. Nonetheless, materials reuse requires adequate planning for waste segregation, which requires provision of specific skip for different forms of waste. With this practice, there is likelihood of on-site reuse of the materials in waste skips (Tam, 2008). This will equally help in preventing waste mixture with soil (Jingkuang and Yousong, 2011).

10.6.1.4 Contractors’ Dedication and Competencies

Contractors’ competencies and dedication is confirmed as an essential requisite for mitigating waste generated by construction activities. The factor has a significant loading with a β value of 0.71 and 51% of variance explained by waste-efficient construction process. This suggests that without contractors’ commitment to construction waste minimisation, no significant progress could be made in reducing waste intensiveness of the construction industry. Teo and Loosemore (2001) suggest that despite the development and advancement in construction waste management research and strategies, there is a deep-rooted waste behaviour in the industry due to poor managerial commitment to reducing waste. In line with this, the study suggests contractors’ commitment and competency as key drivers of waste effectiveness in construction projects.

Knowledge of site team in activities planning and sequence of work could prevent damage to previously completed work, thereby preventing the need for reworks. Expertise knowledge in construction methods and technology would as well ensure that mistakes and subsequent rework is prevented. Although the use of secondary materials is a way of diverting waste from landfill, it has been less adopted as practitioners believe that it requires more effort regarding specification and sourcing (Oyedele et al. 2014). In such instance, commitment of project team to the use of secondary materials is an essential measure for diverting waste from landfill (Wang et al., 2014). This could be achieved by detecting construction activities that could admit reusable materials and by subsequently using the materials.

10.6.1.5 Waste-efficient Site Planning

Effective planning of site activities is confirmed as a key dimension for mitigating waste generated by construction activities. The important dimension of Waste-efficient design has a β value of 0.63, with 79% of its variance explained by the second-order latent factor.

Effective site planning and management is increasingly recognised as a strategic approach for achieving the required performance in construction projects (Forster, 2014). This is because of the understanding that project performance could only be achieved through an effective site management practices.

Efficient planning of site activities is required for preventing errors, reworks and associated waste generation. For instance, a thorough review of project specification during site planning is capable of preventing reworks, which is a major source of construction waste. Site layout planning as a key site planning document is an important document that could prevent waste causative activities such as inadequate site access for materials delivery and double handling of materials (Dainty and Brooke, 2004; Formoso et al., 2002). Good access for materials delivery and central location of materials storage facilities could prevent materials damage due to poor access and double handling. As such, consideration of such measures in site planning would enhance waste minimisation.

As a means of facilitating waste minimisation in construction projects, Site Waste Management Plan (SWMP) is another document that could be prepared during site planning. Before it was repealed in 2013, site waste management regulation required preparation of SWMP for every project above the value of £300,000. It also required dedicated role of site waste manager, who is responsible for coordinating onsite waste management activities. Preparation of such document would enhance adequate planning and communication of proposed strategies for waste management. Apart from establishing a task group or dedicated job role for waste management, strategies for minimising and communicating design change should be developed during site planning process. These would ensure that waste causative activities are adequately considered during planning of construction activities.

10.6.1.6 Collaborative Culture as Requisite for Waste Minimisation

Results of SEM suggest the need for cultural change in the industry as means of engendering waste minimisation. The key dimension of waste-efficient construction has a β value of 0.51 and 55% of its variance is explained by second-order latent factor. A key practice that requires cultural change within the industry is the level of collaboration within the industry. Evidence suggests that inadequate collaboration between designers, procurement team and contractors is a key feature that compromises profitability and effectiveness of the construction industry (Hughes et al., 2012). Traditionally, a client commissions the design team, which will subsequently involve engineers and building service consultants. As a result of fragmented nature of the industry, the drawings are passed from one trade to another, without necessarily working collaboratively. The design documents are then passed to the contractor who undertakes the actual work on the site. This results in what is regarded as over-the-wall syndrome, which is a difficulty that arises when different professionals are working independent of one another towards the same goal. It, therefore, results in late detection of errors and the need for reworks that subsequently result in construction waste generation.

Similarly, it has often been evident that the major causes of construction waste are ineffective project communication and coordination (Osmani, 2012), document delay, and non-involvement of contractors in design decisions (Arain et al., 2004). All these occur as a result of poor collaboration among the project team. Waste-efficient projects require an environment for effective communication, information sharing, early warning system and early contribution of expertise by all parties (Hughes et al., 2012). As such, every ambiguity and inaccuracies would have been resolved before design completion, thereby preventing construction errors, reworks and waste. Similarly, collaborative working between the designers and contractors would assist in addressing constructability of the design, which could otherwise result in error and waste.

Rather than working collaboratively, the whole process is interested in passing blame to another party (Fewings, 2013). This shifting of blame is one of the major factors contributing to ineffectiveness of construction waste management strategies. While the contractors believe that designers contribute to waste generation, designers posit that their activities have nothing to do with waste (Osmani et al., 2008). This hinders likelihood of collaborative waste management effort among all parties involved in project delivery processes. With the industry being characterised by blame culture as in this case, collaborative working environment could not be more important.

10.6.1.7 Policy and Legislation as Key Drivers of Waste Minimisation

A key measure that engenders construction waste minimisation is legislative and policy provision, which has a β value of 0.53, with a causative influence on waste effectiveness of construction process. By its nature, the construction industry is one of the most regulated industries, and its activities have been largely shaped by national and regional legislation. As planning approval is required before any physical construction activities, it means that the project has to fall within the framework provided by the legislation. In the UK construction industry, for example, compliance with the provision of Code for Sustainable Homes was a requirement for all residential building construction. This had driven sustainable building practices as the code became more stringent before its provision was incorporated into building regulations in 2015. Before the compulsory SWMP was repealed (in December 2013), it has been the industry's standard to prepare and monitor detailed SWMP for all projects above £300,000. These practices suggest relevant impacts of legislation in driving sustainable practices within the construction industry.

Since the introduction of landfill tax in 1996, influences of tax and fines on construction waste minimisation has become clear. The impartial tax measure ensures that tax is paid per unit tonne of waste deposited in landfill sites. Results of the SEM suggest increased stringency of existing fiscal measures as a strategy for engendering waste minimisation. This is especially required, as the financial implications of waste management strategy determine its acceptability in the construction industry. For instance, increasing cost of waste landfilling as well as cost of mixed waste would ensure waste separation, reuse and recycling. As the contractors are more concerned about cost implications of waste disposal (Cooper, 1996), such measure is capable of engendering waste management practices. As such, by making waste minimisation and reuse cheaper than its landfilling, substantial proportion of waste would be diverted from landfill.

As a means of promoting good waste performance, tax breaks and incentives are important for the construction industry. Apart from imposing stringent legislations and fiscal policies, the use of incentives and tax break is a key measure for achieving construction waste minimisation. Cooper (1996) posits that stringent waste management legislation and fiscal policies would remain ineffective if there are no ways of facilitating such practices. In line with this, Bartl (2014) opined that since waste generation is in itself a positive factor of economic growth, while also serving as a source of business, sophisticated incentives would be required for decoupling economic growth from waste generation. This finding is similar to earlier suggestion of economic carrot, which is deemed a way of moving waste management practices up the ladder of waste hierarchy within the UK (Wilson, 1996).

Low use of recycled construction materials is attributed to its high cost, despite its perceived low quality (Oyedele et al., 2014). Direct subsidisation of secondary materials, provision of tax break for its manufacturers and suppliers, and provision of economic incentives for waste management infrastructures are measures for enhancing its use in the construction industry. Similarly, sustainable design appraisal tools have remained an effective mechanism for driving sustainability practices across the globe. They set best practice standards for environmental performance of buildings throughout its project delivery processes as well as during operational stage. With the increasing popularity of the sustainability appraisal tools, this study suggests allocation of higher points to waste management practices. Apart from dedicated waste management policies and regulations, allocation of more points to waste in the existing and widely used sustainability appraisal tool could further engender waste management practices in the construction industry. This corroborates earlier findings by Dainty and Brookes (2004), which suggests that inclusion of waste in sustainable design appraisal tools, such as BREAM, is a key motivator for designing out waste. A similar study in Japan (Tam et al., 2004) also concluded that green construction appraisal tools are key drivers of construction waste minimisation.

Notwithstanding these prior studies, no significant importance has been attached to waste in such sustainable design appraisal tools as the UK BREAAM and the US LEED. Most appraisal systems have only considered the extent of material sorting, reuse, and recycling that are incorporated into the management plan (Cha et al., 2009). Currently, 8.5% of possible 110% addresses waste management in BREAAM, while 6.4% of possible 100% address waste management in the Code for Sustainable Homes. Increasing the points allocated to waste means that waste management could be taken as important as land use, materials, pollution, energy and management, which are given 10%, 13.5%, 10%, 15% and 12% respectively in BREEAM. While it would not be taken as a compulsory provision, inclusion and allocation of points to waste management influence factors, according to Cha et al. (2009), could enhance waste management practices and subsequent reduction.

10.6.2 Key Construction Measures for Low Waste Projects

The top-ranked construction measures are based on four key dimensions for engendering waste minimisation. The highest ranked factor is the use of prefabrication construction method instead of cast in-situ, which could otherwise generate large portion of waste. As previously evident, prefabrication technique could reduce waste by well over a half. This could be achieved by using precast units and modules, modular construction and other offsite technologies, all of which are proven waste-efficient techniques (Tam et al., 2007b).

The second and third-ranked factors are supply chain alliance with materials suppliers and use of collaborative procurement routes. The two factors suggest the need for increasing collaboration within the construction industry. This requires collaboration among all project teams as well as alliance with materials suppliers, who are important stakeholders in facilitating waste-efficient materials procurement. By partnering the materials suppliers, there is tendency for take back scheme, supply of precut and preassembled materials and flexibility in supplying materials just in time (Osmani et al., 2008; Al-Hajj and Hamani, 2008).

Knowledge of construction methods and sequence possessed by contractors and building operatives is ranked as the fourth factor for mitigating waste generated by construction activities. This falls within the competencies and dedication of contractors, which is requisite for preventing waste causative activities. By following the right sequence of work, damages to previously completed works and subsequent reworks would be prevented.

Ensuring fewer design changes during construction is ranked fifth among the construction factor for engendering waste minimisation. Formoso et al. (2002) suggest design change as a major cause of reworks and subsequent waste generation in construction projects. This could be due to design errors (Osmani, 2012), change in clients' need or the need to work within a realistic budget (Chan and Kumaraswamy, 1996). As earlier discussed, increasing use of collaborative procurement process and technologies such as IPD and BIM could prevent error-induced design change as well as those due to poor clients' understanding of initial design. Similarly, contractual clauses that limit design changes or freezes design would prevent reworks due to design change and its associated waste generation (Osmani, 2013). However, where a design change is inevitable, adequate communication of such change is important for waste minimisation (Faniran and Caban, 1998).

