BUILDING INFORMATION MODELLING (BIM) AIDED WASTE MINIMISATION FRAMEWORK

by

ZHEN LIU

MSc (Eng), BEng

A Doctoral Thesis submitted in partial fulfilment of the requirements

for the award of Doctor of Philosophy of Loughborough University

March, 2014

DEDICATION

This thesis is dedicated to my family: my wife (Eva Y. F. Wang), my parents in law (Ms. Sun, Y. J. & Mr Wang, Y. F.) who both passed away during my 2nd year (2011) of the research, my mother (Ms. Bao, Y. H.) and my father (Mr. Liu, H. S.), and my posterity.

ACKNOWLEDGEMENTS

Firstly, I am greatful to Professor Baldwin, Andrew N., former dean of School of Civil and Building Engineering, Loughborough University, who was my inintial supervior, travelled to Hong Kong in year 2009 to conduct the 2nd interviews of Ph.D studentship selection with and put his faith in me. Without him, this thesis could be written by somebody else.

Secondly, I would like to express my profound gratitude to my superviors: Dr. Mohamed Osmani and Dr. Peter Demian, who provided guidance, encouragement and support during the research and preparation of the thesis. The constructional advices, critical debates, and provocative comments from Dr. Mohamed Osmani in particular provided valuabe views that were invaluable to the both of research and the thesis.

Thridly, my appreciation is send to Professor Price, A. D. F. and Dr. Tuuli, M. M., who conducted my 1st year, 2nd year and 3rd year viva providing helpful feedbacks. A number of researchers in the School of Civil and Building Engineering gave their time and effort for the research discussion that were appreciated.

Fourthly, the research involved questionnaire survey and interviews for data collection with participating companies which act leading role in UK's building design industry. A number of senior architects (e.g. partners and associates) of those companies are acknowledged for generously giving their time and providing the most valuable information that was vast benefit to the data collection.

Fifthly, the research and thesis would not be made possible without the full studentship of Ph.D study over three years, which was awarded by School of Civil and Building Engineering, Loughborough University.

Finally, I would like to thank my wonderful wife Eva, my parents and parents in law, for their love, sacrifice, understanding and support, without which the research and thesis would have been virtually and really unachievable by me in the first place.

ABSTRACT

Building design can have a major impact on sustainability through material efficiency and construction waste minimisation (CWM). The construction industry consumes over 420 million tonnes of material resources every year and generates 120 million tonnes of waste containing approximately 13 million tonnes of unused materials. The current and on-going field of CWM research is focused on separate project stages with an overwhelming endeavour to manage on-site waste. Although design stages are vital to achieve progress towards CWM, currently, there are insufficient tools for CWM. In recent years, Building Information Modelling (BIM) has been adopted to improve sustainable building design, such as energy efficiency and carbon reduction. Very little has been achieved in this field of research to evaluate the use of BIM to aid CWM during design. However, recent literature emphasises a need to carry out further research in this context.

This research aims to investigate the use of BIM as a platform to help with CWM during design stages by developing and validating a BIM-aided CWM (BaW) Framework. A mixed research method, known as triangulation, was adopted as the research design method. Research data was collected through a set of data collection methods, i.e. self-administered postal questionnaire (N=100 distributed, n=50 completed), and semi-structured follow-up interviews (n=11) with architects from the top 100 UK architectural companies. Descriptive statistics and constant comparative methods were used for data analysis. The BaW Framework was developed based on the findings of literature review, questionnaire survey and interviews. The BaW Framework validation process included a validation questionnaire (N=6) and validation interviews (N=6) with architects.

Key research findings revealed that: BIM has the potential to aid CWM during design; Concept and Design Development stages have major potential in helping waste reduction through BIM; BIM-enhanced practices (i.e. clash detection, detailing, visualisation and simulation, and improved communication and collaboration) have impacts on waste reduction; BIM has the most potential to address waste causes (e.g. ineffective coordination and communication, and design changes); and the BaW Framework has the potential to enable improvements towards waste minimisation throughout all design stages. Participating architects recommended that the adoption of the BaW Framework could enrich both CWM and BIM practices, and most importantly, would enhance waste reduction performance in design. The content should be suitable for project stakeholders, architects in particular, when dealing with construction waste and BIM during design.

Key words: Construction waste minimisation, Construction waste causes during design, Building Information Modelling (BIM), Building design, Sustainable building design, Sustainability.