10.7 Dynamic Interplay among Design, Procurement and Construction Measures

The system dynamic model shows relative impacts of different processes and stages of project delivery. It also suggests that at holistic level, impacts of different strategies extend beyond their stage of implementation. Activities carried out at early stage have significant impacts on subsequent processes. The results of various scenario models performed on the system dynamic model are discussed in the next sub-sections.

10.7.1 Stage-Based Impacts and Associated KPIs

Simulation of dynamic impacts of design, procurement and construction measures indicate that design process has the highest impacts on overall waste efficiency of construction projects. The result suggests that design has a tendency of raising waste-efficiency of construction project to about 75%. This finding shows that like key project performance indicators, such as cost, time and quality (Iskidag and Underwood, 2010); construction waste could be significantly reduced by measures taken during the design stage. In line with this finding, similar studies have illuminated the significance of design processes in reducing waste generated by construction activities. For instance, Osmani et al. (2008), Faniran and Caban (1998) and Ekanayake and Ofori (2004) posit that design stage is important to reducing waste generated by construction activities. Innes (2004) also suggests that design activities could reduce construction waste by up to 33%.

A further evaluation of the key measures contributing to the overall impacts of design suggests that designing for modern methods of construction is the highest contributor to waste effectiveness of design. This involves volumetric modular design, design for preassembled components and specification of prefabricated materials, among others. These sets of measures are requisite to prefabrication construction method, which is evident to reduce waste by well over a half (Tam *et al.*, 2007b). As shown in Figure 9.12, the second significant design strategy, contributing to the highest impacts of design on overall waste generation, is the extent of collaboration involved in the design process. The study suggests that collaborative design process, involving adequate communication, effective design coordination and early involvement of other stakeholders, is a key approach for preventing waste generated by construction activities. The finding shows that collaborative design process has a tendency of reducing waste than error-free design documentation that is prepared in a non-collaborative environment. This is partly due to likelihood of over-the-wall syndrome, which occurs as a result of poor collaboration (Chary, 1988). The dynamic simulation suggests that notwithstanding the competencies of designers as well as ability to produce error-free documentation and standardised design, inadequate collaboration could result in construction waste generation. As such, collaborative procurement route and design for modern method of construction are essential to minimising waste generated by construction activities.

The system dynamic simulation suggests that prefabricated construction method could improve the waste efficiency of construction projects to about 82.5%. This confirms earlier studies by Jaillon et al. (2009) and Tam *et al.* (2007b) who argued that wastage reduction level in prefabricated building is up to 52% and 84.7% respectively. Prefabrication construction method and its associated design for modern method of construction have the highest impact on construction waste minimisation as shown in Figure 9.14. However, for project that is not based on prefabrication technology, waste minimisation tendency of construction process is about 72.5%, which is slightly lower than the overall impacts of design activities. Meanwhile, apart from prefabrication as the key determinant of the overall waste efficiency of construction processes, other measures also have significant impacts. Specifically, collaborative construction process has the second highest impact. This shows similar trend as the design processes, where collaborative design and design for modern method of construction drive the significance of design stage in waste minimisation. Apart from these, contractual provisions and materials reuse are the third and fourth ranked construction measures for driving waste minimisation in construction projects. This confirms earlier findings by Dainty and

Brooke (2004), which suggests that contractual provision is a key measure for driving waste minimisation in construction projects.

Although the procurement processes contribute the least proportion to the overall waste efficiency of construction project, the simulation suggests that it has tendency of reducing waste by an additional 10% over the baseline of 40%. As shown in Figure 9.13, the key contributor to the overall impact of procurement is suppliers' alliance and commitment. This entails supply chain alliance with materials suppliers in reducing construction waste. Such alliance could facilitate take back scheme, flexibility in supplying materials just in time, and modification to products in conformity with project requirements, all of which are proven strategies for waste minimisation (Formoso et al., 2001: Bernold et al., 1991; Dainty and Brooke, 2004). The main underlying concept behind the suppliers' alliance is collaboration among all stakeholders involved in project, including the materials suppliers. Thus, improved collaboration among project stakeholders is capable of driving construction waste minimisation through design, procurement and construction processes.

10.7.2 Underlying Dynamic Drivers of Waste Minimisation

Trends in dynamic simulation of different design, procurement and construction strategies suggest two key measures for effective minimisation of construction waste. The study suggests that by taking care of the two key measures, which are prefabrication technique and collaborative procurement, construction waste would be significantly reduced.

Ranking of significant impacts of adopting various strategies suggests that design for modern methods of construction and its associated construction strategy, prefabrication construction, have the highest impacts on overall waste efficiency of construction projects. Usually, prefabrication construction requires the need to design for prefabrication by specifying prefabricated materials and modular components (Platts, 1994). As the two strategies complement one another, their combined impacts were simulated as shown in Figure 9.16. The graph suggests that prefabricated design and construction is capable of improving waste efficiency of construction project to about

75%. This confirms earlier findings by Jaillon et al. (2009) and Tam et al. (2007b) who suggest that prefabrication construction is capable of reducing construction waste by up to 52% and 84.7% respectively.

Apart from its tendency of reducing waste generated during construction activities, the use of prefabrication supports de-constructability and reusability of building materials (Jaillon and Poon, 2014). As the building components are factory produced and site assembled in most cases, prefabricated building supports disassembly, transportation and reuse of building elements thereby diverting waste from landfill sites (Akinade et al., 2015). Since demolition waste contributes the largest portion of waste generated by the construction industry (WRAP, 2009), the use of prefabrication technique is significant to reducing waste intensiveness of the construction industry. However, notwithstanding the significance of prefabrication method in driving waste minimisation, premium is always paid for using prefabrication method in construction projects (Chen et al., 2010). Based on this, waste minimisation is not usually the key driver for adopting prefabrication in construction projects. This calls for the need to adopt other measures as ranked in Figure 9.15.

The second underlying driver of construction waste minimisation is the use of collaborative procurement routes and collaborative technologies. The result of the dynamic system suggests that collaborative design and collaborative construction are ranked third and fifth among the key strategies for mitigating waste generated by construction activities. Similarly, the highest ranked procurement measure for waste minimisation is suppliers' alliance, which equally points to the need for improved collaboration among project stakeholders, including the materials suppliers. Based on the continuous trend, the three measures were combined to simulate the overall impacts of collaboration on construction waste minimisation.

The result suggests that collaborative procurement route is capable of improving waste efficiency of construction project to about 72%. In order to achieve this, there is need for adequate collaboration right from design stage of project delivery process. The key benefit of such collaboration is that each stakeholder could contribute their expertise, while also understanding the key project requirements (Fewings, 2013). Through adequate collaboration between the designers and contractors, there is tendency of preventing various factors responsible for waste generation, including design errors, poor information sharing and design buildability, among others (Hughes et al., 2012). Complexities in design, poor clients' understanding of initial design and over-the-wall syndrome have been blamed for reworks and subsequent waste generation in construction projects (Arain et al., 2014; Chary, 1988; Koskela, 2004). An effective collaborative process such the IPD and the use of BIM involve the designers, contractors, clients and materials suppliers, among other stakeholders. Involvement of all parties from inception of the project would clear all ambiguities, while diverse expertise knowledge would as well ensure that waste is designed out of the whole process. Poor communication, late information supply, design clash and other potential causes of waste would be avoided, especially as collaborative procurement routes such as IPD and BIM is characterised by improved coordination and communication.

10.8 Chapter Summary

Findings from statistical analyses, structural equation modelling and system dynamic modelling are discussed in the chapter. Although the result of Kruskal-Wallis test suggests that the respondents differ in their perception of early involvement of contractors during design stage, further evidence suggests that it is a reflection of deep-rooted fragmentation and culture of poor collaboration within the construction industry. The need for early collaboration and improved collaboration throughout all stages of project delivery process are discussed in the chapter.

The chapter elaborates on the key and underlying dimensions for designing out waste in construction projects. This could be achieved through standardisation and dimensional coordination, collaborative design process, design for modern methods of construction, and Waste-efficient design documentation. Apart from designers' task competency, construction-related knowledge and inter-professional competencies as essential drivers of low-waste design, behavioural competency of designers is established as the main determinant of their tendency for designing out waste. The underlying dimensions for driving waste minimisation through materials procurement processes were discussed in the chapter. The need for waste-efficient materials purchase management, suppliers' alliance and waste-efficient bill of quantity were elaborated. In addition, the top rated procurement measures, including accurate materials take-off and take back scheme, were also discussed in the chapter. At the construction stage of project delivery processes, the underlying measures for driving waste minimisation, including prefabrication, contractual provisions, materials reuse, contractors' commitment, effective site planning and collaborative procurement, were discussed in the chapter. In addition, the significance importance of legislative provisions in driving waste minimisation behaviour is discussed in the chapter.

Based on the results of various scenarios modelling in system dynamic modelling, the design stage is established as the most significant stage for driving waste minimisation in construction projects. Nonetheless, other stages and processes of project delivery processes were also established as being important for diverting substantial construction waste from landfill, especially as the activities carried out at one stage have impacts on the other stages of project delivery processes. Similarly, due to repetitive patterns in the results from system dynamic modelling, two key practices and strategies were established and elaborated as the dynamic drivers of construction waste minimisation. These include the use of prefabrication method and increasing collaboration among project stakeholders. The significance of these measures, as well as their overall impacts on construction waste minimisation, is discussed in the chapter.

CHAPTER 11: CONCLUSION AND RECOMMENDATIONS

11.1 Chapter Overview

This chapter culminates the study by summarising the whole study and the outcomes of data collection and analysis. The next section provides a holistic summary of the study, covering the goal, research design, data collection and data analytical techniques adopted in the study. This is then followed by key findings of the study, which is presented in line with the aim and objectives of the study as earlier presented in the first chapter. Implications of the study for theory and practice, as well as its limitation, are presented before culminating the chapter with directions for future research.

11.2 Summary of the study

The construction industry contributes the highest portion of waste to landfill, and it consumes a large portion of mineral resources excavated from nature (Anink et al., 1996). Due to negative environmental impacts of waste generation, waste intensiveness of the industry has remained a major concern for the global sustainability agenda (Anderson and Thornback, 2002). In order to reduce waste generated by construction activities, this study investigates design, procurement and construction strategies for minimising waste in construction projects. Apart from investigation of the key and underlying measures for construction waste mitigation, the study considers interrelationship between stages of projects' lifecycle. This is as evidence suggests that activities carried out at earlier stage are capable of engendering occurrences at later stages of the dynamic construction processes.

In order to achieve the aim of the study, various methods of data collection and analyses were used in the study. Following the tenets of critical realism philosophy, the study combined qualitative and quantitative approaches at intensive and extensive stages respectively. At the early stage of the study, data were collected through systematic literature review and four focus group discussions, involving 30 experts from the construction industry. Using Atlas-ti for qualitative data analysis, thematic analysis was carried out to determine strategies for driving waste minimisation through design, materials procurement and construction processes. After combining factors emerging from literature and focus group discussions, 78 unique factors were established for design and design competencies, while 39 and 93 factors were established for procurement and construction strategies respectively.

The identified factors were used to develop a questionnaire, which was pilot tested before being administered to expert within the UK construction industry. Through this process, 302 responses were received with 285 used for further analysis, including reliability analysis, descriptive statistics, non-parametric test and multivariate analysis. These sets of statistical analyses helped in establishing the critical success factors for engendering waste minimisation through design, procurement and construction processes.

Structural equation models were developed to establish the underlying design, procurement and construction strategies for construction waste minimisation. Results of reliability analysis and data screening were used to ensure that only relevant factors were included in the models. Through rigorous processes of fitness, re-specification and modification of measurement and structural components of the model, the underlying design, procurement and construction measures enabling waste minimisation were established. The underlying competencies for driving waste minimisation were also confirmed.

Based on the aim of this study, which extends beyond unitary study of various strategies contributing to waste minimisation, a system dynamic model was developed to investigate the dynamic relationship and interplay among the key strategies established through the structural equation modelling. A case study of a completed project was used to establish the extent by which the various strategies were adopted as well as the overall waste efficiency of the project. Through the adoption rate and factor weight established in structural equation modelling, mathematical equations were developed to convert cause-and-effect diagram to stock-and-flow diagram for model simulation.

After series of model testing and validation processes, various scenario modellings were performed to establish significant impacts of different strategies on overall waste minimisation in construction projects. This helped in ranking the strategies based on their dynamic impacts. Relative impacts of each of the design, materials procurement and construction processes were also simulated and determined. Also, similar strategies were combined to simulate the holistic effects of related strategies on overall waste minimisation in construction projects.

11.3 Key Findings of the Study

Findings of the study are discussed in line with the aim and objectives that the study was designed to achieve. The first and second parts of this section are based on the first objective of the study, which is to investigate the critical success factors and underlying measures for mitigating waste in construction projects. Based on the results of structural equation modelling, the first part concludes on the underlying measures for enabling construction waste minimisation through design, materials procurement and construction processes. The second part concludes on the critical success factors for waste minimisation. The third part is in line with the second objective, and it combines findings from statistical analysis and structural equation modelling to conclude on competencies for designing out waste. The last two parts of this section provide conclusions on the third and fourth objectives by elaborating on the dynamic drivers of construction waste minimisation at holistic level using findings from system dynamic modelling.

11.3.1 Underlying Measures enabling construction waste minimisation

Results of the structural equation confirmed underlying design, procurement and construction measures for enabling waste minimisation in construction projects. The findings suggest that four key measures are essential for designing out waste. The first measure is standardisation and dimensional coordination of building element, which encompasses such measures as coordination of building elements, design for standard materials supplies, and space optimisation. Efficient implementation of this key measure would prevent materials offcut, which is known to be a major cause of construction waste generation (Formoso et al., 2002). The second underlying measures for designing out waste is collaborative design process, which requires involvement of contractors at early design stage, as well as adequate communication and collaboration among project team. The significance of this strategy is that it is important for preventing waste due to rework, which is usually caused by design error, design clash, late information supply, and poor understanding of design, among others (Tam et al., 2007a). Increasing collaboration would, therefore, ensure that each stakeholder contributes their competencies right from design stage, while also having collaborative agreement that enhances communication and information sharing.

Design for modern methods of construction is established as the third underlying measures for designing out waste in construction projects. This strategy entails volumetric modular design, specification of prefabricated materials and design for offsite technologies. Although prefabricated construction could significantly reduce construction waste, designing for modern methods of construction is a requisite step in prefabricated construction. The fourth underlying strategy for designing out waste is design documentation, which could be evaluated based on its accuracy and comprehensiveness. Waste-efficient design documents are characterised by being free from errors and buildability issues, while it provides adequate information for waste-efficient construction processes.

Materials procurement process is an important process for driving waste minimisation in construction projects. This is not only because of understanding that materials contribute substantial proportion of project cost, but also that various waste causative factors have been traced to the processes of materials procurement (Faniran and Caban, 1998; Dainty and Brooke, 2004). In order to drive waste minimisation through materials procurement processes, three key underlying measures were established in the study. Low waste materials purchase management is confirmed as the first underlying measures for driving waste minimisation through materials procurement. It mainly entails purchase of materials with low waste output as well as secondary materials that support was diversion from landfill sites. It also advocates for the use of JIT procurement system, where materials are supplied when needed on site. The strategy is capable of preventing offcut, materials breakage and leftover, all of which are key causes of waste generation (Al-Hajj and Hamani, 2011; Del Río Merino et al., 2009).

The second materials procurement strategy for engendering waste minimisation is suppliers’ alliance and commitment, which requires involvement of materials suppliers as an important stakeholder in project delivery processes. Through this involvement, take back scheme could be implemented, and suppliers could be more flexible in supplying small quantity of materials thereby preventing materials leftover and breakages. The waste efficiency of bill of quantity is confirmed as the third dimension for mitigating waste through materials procurement processes. This involves correct and accurate materials take off that is devoid of waste allowance and subsequent over ordering of materials.

At construction stage of project delivery processes, seven dimensions for preventing waste generation were confirmed. A waste-efficient project is characterised by maximisation of materials reuse during the construction activities. This requires adequate segregation of different materials, by providing skips for specific materials and through adequate communication of materials reuse strategies. The second factor underlying low waste construction project is the site planning, which could essentially drive waste minimisation. Site layout planning, site waste management plan, communication strategies, review of project specification are part of site planning measures for driving waste minimisation. Another key underlying strategy for minimisation waste during construction process is the use of prefabrication technique. This strategy is in line with the propositions of lean construction principles, and it involves the use of precast components and modules, modular construction technique and other offsite technologies. Through this measure, waste due to wet trades, offcuts, materials breakage and reworks could be prevented (Hassan et al., 2012; Dainty and Brooke, 2004).

Contractors' competencies and dedication is also confirmed as another underlying strategy for driving waste minimisation in construction projects. The study suggests that without committed and dedicated contractors, other waste management strategies could not be effective. This is especially as poor work sequence could result in breakage of previously completed work, thereby resulting in reworks and subsequent waste generation. In addition, it is when contractors are committed to waste minimisation that materials reuse or secondary materials could be considered. Nonetheless, such commitment could be engendered by contractual and legislative provisions that penalise and reward waste generation and minimisation respectively. Usually, waste minimisation is of secondary importance in many construction projects. This is especially as project performance is measured through such key performance indicators as cost, time and quality. The study, therefore, suggests that by making waste minimisation a part of key performance indicators, substantial volume of waste would be diverted from landfill.

Apart from strategies for minimisation waste in construction project, an overarching approach to preventing waste is improved collaboration within the construction industry. Currently, the construction industry is characterised by fragmentation and poor collaboration among project stakeholders. This results in information loss, poor communication and blame shifting rather than ensuring collaborative working environment (Fewings, 2013). This is despite the fact that each profession has its unique input, which could be valuable throughout the process of project delivery. In concurrence with this, the study confirmed collaborative culture as a key driving force for engendering waste minimisation in construction projects.

11.3.2 Critical Success Factors for Construction Waste Minimisation

The results of descriptive statistics show relative importance attached to various design, procurement and construction strategies for driving waste minimisation. At the design stage, the critical success factors are error free design, early involvement of contractors, design for standard dimensions and units, design coordination, and design freeze at the end of design process in respective order. These set of factors point to the need for certainty in design and prevention of factors that could lead to reworks and excessive materials offcut.

In order to drive waste minimisation through materials procurement processes, the established critical success factors include effective materials take-off, take back scheme, optimisation of materials purchase, modification to product size and shape, and purchase of preassembled components in order of their significance. The top three factors are related to measures for preventing materials leftover, which is evident as a major cause of construction waste (Dainty and Brooke, 2004). The fourth and fifth critical success factors are concerned with strategies for preventing materials offcut, another established cause of construction waste (Formoso et al., 2002). This suggests that materials procurement processes could essentially drive waste minimisation by optimising materials ordering to prevent leftover and by using the process to support pre-cut, preassembled and durable materials.

At the construction stage of project delivery process, the critical success factors for driving waste minimisation include prefabricated construction method, supply chain alliance with materials suppliers, collaborative procurement route, contractors' dedication and less design change. While the highest ranked factor reinforces the significance of prefabrication and autonomation in construction waste minimisation, the second, third and fifth ranked factor buttress the importance of collaboration in achieving construction waste efficiency. The third-ranked factor shows that competencies of contractors in project planning, as well as their waste behavioural competency, is important to driving waste minimisation.

11.4 Critical Competencies for minimising waste in construction projects

Despite the established significance of design in minimising construction waste, various studies have suggested that designers lack adequate competencies for driving low waste projects (Mansikkasalo et al., 2014; Sassi and Thompson, 2008). Due to this, the study has investigated the key and underlying competencies for designing out waste in construction projects. Results of the structural equation modelling confirmed four underlying competencies for designing out waste in construction projects. Most importantly, behavioural competency, which is a reflection of designers' personal commitment and belief, is confirmed as the key requisite competency for driving low waste project. This is especially important, as the likelihood of implementing strategies for designing out waste is determined by their belief in design as the main cause of waste generation. Proficiency in design task, which is the main role of designer, is also confirmed as a key underlying strategy for waste minimisation. Through proficiency in main design techniques such as error free design, dimensional coordination, clash prevention, and detailing, among others, waste causative factors would be prevented.

As design is essentially a graphical representation of buildings for subsequent construction, designers’ knowledge of construction is confirmed as a key competency for designing out waste. This knowledge would enhance adequate specification, detailing and integration of reusable elements into design. Similarly, inter-professional collaborative competency is confirmed as an underlying competency for designing out waste. These include ability to coordinate design from all trades as well as adequate communication of design information in collaborative environment.