.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

3D	Three dimensional
4D	3D + time sequencing
5D	4D + cost
AEC	Architectural, engineering and construction
API	Application programming interface
AR	Augmented reality
BaW	Building information modelling aided construction waste minimisation
BIM	Building information modelling
CAD	Computer-aided design
COBie	Construction Operations Building Information Exchange for facility management
CW	Construction waste
CWM	Construction waste minimisation
FM	Facility management
gbXML	The Green Building XML (Extensible Markup Language) scheme
GIS	Geographical information system
GSL	Government Soft Landings
HVAC	Heating, ventilation, air-conditioning system
IFC	Industry Foundation Classes
IPD	Integrated project delivery
LOD	Level of detail
NBS	National Building Specification
RFID	Radio frequency identification

RIBA	Royal Institute of British Architects
SBD	Sustainable building design
SCM	Supply chain management
VR	Virtual reality
WM	Waste minimisation

CHAPTER ONE

Introduction

1.1. Research background

Sustainable development continues to gain much attention throughout the World. It is widely accepted as being a "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*" (Brundtland, 1987). The construction industry has a significant direct and indirect impact on resources (e.g. materials, energy and water), built environment of infrastructure and buildings for economic development (Bourdeau, 1999). Sustainable construction is expected to average a global annual growth of 22.8% from 2012 to 2017 (HM Government, 2013a). Currently, the UK construction industry consists of more than 300,000 companies (UKCG, 2009), employs over three million people (ONS, 2011), contributes nearly 7% to the total UK GDP (Gross Domestic Product) (CBI, 2013), and forecasts an annual growth of 6% by 2021 (BIS, 2012). On the other hand, existing UK buildings account for 45% of all energy consumed and an additional 5% to construct new buildings (DTI, 2007). Construction and demolition sections also generate 32% (Defra, 2004) and 44% (Defra, 2013c) of all waste generated within UK and England respectively. Thus, the construction industry has been targeted by UK government as a priority sector for reduction of carbon emission, energy consumption, and material resources usage. The latter increased from 420 million tonnes in 2003 (Environment Agency, 2003) to 470 million tonnes in 2013 (Defra, 2013c).

Construction waste is any material for construction considered to be redundant caused by various design and construction activities throughout the project lifecycle. Currently, the UK construction industry produces 120 million tonnes of waste (UK Green Building Council, 2013), of which 13 million tonnes of materials that have been delivered to the site but have never been used (Environment Agency, 2003). Owing to a continuous increase of construction waste entering landfill, the Strategy for Sustainable Construction 2008 (HM Government, 2008) identified construction waste as a priority waste stream and set a waste reduction target halving construction, demolition and excavation waste to landfill by 2012 compare to 2008, as such the Strategic Forum for Construction has been commissioned to monitor the waste reduction target. Consequently, halving waste reduction has been achieved except for increased excavation waste (Defra, 2013c, WRAP, 2013b). Defra (2013c) called for more waste prevention actions to reduce the arising waste destined for landfill. Moreover, reducing construction waste has been driven by economic and environmental consideration due to the cost of waste, which is about 15 times that of disposal (NSCC, 2007). Thus, the construction industry has been exploring and developing effective and efficient approaches to minimise waste generation.

In the context of this research, construction waste minimisation (CWM) is a process for preventing, eliminating or reducing waste at its source during design (Crittenden and Kolaczkowski, 1995; Riemer and Kristoffersen, 1999; Tam *et al*., 2002; Osmani, 2013). Current CWM practices and research studies were mainly based on: designing out waste (Keys *et al*., 2000; WRAP, 2009; Osmani, 2013); on-site waste auditing and waste control (Formoso *et al*., 1999; Poon *et al*., 2001; Shen *et al*., 2004). Furthermore, a number of studies have attempted to evaluate construction waste causes in relation to project lifecycle stages (Gavilan and Bernold, 1994; Bossink and Brouwers, 1996; Ekanayake and Ofori, 2000; Kulatunaga *et al*., 2006; Osmani, 2013). However, little has been published on the development of effective construction waste minimisation techniques and tools during design stages.

Building Information Modelling (BIM) is an emerging modelling philosophy, which has recently being gradually adopted across the Architectural, Engineering and Construction (AEC), and Facility Management (FM) industry (Succar, 2009). BIM has been applied to simulate the planning, design, construction and operation of a facility through developing and using computer-generated BIM models. This assisted architects, engineers and contractors to visualise and simulate what is being built in a virtual environment, enabling them to identify potential problems of design, construction or operation (Azhar *et al*., 2008). Furthermore, BIM as a real-time interactive platform for collaborative working has been used for multidisciplinary coordination and communication to manage a large amount of data for complex projects in the AEC industry (Baldwin *et al*., 2009a; Singh *et al*., 2011).