Significance ranking of design competencies for waste minimisation suggests that ability to coordinate dimension of building elements and components is the highest ranked competency. This is followed by proficiency in design coordination across trades and ability to produce error-free design respectively. Proficiency in clash prevention and ability to provide comprehensive design information are the fourth and fifth ranked competencies. As these sets of competencies are essential for preventing waste causative factors, possession of the skillsets is requisite for designing out waste in construction projects.

11.4.1 Key Dynamic Drivers of Construction Waste Minimisation

Results of various simulations on system dynamic modelling suggest that the impacts of implementing a strategy extend beyond its unitary level. Activity carried out at a stage has far-reaching effects on other stages of project delivery process. Through simulation of dynamic impacts and interrelationship among key dimensions for waste mitigation, relative importance of the strategies was established.

Most significant among waste minimisation strategy is design for modern methods of construction, which could be equally referred to as design for prefabricated elements. Notwithstanding that prefabrication is confirmed as a key measure that is capable of reducing construction waste, failure to design for modern methods of construction would make prefabricated construction infeasible. As such, the significance of designing for modern method of construction extends beyond unitary dimension.

Apart from prefabricated construction, which has the second highest dynamic impacts at holistic level, collaborative design process is the next significant measure in terms of its holistic impacts on project waste efficiency. This strategy ensures that all project stakeholders collaborate right from design stage, thereby preventing all waste causative factors that are associated with inadequate communication, information loss, poor design interpretation, design clash and reworks due to errors, among others (Arain et al., 2004; Charry, 1998). Similar to this, collaborative construction process has the fifth highest dynamic impacts on project waste efficiency. This suggests that collaboration is not only required at the design stage of project delivery process, increasing collaborative working process is required through the whole processes of project delivery process. Meanwhile, ranking fourth among the strategies is design for standardisation and dimensional coordination. This strategy requires design optimisation in line with standard materials supply, thereby preventing waste due to offcuts. By coordinating and optimising design dimensions, building materials would be easily reusable in other projects.

Other than relative significance of different strategies, an investigation of the significant impacts of design, procurement and construction processes to waste minimisation suggests that design has the highest dynamic impacts in driving waste management practices. This is especially as the step taken during the design process would affect other activities during materials procurement and construction stages. While design could improve waste efficiency to about 75%, materials procurement and construction processes could raise project waste efficiency to 50% and 72.5% respectively. This advocates for the need to plan for waste minimisation right from design stage of project delivery process, where the cost of change is cheaper.

11.4.2 Underlying Strategies for Holistic Waste Minimisation

Across all the dynamic simulation, two key patterns that majorly drive waste minimisation are prefabricated construction and collaborative procurement route. The result suggests that either or both of the strategies are capable of engendering significant waste minimisation in construction projects. While prefabrication method demands design for modern methods of construction as well as prefabrication construction, collaborative procurement route demands collaborative design, collaborative culture in construction, and suppliers’ alliance, all of which are confirmed as significant strategies for waste minimisation.

11.5 Implications for Practice

Findings of this study have significant implications for practices throughout every stage of project delivery processes. The study shows that design stage is very crucial for construction waste minimisation. Based on this, there is need for increasing dedication among the design professionals by considering waste during the design process. The established design competency is an agenda for professional development among the designers. While inter-professional collaborative competency is particularly required of design managers, proficiency and conventionalism in basic design task, and knowledge of construction operation and materials are expected to be improved among designers, as they are important for designing out waste.

While seeking to design out waste, the main focus of designers should be on optimisation of building design in line with standard materials supplies. This specifically becomes the key driving force when project does not involve prefabricated construction method. At project level, design process usually involves inadequate coordination and poor collaboration among design professionals. Rather than the usually fragmented approach, this study suggests the need for integrated approach in design process. Gaining more importance in the construction industry is the use of BIM for design coordination. Use of this technique would enhance collaboration required for driving waste minimisation through design activities.

In order to reduce construction waste, there is need for increasing attention to materials procurement strategies. While materials suppliers are usually considered as external stakeholders in construction, adequate waste minimisation requires increasing alliance with materials suppliers. This would ensure that they facilitate waste minimisation by supplying pre-cut, preassembled and suitable materials. Such alliance could as well facilitate take back scheme and JIT delivery, which are proven to prevent materials leftover and subsequent waste generation (Negapan et al. 2013; Dainty and Brooke, 2004).

The increasing use of prefabricated construction method is requisite for reducing waste intensiveness of the construction industry. This is especially as the findings suggest that the construction technique is capable of reducing substantial proportion of waste. The construction technique ensures that building elements and components are offsite-produced and site assembled. In such case, waste-inducing practices such as offcuts would have been prevented.

While it is clear that prefabrication technique could not be employed on every project due to its higher cost (Chen et al., 2010), another key measure that could equally facilitate waste minimisation is the use of collaborative procurement route. The study suggests that most factors responsible for waste generation could be adequately prevented by using collaborative procurement routes, which enhance adequate communication and information sharing among project stakeholders. This would as well ensure that all professionals contribute their unique competencies that are not only essential for waste minimisation, but also for driving key project performance indicators such as cost, time and quality.

11.6 Theoretical Implications of the Study

In concurrence with the theory of lean construction, this study confirms autonomation as a requisite for holistic waste minimisation. Through structural equation modelling and system dynamic modelling, prefabrication and collaboration were confirmed as the key drivers of construction waste minimisation. This confirms the relevance of Lean construction theory, which advocates for increasing use of prefabrication and improved collaborative process.

Although there is an existence of waste behaviour within the construction industry, the study suggests that waste behaviour is not as a result of behavioural intention of building operatives. This is especially as the results of Structural Equation Modelling (SEM) suggest that human resource management is less significant in driving waste minimisation. Rather, the study confirms prevalence of deep-rooted non-collaborative culture as the key driver of waste behaviour within the industry. As a result of poor collaboration, there is poor project coordination and shifting of waste management responsibility among project stakeholders. This results in errors, reworks and subsequent waste generation. Rather than concentrating on human behavioural intention at individual level, there is need to drive project waste minimisation through collaborative procurement and contractual clauses. This would engender commitments to waste minimisation among project participants.

This study shows that the adopted task-contextual competency model is a valuable framework for mapping out competencies required for effective task performance. Concurring with the tenet of its theoretical basis, the study suggests that both task and contextual performance are measures of competencies for designing out waste. The result of structural equation modelling shows that behavioural competency, which is a contextual skill, has the highest factor weight among the constructs of competencies. Taking factor weight as a measure of significance, the finding confirms the antecedent position that contextual performance, such as interpersonal relationship are more likely to enhance effective performance in designing out waste. This suggests that, as rightly predicted by the task-contextual model, proficiency in design tasks is not enough for designing out waste. It rather requires effective contextual competencies, which could, however, be seen as being external to the fundamental roles of designers. For instance, apart from proficiency in design task, adequate inter-professional collaboration and construction-related knowledge are required for designing out waste.

The dynamic system theory and its associated system dynamic modelling suggest weaknesses in studying construction activities at unitary level. Just like activities on project critical path, measures with impacts on other stages have more dynamic influence on construction waste minimisation. It is, therefore, important that complex and interrelated processes like construction are studied at dynamic level, rather than providing solutions that are conceived from unitary perspective.

11.7 Limitations of the Study

Albeit the robustness of its methodological approach that extends beyond studying construction waste at unitary level, the study has some limitations in terms of its scope. It is, therefore, important that the findings of this study are interpreted in line with its scope and limitation. The data for the study has been collected from the UK construction industry. While effort was made to enhance generalizability through probabilistic sampling of participants and critical sampling of project roles, findings of this study could not be generalised to other countries than the UK. Similarly, focus group discussions and questionnaire were designed to collect data on building projects. As such, no attempt was made to investigate strategies for waste minimisation in civil engineering projects such as road and other infrastructural facilities. This is due to some differences in construction methods and materials use between building and civil engineering projects. Based on this limitation, result of this study should be interpreted as strategies for minimising waste in building construction projects.

Another limitation of the study is its evaluation of waste from materials perspective. Although the theory of lean construction served as a theoretical lens for the study, waste has not been studied from lean perspective. Within the context of lean, waste is approached from both materials and non-materials perspective, including time loss (Koskela, 2004). This study has only approached waste from materials aspect, especially as the study is motivated by the need to improve environmental performance of the construction industry. From this perspective, materials waste is of paramount importance (Faniran and Caban, 1998).

A key component of the study is an investigation of competencies for minimising waste in construction project. However, this aspect of the study has only addressed design competencies for driving low waste construction projects. This limitation is partly due to the lack of significant information on competencies required at procurement and construction stages of project delivery process. Findings from focus group discussions also suggest that most competencies for engendering construction waste minimisation are design-related. This is especially as the design, design documents and designers have been blamed for onsite waste generation (Osmani et al., 2008; Sassi and Thompson, 2008).

11.8 Directions for Future Research

As earlier stated, this study has been carried out within the UK. Other studies could investigate generalizability of its findings to the global construction industry by collecting data from other countries and comparing its findings with this study. Similarly, as this study covers only building projects, future research could specifically investigate strategies for minimising waste in civil engineering projects. This would allow comparison of strategies for waste minimisation in building and civil engineering projects.

This study has been unable to comprehensively investigate competencies for driving waste minimisation at construction stage of project delivery process. As design competencies were established, other studies could investigate key competencies for driving waste minimisation at construction stages of project delivery processes. Materials suppliers’ capacity for supporting waste minimisation could as well be investigated.

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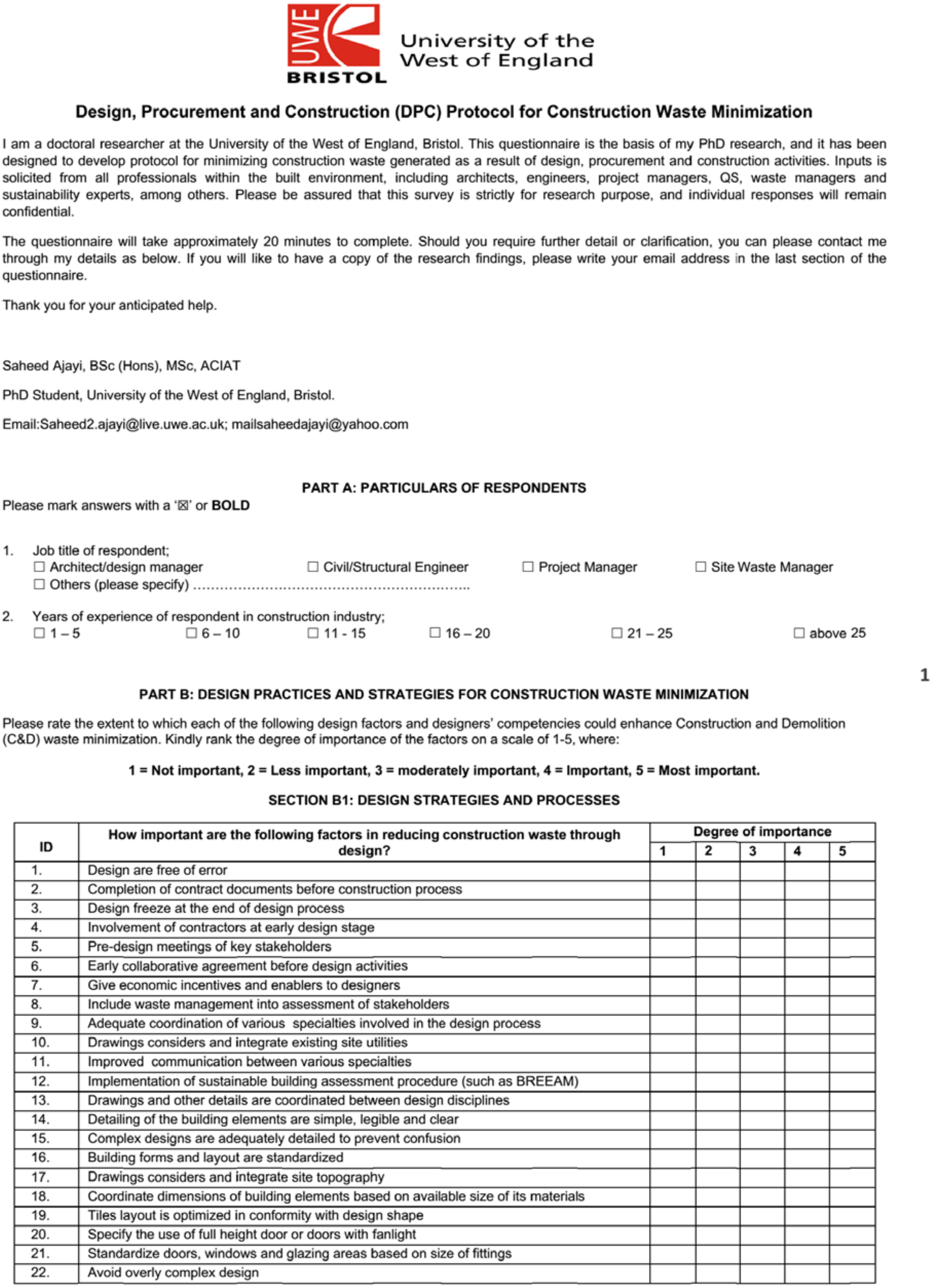
APPENDICES

Appendix 1: Sample of the Main Questionnaire



University of the West of England
BRISTOL

Design, Procurement and Construction (DPC) Protocol for Construction Waste Minimization

I am a doctoral researcher at the University of the West of England, Bristol. This questionnaire is the basis of my PhD research, and it has been designed to develop protocol for minimizing construction waste generated as a result of design, procurement and construction activities. Inputs is solicited from all professionals within the built environment, including architects, engineers, project managers, QS, waste managers and sustainability experts, among others. Please be assured that this survey is strictly for research purpose, and individual responses will remain confidential.

The questionnaire will take approximately 20 minutes to complete. Should you require further detail or clarification, you can please contact me through my details as below. If you will like to have a copy of the research findings, please write your email address in the last section of the questionnaire.

Thank you for your anticipated help.

Saheed Ajayi, BSc (Hons), MSc, ACIAT

PhD Student, University of the West of England, Bristol.

Email:Saheed2.ajayi@live.uwe.ac.uk; mailsaheedajayi@yahoo.com

PART A: PARTICULARS OF RESPONDENTS

Please mark answers with a '☒' or **BOLD**

1. Job title of respondent;
   ☐ Architect/design manager ☐ Civil/Structural Engineer ☐ Project Manager ☐ Site Waste Manager
   ☐ Others (please specify) ……………………………………………………..
2. Years of experience of respondent in construction industry;
   ☐ 1 – 5 ☐ 6 – 10 ☐ 11 - 15 ☐ 16 – 20 ☐ 21 – 25 ☐ above 25

PART B: DESIGN PRACTICES AND STRATEGIES FOR CONSTRUCTION WASTE MINIMIZATION

Please rate the extent to which each of the following design factors and designers' competencies could enhance Construction and Demolition (C&D) waste minimization. Kindly rank the degree of importance of the factors on a scale of 1-5, where:

1 = Not important, 2 = Less important, 3 = moderately important, 4 = Important, 5 = Most important.

SECTION B1: DESIGN STRATEGIES AND PROCESSES

ID	How important are the following factors in reducing construction waste through design?	Degree of importance				
		1	2	3	4	5
1.	Design are free of error					
2.	Completion of contract documents before construction process					
3.	Design freeze at the end of design process					
4.	Involvement of contractors at early design stage					
5.	Pre-design meetings of key stakeholders					
6.	Early collaborative agreement before design activities					
7.	Give economic incentives and enablers to designers					
8.	Include waste management into assessment of stakeholders					
9.	Adequate coordination of various specialties involved in the design process					
10.	Drawings considers and integrate existing site utilities					
11.	Improved communication between various specialties					
12.	Implementation of sustainable building assessment procedure (such as BREEAM)					
13.	Drawings and other details are coordinated between design disciplines					
14.	Detailing of the building elements are simple, legible and clear					
15.	Complex designs are adequately detailed to prevent confusion					
16.	Building forms and layout are standardized					
17.	Drawings considers and integrate site topography					
18.	Coordinate dimensions of building elements based on available size of its materials					
19.	Tiles layout is optimized in conformity with design shape					
20.	Specify the use of full height door or doors with fanlight					
21.	Standardize doors, windows and glazing areas based on size of fittings					
22.	Avoid overly complex design					

ID	How important are the following factors in reducing construction waste through design?	Degree of importance				
		1	2	3	4	5
23.	Specification of prefabricated structural materials					
24.	Design for preassembled components such as bathroom and kitchen pods					
25.	Employ volumetric modular design principles					
26.	Specify the use of dry wall partitions (e.g. timber walling)					
27.	Specify durable materials to avoid need for early replacement					
28.	Design for collapsible and easily demountable components					
29.	Produce disassembly and deconstruction plan					
30.	Specify the use of joint system without gluing and nailing					
31.	Carefully integrate building sub-system					
32.	Coordination of structural grid and planning grid					
33.	Specifications are detailed and devoid of under/over ordering					
34.	Waste management plan is prepared along with design					
35.	Drawings and other details are devoid of clash					
36.	Bar bending list is prepared as part of documentations					
37.	Drawing and specifications are written in conventional languages understood by all					
38.	Drawing documents are legible					
39.	Waste scenario planning					
40.	Specification of the use of framing techniques					
41.	Design for standard dimensions and units					
42.	Specification of collapsible partition for flexible use of space					

SECTION B2: DESIGNERS' COMPETENCIES FOR DRIVING LOW WASTE PROJECTS

2

ID	How important are the following designers' competencies in designing out waste?	Degree of importance				
		1	2	3	4	5
1.	Ability to produce designs that are devoid of error					
2.	Knowledge and ability to design for standard materials supply					
3.	Knowledge of construction methods					
4.	Knowledge of construction sequence					
5.	Ability to produce drawings in response to site shape and topography					
6.	Ability to produce coherent and comprehensive design information					
7.	Knowledge of materials durability that prevents early replacement of materials					
8.	Ability to consider different design options based on their likely waste output					
9.	Proficiency in detailing of design elements					
10.	Proficiency in materials specification					
11.	Ability to identify and integrate reusable elements into design					
12.	Proficiency in design tools and vocabularies					
13.	Proficiency in design flexibility and adaptability					
14.	Ability to coordinate dimension of building elements and components					
15.	Ability to effectively design for preassembled components					
16.	Knowledge and specification of secondary materials					
17.	Awareness and belief in design causes of waste					
18.	Ability to coordinate design from all trades					
19.	Inter-professional conflict resolution					
20.	Adequate knowledge of roles and responsibility of all team members					
21.	Effective communication of design information within/across trades					
22.	Ability to detect and prevent clash in design					
23.	Ability to collaborate with the project team					
24.	Awareness and use of standard detail and specification					
25.	Ability to ensure constructability of design					
26.	Awareness of materials quality and durability					
27.	Proficiency in waste scenario planning					

PART C: MATERIALS PROCUREMENT PRACTICES AND STRATEGIES FOR WASTE MINIMIZATION.

Please rate the extent to which each of the following factors could enhance construction and demolition waste minimization through materials procurement. Kindly rank the degree of importance of the factors on a scale of 1-5, where:

1 = Not important, 2 = Less important, 3 = Moderately important, 4 = Important, 5 = Most important.