At present, the UK was recognised as a global leader in the development of BIM technology and its processes (CBI, 2013). The recent UK Construction Strategy 2050 (HM Government, 2013a, page 60) believed that "*BIM allows companies to make more intelligent use of data, which enables waste to be stripped out of the construction process*". Attempts have been made in the last few years to use BIM to improve construction project performance (Azhar *et al*., 2008) and sustainable building design (SBD), namely energy efficiency and carbon reduction (Wong and Fan, 2013). Additionally, a number of studies recommended the use of BIM to assist construction waste management (Ahankoob *et al*., 2012; O'Reilly, 2012; Porwal and Hewage, 2012; Cheng and Ma, 2013; Hewage and Porwal, 2012; Porwal, 2013; WRAP, 2013a).

1.2. Research justification

Studies in the field of construction waste minimisation (section 3.2.5) indicated that the majority of current CWM practices were mainly focused on on-site construction stage and less effort was investigated to reduce waste during design. Construction waste forecasting tools, such as design-based waste assessment (Ekanayake and Ofori, 2004) and online waste forecasting (WRAP, 2011), have been used to assist construction waste reduction during design stages. However, these tools aimed to capture live data of waste and provide improvements to resource efficiency in terms of waste minimisation. None of them have taken CWM decision making into consideration during design stages and early design stages in particular. Design stages are critical in terms of a significant portion of construction waste caused by problems which occur in the design stages (Bossink and Brouwers, 1996; Faniran and Caban, 1998; Rounce, 1998; Ekanayake and Ofori, 2000; Keys *et al.*, 2000; Poon, 2007; Osmani *et al.*, 2008), and have greater opportunities than later stages to reduce on-site waste generation (WRAP, 2007), since design decisions have the most influence on the waste generation (Innes, 2004).

BIM is currently being implemented to achieve various performance targets throughout all project lifecycle stages (Hjelseth, 2010; Scherer and Schapke, 2011; Jiao et al., 2013b). These include improving and enhancing simulation and analysis, coordination and communication for collaborative working, lifecycle information assessment and management, and sustainable design across project lifecycle stages. The Royal Institute of British Architects (RIBA) recently issued a BIM Overlay to the RIBA Outline Plan of Work stages in conjunction with the RIBA Green Overlay (Sinclair, 2012), which provides guidance on design activities required at each building design stage for design and management of construction projects within the BIM environment. However, recent studies argued that construction waste minimisation could be supported and enhanced through the use of BIM, particularly through the Design stage (O'Reilly, 2012; Hamil, 2013; WRAP, 2013a).

An increasing body of literature suggested the importance to investigate the impact of adopting information communication related techniques and tools, such as BIM, to assist minimising construction waste during building design and construction (Sacks *et al.*, 2010; Ningappa, 2011; Whyte, 2012). A number of studies have attempted to investigate the use of BIM to address construction waste, such as waste reduction by enhanced coordination (Ahankoob *et al.*, 2012), waste reduction through informed design decision making (O'Reilly, 2012), structural reinforcement of rebar reduction (Porwal and Hewage, 2012), waste related resource efficiency (WRAP, 2013a), demolition waste management (Cheng and Ma, 2013), on-site waste management (Hewage and Porwal, 2012), and waste management (Porwal, 2013). Moreover, BIM is believed to have the potential to reduce construction waste during design and construction through the building design and construction industry (Hamil, 2013; HM Government, 2013a).

Additionally, the Waste Resources Action Programme (WRAP, 2013a) developed guidelines in achieving resource efficiency through the implementation of BIM, attempting to align it with lifecycle stages of building projects, from concept to handover. However, these guidelines focused on energy efficiency and carbon reduction, and gave little consideration to the context of construction waste minimisation.

Most current CWM practices (see section 2.2.5) focused on the Construction stage for handling on-site waste, rather than the Design stages which hold the greatest waste reduction opportunities. The current BIM practices (see section 2.3.3) are implemented across project stages and towards sustainability. However, there were two studies that have developed BIM-aided tools for waste management in specific building project lifecycle stages, such as reducing bar material usage in Technical Design and Production Information stages (Porwal and Hewage, 2012), and managing waste during Demolition stage (Cheng and Ma, 2013); and one study explored the BIM potential to help architects with CWM during design without providing any method for the use of BIM to drive out waste (O'Reilly, 2012). Hence, there is a need for a comprehensive investigation of BIM as a platform to aid CWM, and development and validation of a BIM-aided CWM Framework for architect to use throughout design stages.