ID	How important are the following procurement measures in minimizing C&D waste	Degree of importance				
		1	2	3	4	5
1.	Procurement route that minimizes packaging					

ID	How important are the following procurement measures in minimizing C&D waste	Degree of importance				
		1	2	3	4	5
2.	Supplier flexibility in providing small quantities of materials					
3.	Modification to products size and shapes in conformity with design					
4.	Collecting package materials back by suppliers					
5.	Collecting back recyclable materials					
6.	Provision for unused materials to be taken away from site (take back scheme)					
7.	Procurement and use of preassembled components					
8.	Purchase of pre-cut materials					
9.	Optimization of materials purchase to avoid over/under ordering					
10.	Purchase durable materials					
11.	Buying materials with reusable packaging					
12.	Effective materials take-off					
13.	Avoid frequent variation order					
14.	Order material with high content of recycled product					
15.	Procure recycled aggregate instead of virgin aggregates					
16.	Protection of materials during loading and unloading					
17.	Good site access for delivery vehicle					
18.	Avoid loosely supplied materials					
19.	Vendors that supply quality and recycled materials					
20.	Waste minimization clause in procurement contract					
21.	Design freeze before materials procurement					
22.	Discussion of waste minimization methods with materials suppliers					
23.	Purchase of secondary materials					
24.	Materials purchase in adherence to materials specification					
25.	Use of correct materials to prevent replacement/rework					
26.	Efficient materials delivery schedule					
27.	Planning for good delivery schedule onsite					
28.	Use of Just-In-Time (JIT) procurement system					
29.	Reduced excess order to avoid breakage					
30.	Improved materials handling system					

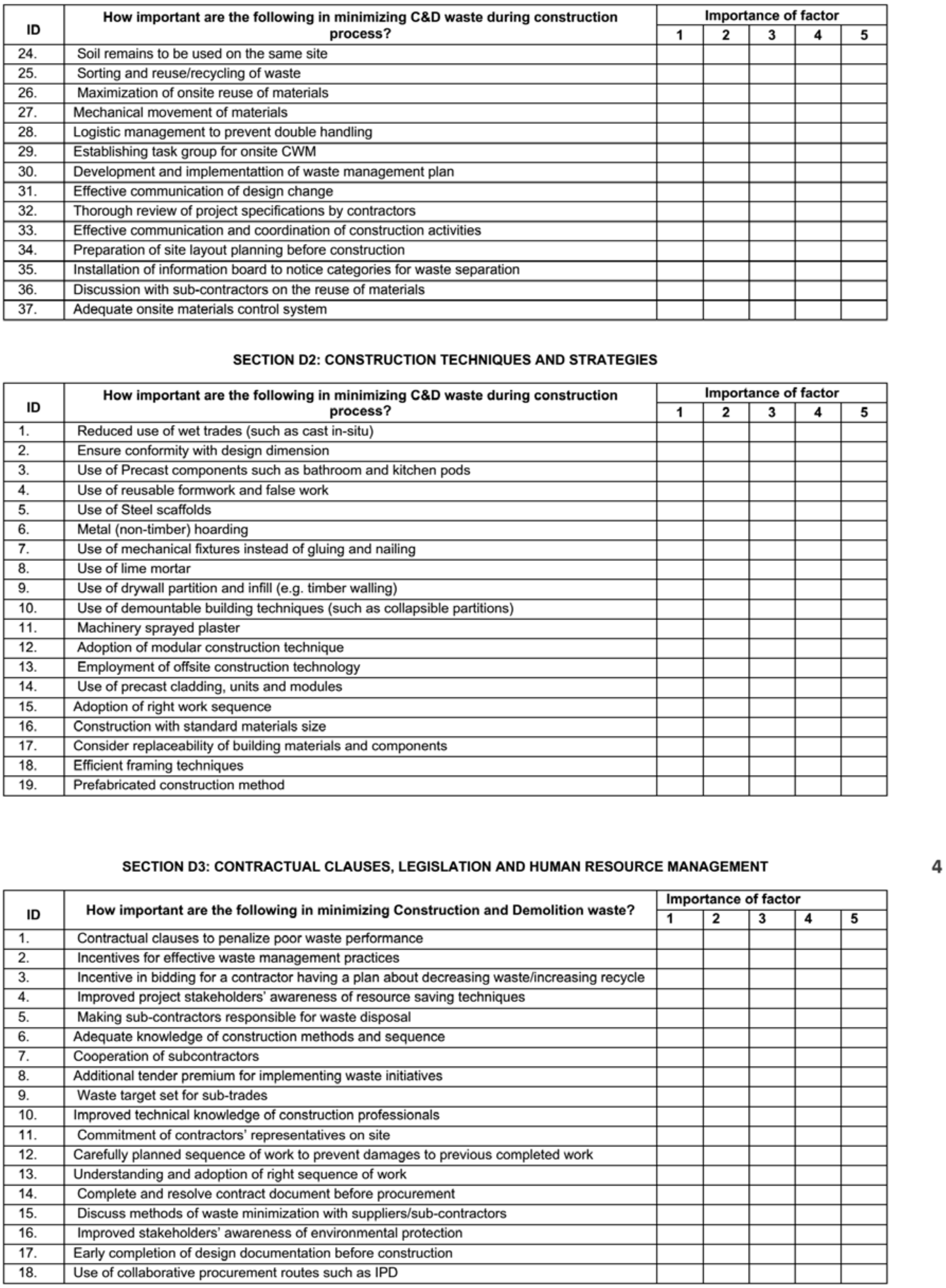
PART D: CONSTRUCTION PRACTICES AND STRATEGIES FOR WASTE MINIMIZATION

Please rate the level of importance of the following strategies/measures for reducing construction and demolition waste. Kindly rank the degree of importance of the factors on a scale of 1-5, where:

1 = Not important, 2 = Less important, 3 = Moderately important, 4 = Important, 5 = Most important.

SECTION D1: CONSTRUCTION SITE MANAGEMENT PRACTICES

ID	How important are the following in minimizing C&D waste during construction process?	Importance of factor				
		1	2	3	4	5
1.	Detect the construction activities that can admit reusable materials from the construction					
2.	Recycling target to be set for every project					
3.	Use of safe materials storage facilities					
4.	Onsite movement of materials through mechanical means					
5.	Prevention of double handling of materials					
6.	Use of reclaimed materials					
7.	Construction with standard materials					
8.	On-site materials compactors					
9.	Reuse of off-cuts materials (such as wood)					
10.	Use of demolition materials and excavation for landscape					
11.	Prefabrication space in the work site for correct management of C&D waste					
12.	Follow the project drawings/designs					
13.	Periodic checks on the use of C&D waste containers					
14.	Preventing waste mixture with soil					
15.	Providing bins for collecting wastes for each sub-contractor					
16.	Dedicated space for sorting of waste					
17.	Ensure fewer design changes during construction					
18.	Setting up temporary bins at each building zone					
19.	Adequate site access for materials delivery and movement					
20.	Waste auditing to monitor and record environmental performance on-site					
21.	Central areas for cutting and storage					
22.	Provision of waste skips for specific materials (waste segregation)					
23.	Reuse material scraps from cutting stock-length material into shorter pieces					



ID	How important are the following in minimizing C&D waste during construction process?	Importance of factor				
		1	2	3	4	5
24.	Soil remains to be used on the same site					
25.	Sorting and reuse/recycling of waste					
26.	Maximization of onsite reuse of materials					
27.	Mechanical movement of materials					
28.	Logistic management to prevent double handling					
29.	Establishing task group for onsite CWM					
30.	Development and implementattion of waste management plan					
31.	Effective communication of design change					
32.	Thorough review of project specifications by contractors					
33.	Effective communication and coordination of construction activities					
34.	Preparation of site layout planning before construction					
35.	Installation of information board to notice categories for waste separation					
36.	Discussion with sub-contractors on the reuse of materials					
37.	Adequate onsite materials control system					

SECTION D2: CONSTRUCTION TECHNIQUES AND STRATEGIES

ID	How important are the following in minimizing C&D waste during construction process?	Importance of factor				
		1	2	3	4	5
1.	Reduced use of wet trades (such as cast in-situ)					
2.	Ensure conformity with design dimension					
3.	Use of Precast components such as bathroom and kitchen pods					
4.	Use of reusable formwork and false work					
5.	Use of Steel scaffolds					
6.	Metal (non-timber) hoarding					
7.	Use of mechanical fixtures instead of gluing and nailing					
8.	Use of lime mortar					
9.	Use of drywall partition and infill (e.g. timber walling)					
10.	Use of demountable building techniques (such as collapsible partitions)					
11.	Machinery sprayed plaster					
12.	Adoption of modular construction technique					
13.	Employment of offsite construction technology					
14.	Use of precast cladding, units and modules					
15.	Adoption of right work sequence					
16.	Construction with standard materials size					
17.	Consider replaceability of building materials and components					
18.	Efficient framing techniques					
19.	Prefabricated construction method					

SECTION D3: CONTRACTUAL CLAUSES, LEGISLATION AND HUMAN RESOURCE MANAGEMENT

ID	How important are the following in minimizing Construction and Demolition waste?	Importance of factor				
		1	2	3	4	5
1.	Contractual clauses to penalize poor waste performance					
2.	Incentives for effective waste management practices					
3.	Incentive in bidding for a contractor having a plan about decreasing waste/increasing recycle					
4.	Improved project stakeholders' awareness of resource saving techniques					
5.	Making sub-contractors responsible for waste disposal					
6.	Adequate knowledge of construction methods and sequence					
7.	Cooperation of subcontractors					
8.	Additional tender premium for implementing waste initiatives					
9.	Waste target set for sub-trades					
10.	Improved technical knowledge of construction professionals					
11.	Commitment of contractors' representatives on site					
12.	Carefully planned sequence of work to prevent damages to previous completed work					
13.	Understanding and adoption of right sequence of work					
14.	Complete and resolve contract document before procurement					
15.	Discuss methods of waste minimization with suppliers/sub-contractors					
16.	Improved stakeholders' awareness of environmental protection					
17.	Early completion of design documentation before construction					
18.	Use of collaborative procurement routes such as IPD					

ID	How important are the following in minimizing Construction and Demolition waste?	Importance of factor				
		1	2	3	4	5
19.	Use of common collaborative platform for information sharing					
20.	Supply chain alliance with materials suppliers					
21.	Clear definition and communication of waste management strategies					
22.	Supervising waste management by a residential officer					
23.	Little or no overtime for construction workers					
24.	Employing workers/task group responsible for on-site waste management					
25.	Waste management and materials handling vocational trainings for operatives					
26.	Dedicated site team or specialist sub-contract package for on-site waste management					
27.	Educate clients about measures to reduce waste levels					
28.	Government to develop market structure for recycled materials					
29.	Reducing landfill tax for separated wastes and raising fees for mixed wastes					
30.	Tax break for waste treatment equipment and secondary materials manufacturers/suppliers					
31.	Increased stringency of waste management regulations					
32.	Integrate CWM into the assessment of construction contractor					
33.	Award of more points to waste management in sustainable design appraisal					

PART E: GENERAL QUESTIONS

1.	To what extent do your company considers waste minimization in projects?	Not at all	Not often	Not sure	Quite often	Very often

For each of the following questions, kindly rank their degree of importance on a scale of 1-5, where: **1 = Not important, 2 = Less important, 3 = Moderately important, 4 = Important, 5 = Most important.**