Moreover, although waste cost and materials waste could be reduced by implementing BIM during design is widely accepted (AIA, 2007; Krygiel and Nies, 2008; Hardin, 2009; Smith and Tardif, 2009; Nisbet and Dinesen, 2010; Hamil, 2013; Porwal, 2013; Gurevich and Sacks, 2014), there is a lack of comprehensive BIM decision support tool to support architect to minimise waste throughout building design stages. Architects should consider environmental performance criteria (e.g. water, energy and waste) under an effective platform, such as BIM, (Krygiel and Nies, 2008; McGraw-Hill, 2010). Furthermore, UK Construction Strategy 2050 (HM Government, 2013a) and Hamil (2013), who is a BIM expert and director of design and innovation at RIBA Enterprises, believed that BIM potentially could help with waste reduction during building design.

Therefore, there is a consensus in the literature that BIM could effectively drive CWM during building design stages. However, findings of existing studies in the field are mainly related to its potential in specific design stages, such as Technical Design. As such, no efforts have made to develop integrated BIM-aided CWM decision making tools and methodologies for architects to use throughout all building design stages, which is this research focused on.

1.3. Research aim and objectives

The aim of this research is to investigate the use of BIM as a platform to aid construction waste minimisation, and to develop and validate a BIM-aided waste minimisation (BaW) Framework in design. In order to achieve this, the following six objectives are proposed:

1. Explore construction waste minimisation drivers and examine construction waste causes.
2. Examine and evaluate current construction waste minimisation practices including approaches, techniques and tools.
3. Examine and evaluate current BIM practices including approaches, techniques and tools.
4. Explore the potential use of BIM as a platform to aid construction waste minimisation during design.
5. Assess the relationship between construction waste causes and BIM practices; and investigate the potential use of BIM to assist architects in reducing waste throughout the design stages.
6. Develop and validate a BIM-aided waste minimisation Framework to reduce construction waste during design.

1.4. Research methodology overview

As discussed in Chapter 3, the research adopted a triangulation approach to achieve the research aim and objectives and contains five phases as shown in Figure 1.1. Figure 1.2 illustrates the outlined process of adopted research methods for data collection and data analysis, along with the outcomes of each method.

1.4.1 Literature review

As discussed in Chapter 2, a comprehensive literature review aimed to explore construction waste minimisation drivers and examine waste causes. It also examined both current CWM and BIM practices (including approaches, techniques and tools). The review provided a solid foundation for the subsequent data collection stages and the formulation of the BIM-aided waste minimisation Framework.

The findings obtained from the literature review helped to identify the relationship between the use of BIM and construction waste minimisation, and establish a clear direction for the data collection requirements. The literature revealed that there is no research study that has explored the potential use of BIM as a vehicle to aid improvements to waste minimisation during building design.

1.4.2 Questionnaire

Based upon the literature review findings, the quantitative questionnaire survey was designed to examine current BIM practices in building design and explore the potential use of BIM as a potential platform to aid construction waste minimisation during design. The questionnaire contained seven sections: background to the survey, BIM in building design, BIM as a potential platform to minimise waste during design, BIM barriers in building design, BIM incentives in building design, further comments and further research (see Appendix 2.1.2). Quantitative data was collected through the use of a self-administered postal survey. Based on the adopted multistage cluster sampling method (see section 3.5.2.1), questionnaires (N=100) were distributed to selected architects (i.e. partners and associates) from the Top 100 UK Architects listed on the building magazine, who had knowledge and experience of sustainability, and also involvement in management. By the end of the seven week questionnaire period, the questionnaire survey achieved a 50% response rate. The detailed questionnaire survey process is discussed in Chapter 3 (see section 3.5.2.1), and the results are reported in Chapter 4.

1.4.3 Interviews

The qualitative face-to-face and semi-structured interviews were employed to further investigate issues related to the potential use of BIM for CWM that emerged from the literature review and the questionnaire survey. The interview template included five sections: background information, current CWM in building design, current use of BIM in building design (including sustainable design), BIM to address construction waste causes, and further thoughts of interviewees (see Appendix 2.2). Interviews were conducted with 11 questionnaire responding architects who have experience in the use of BIM for sustainable building design. The details of the interview process are discussed in Chapter 3 (section 3.5.2.2), with the results being presented in Chapter 5.

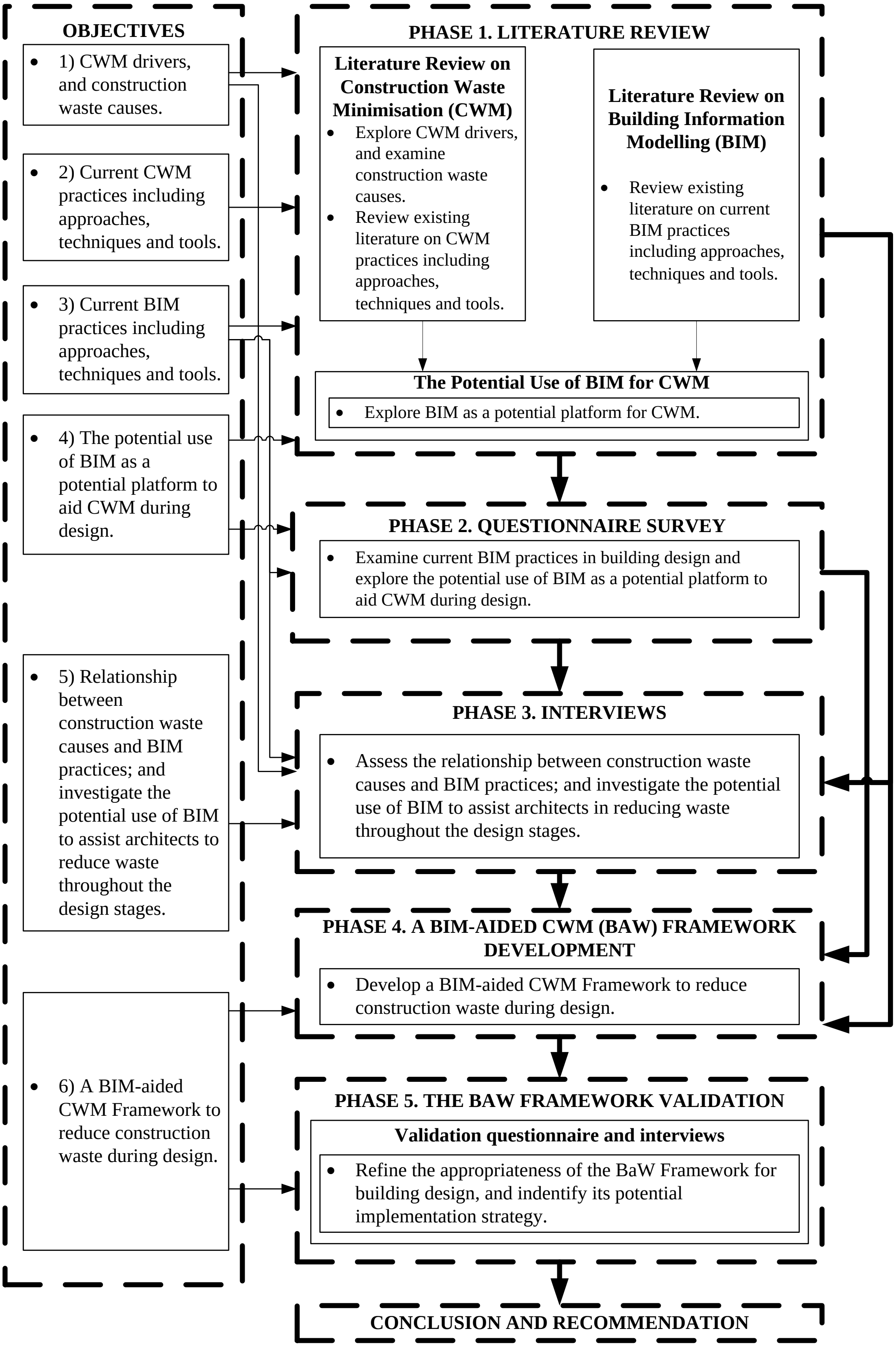
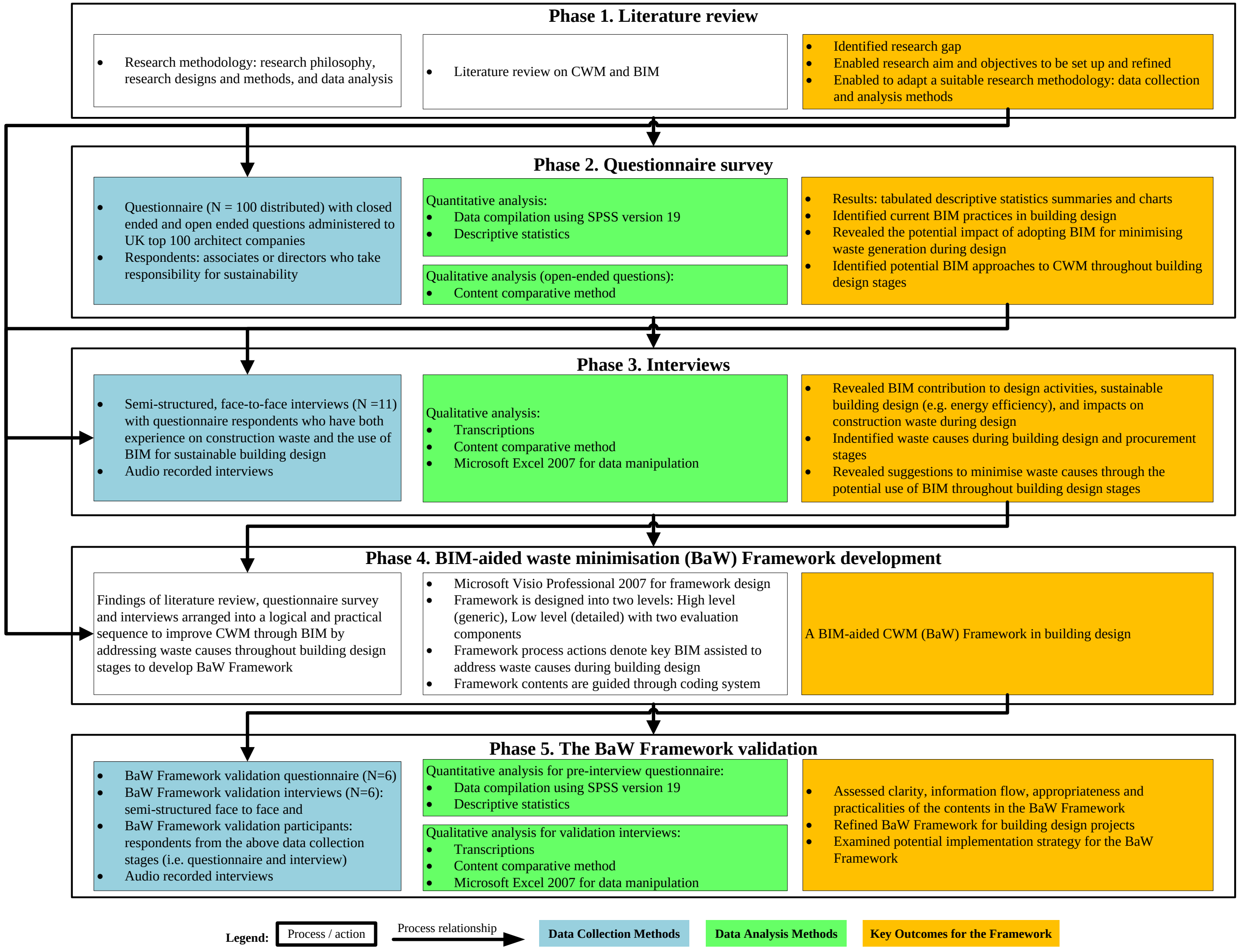