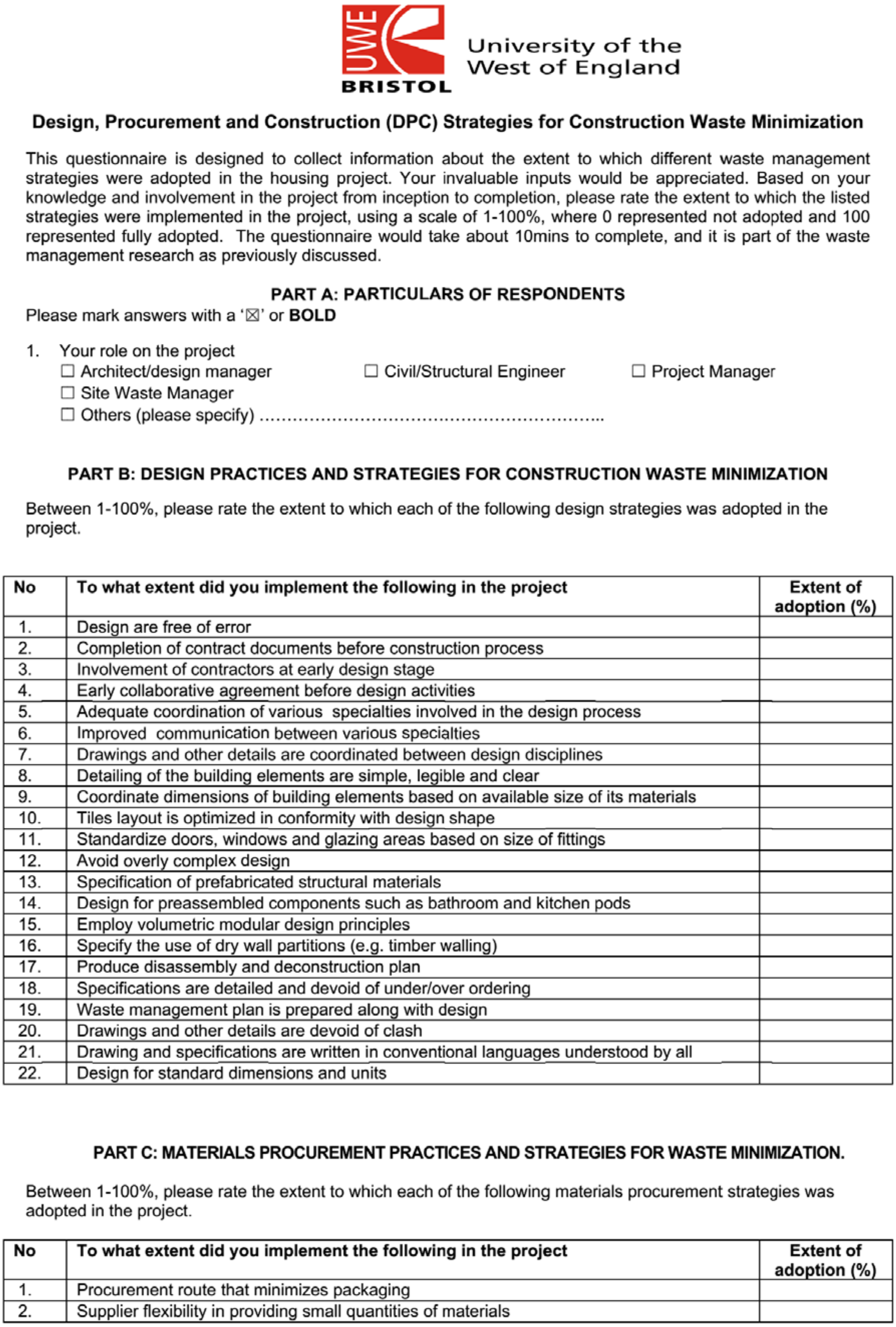
ID	How important are the following in reducing waste generated by construction activities?	Degree of importance				
		1	2	3	4	5
2.	Consideration and prevention of waste through design activities (designing out waste)					
3.	Competencies of designers in designing out waste					
4.	Waste minimization through measures taken in materials procurement					
5.	Commitment and dedication of materials suppliers to construction waste reduction					
6.	Contractual documents that stipulates waste minimization as a key goal					
7.	Management of building operatives and other workers onsite					
8.	Government legislative and fiscal measures that target waste prevention					
9.	Construction techniques					
10.	Site management practices					
11.	Consideration of end of life (deconstruction) right from design stage					
12.	Consideration and prevention of waste through design activities (designing out waste)					

PART F: ADDITIONAL INFORMATION

If you have further comments or suggestions about design, procurement and construction strategies for waste minimization, please write it in the box below.

You have reached the end of the survey. Many thanks for your time and cooperation; it is highly appreciated.

Appendix 2: Sample of the Questionnaire used for System Dynamic Modelling (SDM)



BRISTOL University of the West of England

Design, Procurement and Construction (DPC) Strategies for Construction Waste Minimization

This questionnaire is designed to collect information about the extent to which different waste management strategies were adopted in the housing project. Your invaluable inputs would be appreciated. Based on your knowledge and involvement in the project from inception to completion, please rate the extent to which the listed strategies were implemented in the project, using a scale of 1-100%, where 0 represented not adopted and 100 represented fully adopted. The questionnaire would take about 10mins to complete, and it is part of the waste management research as previously discussed.

PART A: PARTICULARS OF RESPONDENTS

Please mark answers with a '☒' or **BOLD**

1. Your role on the project
   - ☐ Architect/design manager ☐ Civil/Structural Engineer ☐ Project Manager
   - ☐ Site Waste Manager
   - ☐ Others (please specify) ……………………………………………………..

PART B: DESIGN PRACTICES AND STRATEGIES FOR CONSTRUCTION WASTE MINIMIZATION

Between 1-100%, please rate the extent to which each of the following design strategies was adopted in the project.

No	**To what extent did you implement the following in the project**	**Extent of adoption (%)**
1.	Design are free of error	
2.	Completion of contract documents before construction process	
3.	Involvement of contractors at early design stage	
4.	Early collaborative agreement before design activities	
5.	Adequate coordination of various specialties involved in the design process	
6.	Improved communication between various specialties	
7.	Drawings and other details are coordinated between design disciplines	
8.	Detailing of the building elements are simple, legible and clear	
9.	Coordinate dimensions of building elements based on available size of its materials	
10.	Tiles layout is optimized in conformity with design shape	
11.	Standardize doors, windows and glazing areas based on size of fittings	
12.	Avoid overly complex design	
13.	Specification of prefabricated structural materials	
14.	Design for preassembled components such as bathroom and kitchen pods	
15.	Employ volumetric modular design principles	
16.	Specify the use of dry wall partitions (e.g. timber walling)	
17.	Produce disassembly and deconstruction plan	
18.	Specifications are detailed and devoid of under/over ordering	
19.	Waste management plan is prepared along with design	
20.	Drawings and other details are devoid of clash	
21.	Drawing and specifications are written in conventional languages understood by all	
22.	Design for standard dimensions and units	

PART C: MATERIALS PROCUREMENT PRACTICES AND STRATEGIES FOR WASTE MINIMIZATION.

Between 1-100%, please rate the extent to which each of the following materials procurement strategies was adopted in the project.

No	**To what extent did you implement the following in the project**	**Extent of adoption (%)**
1.	Procurement route that minimizes packaging	
2.	Supplier flexibility in providing small quantities of materials	

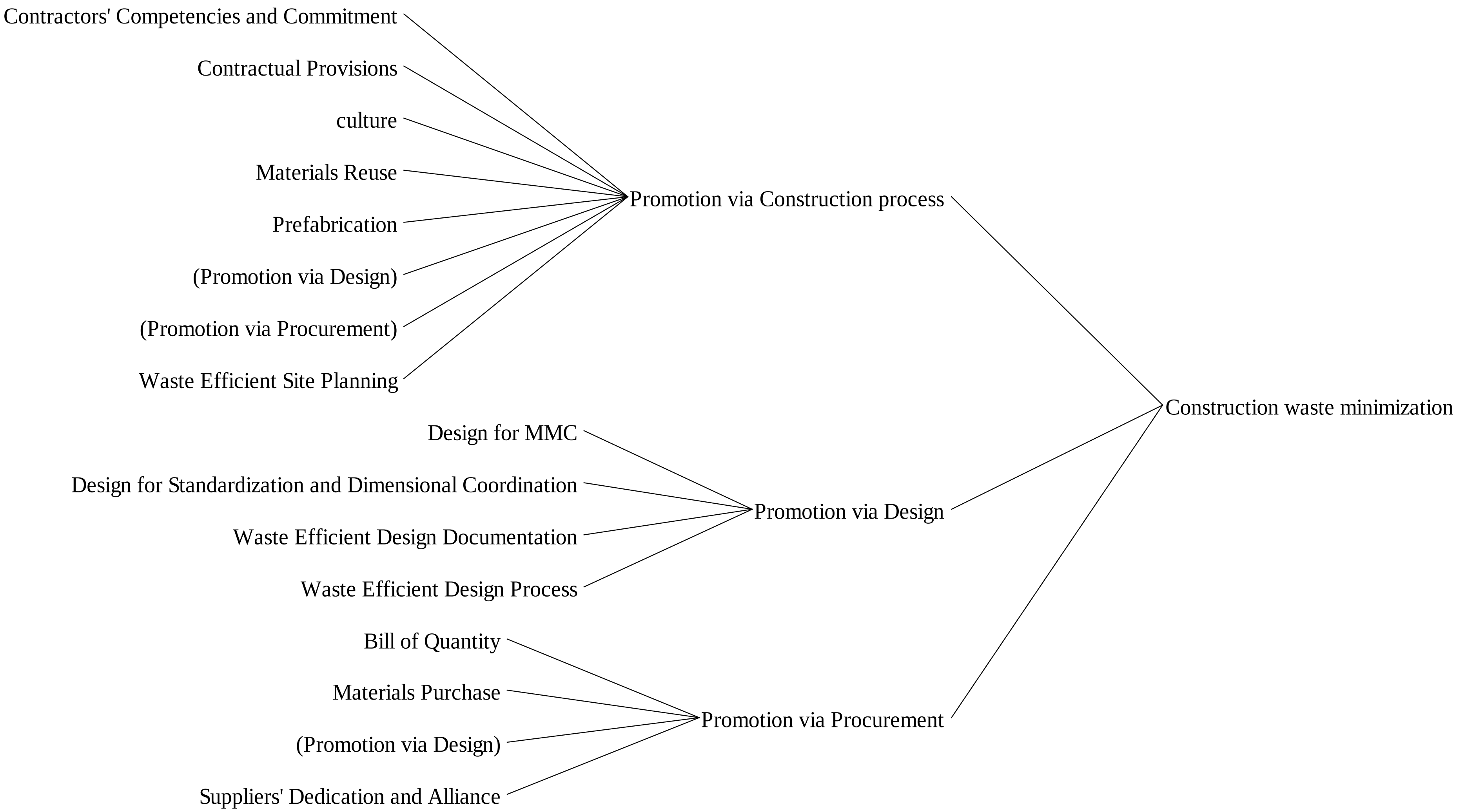
3.	Modification to products size and shapes in conformity with design	
4.	Collecting package materials back by suppliers	
5.	Provision for unused materials to be taken away from site (take back scheme)	
6.	Procurement and use of preassembled components	
7.	Purchase of pre-cut materials	
8.	Optimization of materials purchase to avoid over/under ordering	
9.	Purchase durable materials	
10.	Buying materials with reusable packaging	
11.	Effective materials take-off	
12.	Avoid frequent variation order	
13.	Order material with high content of recycled product	
14.	Procure recycled aggregate instead of virgin aggregates	
15.	Use of Just-In-Time (JIT) procurement system	