Figure 1.1 Research methodology flow chart



Phase 1. Literature review

- Research methodology: research philosophy, research designs and methods, and data analysis

- Literature review on CWM and BIM

- Identified research gap
- Enabled research aim and objectives to be set up and refined
- Enabled to adapt a suitable research methodology: data collection and analysis methods

Phase 2. Questionnaire survey

- Questionnaire (N = 100 distributed) with closed ended and open ended questions administered to UK top 100 architect companies
- Respondents: associates or directors who take responsibility for sustainability

Quantitative analysis:
- Data compilation using SPSS version 19
- Descriptive statistics

Qualitative analysis (open-ended questions):
- Content comparative method

- Results: tabulated descriptive statistics summaries and charts
- Identified current BIM practices in building design
- Revealed the potential impact of adopting BIM for minimising waste generation during design
- Identified potential BIM approaches to CWM throughout building design stages

Phase 3. Interviews

- Semi-structured, face-to-face interviews (N =11) with questionnaire respondents who have both experience on construction waste and the use of BIM for sustainable building design
- Audio recorded interviews

Qualitative analysis:
- Transcriptions
- Content comparative method
- Microsoft Excel 2007 for data manipulation

- Revealed BIM contribution to design activities, sustainable building design (e.g. energy efficiency), and impacts on construction waste during design
- Indentified waste causes during building design and procurement stages
- Revealed suggestions to minimise waste causes through the potential use of BIM throughout building design stages

Phase 4. BIM-aided waste minimisation (BaW) Framework development

Findings of literature review, questionnaire survey and interviews arranged into a logical and practical sequence to improve CWM through BIM by addressing waste causes throughout building design stages to develop BaW Framework

- Microsoft Visio Professional 2007 for framework design
- Framework is designed into two levels: High level (generic), Low level (detailed) with two evaluation components
- Framework process actions denote key BIM assisted to address waste causes during building design
- Framework contents are guided through coding system

A BIM-aided CWM (BaW) Framework in building design

Phase 5. The BaW Framework validation

- BaW Framework validation questionnaire (N=6)
- BaW Framework validation interviews (N=6): semi-structured face to face and
- BaW Framework validation participants: respondents from the above data collection stages (i.e. questionnaire and interview)
- Audio recorded interviews

Quantitative analysis for pre-interview questionnaire:
- Data compilation using SPSS version 19
- Descriptive statistics

Qualitative analysis for validation interviews:
- Transcriptions
- Content comparative method
- Microsoft Excel 2007 for data manipulation

- Assessed clarity, information flow, appropriateness and practicalities of the contents in the BaW Framework
- Refined BaW Framework for building design projects
- Examined potential implementation strategy for the BaW Framework

Figure 1.2 Research process outline

1.4.4 BIM-aided waste minimisation (BaW) Framework design and development

Based on the research quantitative and qualitative results, a BIM-aided waste minimisation (BaW) Framework was designed and developed to facilitate CWM during building design (see Appendix 2.3.2.1, 2.3.2.2, 2.3.2.3, and 2.3.2.4). The BaW Framework design and development method is discussed in Chapter 3. It was based upon a BIM process for building design (current BIM-aided energy efficiency process in particular), to address waste causes. A detailed description in the design and development of the proposed Framework is explained in Chapter 7 (section 7.2).

1.4.5 BaW Framework validation

The BaW Framework validation was designed to refine the appropriateness of its contents and processes and indentify its potential implementation strategy. The adopted methodology for validation is discussed in section 3.5.4.2, which used a combination of quantitative and qualitative methods (i.e. validation questionnaire and interviews). The validation process involved two main stages: the BaW Framework pre-validation pilot study and twofold validation process comprising questionnaire followed by a series of face-to-face and semi-structured interview. The validation questionnaire comprised five sections: High-level BaW Framework validation, Low-level BaW Framework validation, two evaluation processes in the Low-level BaW Framework validation, BaW Framework implementation strategy, and further comments (see Appendix 2.3.2). The follow-up validation interview template contained six sections: background information, High-level BaW Framework validation, Low-level BaW Framework validation, two evaluation processes in the Low-level BaW Framework validation, BaW Framework implementation strategy, and further comments (see Appendix 2.3.3).

The validation sampling frame was drawn from those who were involved in the questionnaire survey (Phase 2) and semi-structured interviews (Phase 3). The results of the validation are presented in Chapter 7 (see section 7.3).

1.5. Research contributions to knowledge

This research has explored the potential use of BIM as a vehicle to drive construction waste minimisation and to develop and validate a BIM-aided waste minimisation Framework during design. To date, no research effort has been conducted to specifically adopt BIM as a platform to reduce construction waste during design stages. Therefore, the outcome of this research provides an enriched understanding of how the use of BIM can impact on waste generation. The specified research contributions discussed in Chapter 8, section 8.3, are summarised below:

- This research has added value and extended existing knowledge in the current use of BIM for building design and sustainable building design. The process for the use of BIM in building design and sustainable building design include: visualisation and simulation, detailing, clash detection, coordination and communication, energy efficiency, carbon reduction and building material specification.
- Barriers and incentives to implement BIM for CWM during building design have been explored and assessed in this research.
- This research contributes to current knowledge of investigating the use of BIM for CWM by adopting mixed methods research strategy and demonstrating its implementation via sequential questionnaire and interviews within construction management.
- This research has added value to existing knowledge in the BIM-enhanced design related activities (e.g. visualisation and simulation, detailing, clash detection, coordination and communication) for addressing construction waste causes throughout design stages.
- The BaW Framework has been developed and validated to improve construction waste minimisation performance through the use of BIM during building design stages. This provides a roadmap for the use of BIM to aid waste minimisation through targeting potential waste causes and suggesting potential action for improvements in building design projects.

1.6. Scope of research

Based on the above discussion regarding research justification, the scope of this research was focused on architectural building design because of the following aspects:

- the key role of CWM decision making during design;
- the lack of comprehensive BIM decision making tools to support architects in minimising waste throughout building design stages; and
- a lack of research on the BIM-aided-CWM framework for architectural use across building design stages.

Thus, architects were selected as the target group of this research.

In addition, the scope of this research covered building design stages. As such, this research did not consider other building project stages, such as Procurement, Construction, and Post-construction. Therefore, this research concentrated on how BIM can help architects with CWM decision making during each of the building design stages of their projects.

Within the scope of this research, this thesis does not specifically strive to focus on the process of BIM tools implementation, but on a more detailed strategic framework related to building design decision making.

1.7. Thesis structure

The thesis is divided into eight chapters as organised below:

Chapter 1 is an overview into the research and the thesis structure. It discusses the background to the research and its justification; states the research aim and objectives; and presents an overview of the adopted research methodology and main contributions to knowledge.