PART D: CONSTRUCTION PRACTICES AND STRATEGIES FOR WASTE MINIMIZATION

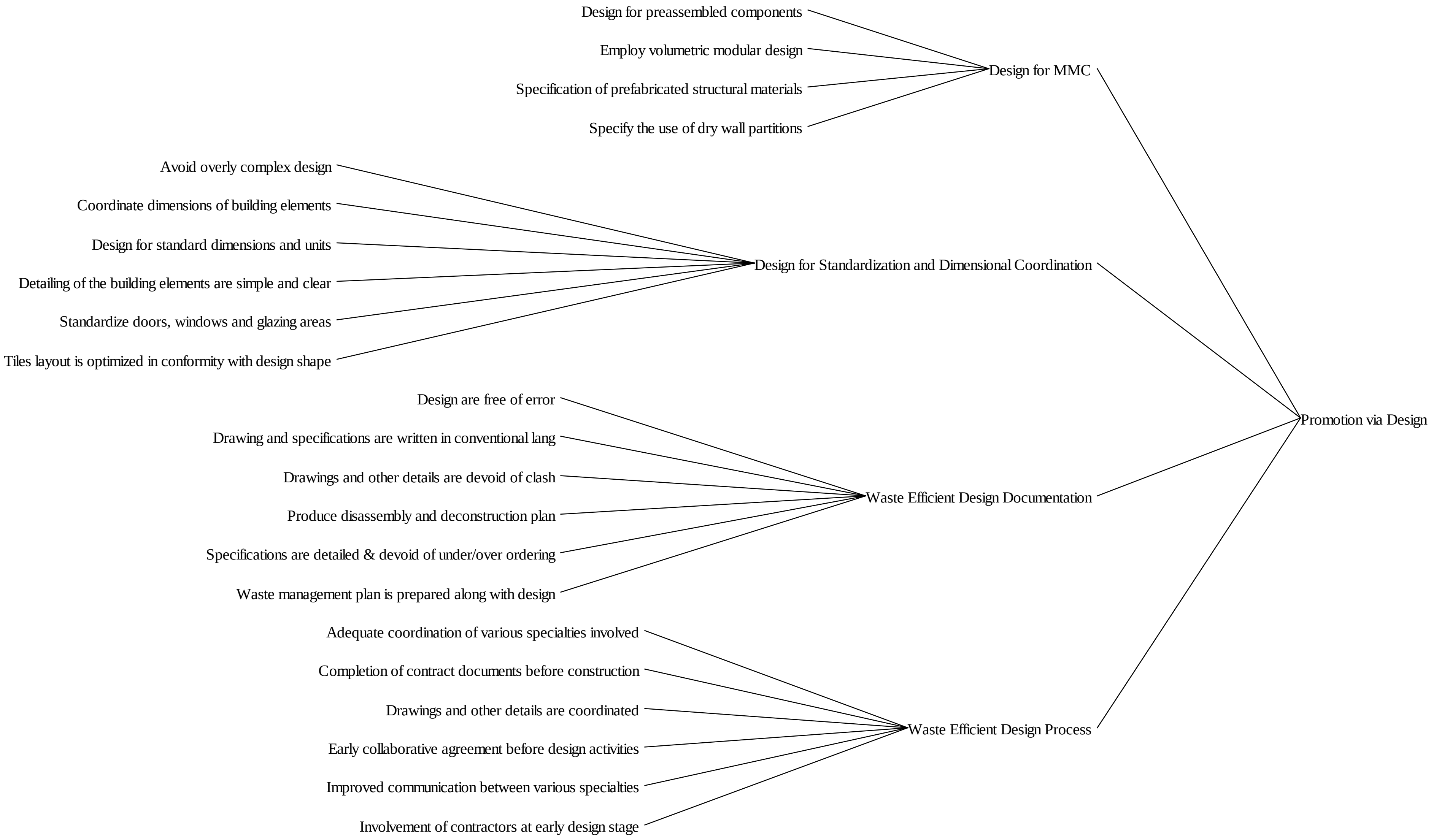
Between 1-100%, please rate the extent to which each of the following construction strategies was adopted in the project.

No	To what extent did you implement the following in the project	Extent of adoption (%)
1.	Detect the construction activities that can admit reusable materials from the construction	
2.	Use of reclaimed materials	
3.	Construction with standard materials	
4.	Reuse of off-cuts materials (such as wood)	
5.	Use of demolition materials and excavation for landscape	
6.	Periodic checks on the use of C&D waste containers	
7.	Ensure fewer design changes during construction	
8.	Reuse material scraps from cutting stock-length material into shorter pieces	
9.	Soil remains to be used on the same site	
10.	Maximization of onsite reuse of materials	
11.	Establishing task group for onsite CWM	
12.	Development and implementation of waste management plan	
13.	Effective communication of design change	
14.	Thorough review of project specifications by contractors	
15.	Preparation of site layout planning before construction	
16.	Discussion with sub-contractors on the reuse of materials	
17.	Reduced use of wet trades (such as cast in-situ)	
18.	Use of Precast components such as bathroom and kitchen pods	
19.	Use of mechanical fixtures instead of gluing and nailing	
20.	Use of lime mortar	
21.	Use of demountable building techniques (such as collapsible partitions)	
22.	Adoption of modular construction technique	
23.	Employment of offsite construction technology	
24.	Use of precast cladding, units and modules	
25.	Adoption of right work sequence	
26.	Efficient framing techniques	
27.	Contractual clauses to penalize poor waste performance	
28.	Making sub-contractors responsible for waste disposal	
29.	Adequate knowledge of construction methods and sequence	
30.	Waste target set for sub-trades	
31.	Carefully planned sequence of work to prevent damages to previous completed work	
32.	Complete and resolve contract document before procurement	
33.	Use of collaborative procurement routes such as IPD	
34.	Use of common collaborative platform for information sharing	
35.	Supply chain alliance with materials suppliers	
36.	Clear definition and communication of waste management strategies	

Thank you for your invaluable input!

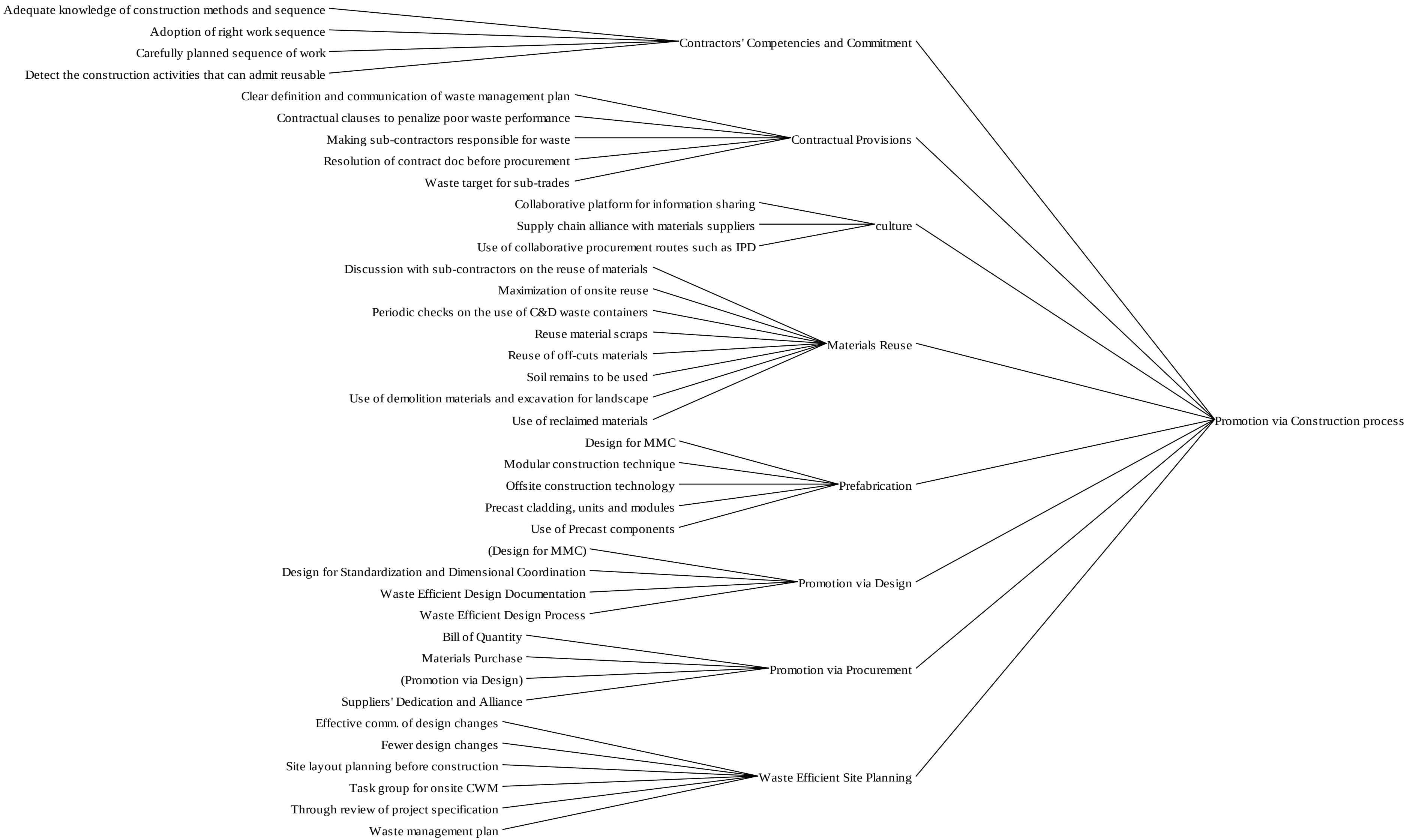


Appendix 3: Cause tree diagram for waste-efficient construction projects



Appendix 4: Cause tree for waste-efficient design

Appendix 5: Cause tree for waste-efficient materials procurement processes



Appendix 6: Cause tree for waste-efficient construction processes