Chapter 2 presents a comprehensive review of literature and a critical debate in the context of the research that covers construction waste minimisation and BIM including current practices (e.g. approaches, techniques and tools).

Chapter 3 provides a detailed discussion of the research methodology, which includes research philosophy, research strategies/approaches and research design and methods. Subsequently, the adopted research methodology is discussed and covers: the literature review, data collection of applied research techniques (i.e. questionnaire survey, interview, and the BaW Framework development and validation), and data analysis for quantitative and qualitative data.

Chapter 4 describes the findings and analysis of the questionnaire survey results. This contains background information, current use of BIM in building design and sustainable building design, and BIM as a potential tool to minimise waste in building design.

Chapter 5 presents the findings and analysis of interview results. It includes background information; current construction waste minimisation practices regarding its barriers and uses in building design projects and construction waste causes throughout each stage of building design; current use of BIM in building design (i.e. for detailing, clash detection, visualisation and simulation, coordination and communication) including sustainable building design, and barriers in its use in building design; the use of BIM to address waste causes.

Chapter 6 presents a discussion of emerging themes from the research based upon the BaW Framework in the light of the literature research outcomes.

Chapter 7 presents the design and development of the BaW Framework and its validation. It describes the structure of the Framework and its two levels (i.e. High-level and Low-level with two evaluation process components). It also discusses the Framework validation results including key improvements that emerged and potential implementation strategies for the Framework.

Chapter 8 brings together the research findings and draws conclusions with specific reference to the research objectives, contributions to knowledge and research limitations. It also suggests a number of recommendations for further research, and important information to the building design and construction industry.

CHAPTER TWO

Literature Review

2.1. Introduction

This chapter presents the literature review which seeks to investigate the relationship between construction waste minimisation (CWM) and BIM. It reviews the literature across three main areas: CWM, BIM, and relationship between BIM and CWM.

The first section clarifies appropriate definitions and terms of construction waste. Subsequently, waste minimisation drivers, waste classification and waste causes are examined. This is followed by an assessment of current CWM practices, including approaches, techniques and tools.

The second section explores the definition and development of BIM by examining its history, standards, guidelines and practices. It includes a discussion on current BIM approaches, techniques and tools. It also investigates barriers and incentives to BIM adoption in the construction industry.

The third section reviews the potential use of BIM to aid CWM. The last section discusses gaps in the literature related to the relationship between CWM and BIM.

2.2. Construction waste minimisation

2.2.1 Definitions

2.2.1.1 Construction waste

There is no clear consensus on the definition of construction waste (CW) (Zhao *et al.*, 2010). The growing body of literature within the field of CW contains classified CW definition based upon a lifecycle approach, material composition, and waste causes.

From the lifecycle point of view, CW is defined as any by-products generated and removed from construction activities (e.g. land excavation, on-site construction, refurbishment and demolition) throughout project lifecycle (Shen *et al.*, 2004; Poon, 2007; Hao *et al.*, 2007). In terms of waste material composition, CW is related to materials, such as steel, brick, and pipe, which are arising from the construction activities and considered redundant (Greenwood, 2003; Poon *et al.*, 2004). In regard to CW causes, CW is associated with designing out waste (Rounce, 1998; Osmani *et al.*, 2008; McKechnie and Brown, 2007; Baldwin *et al.*, 2009b; WRAP, 2009; Osmani, 2013), time delays, quality, costs, lack of safety, re-work, unnecessary transportation trips, long distances, improper choice of management, methods or equipment and poor constructability (Koskela, 1992; Alarcon, 1993; Serpell *et al.*, 1995; Ishiwata, 1997). Hence, the adopted definition of CW for this research is any material for construction considered to be redundant caused by various design and construction activities throughout the project lifecycle.

2.2.1.2 Construction waste management

Construction waste management is a process for managing waste through eliminating it where possible, minimising it where feasible and re-using and recycling materials where possible (Ferguson *et al.* 1995; Faniran and Caban, 1998; Teo and Loosemore, 2001). It encourages the generation of less waste, to re-use, recycle and recover waste (Yahya and Boussabaine, 2006).

Studies by Gavilan and Bernold (1994) and Peng *et al.* (1997), Faniran and Caban (1998) proposed a mapping of construction waste management hierarchy based on priorities from construction waste management options. These priorities covered avoiding waste, re-using waste, recycling waste and lastly, disposing of waste where the first three options are not feasible. The hierarchy was concurred from a construction waste management hierarchy review with industry professionals, e.g. contractors and architects, conducted by Defra (2011). Results from the recommended construction waste management hierarchy structure produced prevention (i.e. avoiding and reducing), re-use, recycling and landfill/disposal for searching out opportunities for waste minimisation (Defra, 2013a). The hierarchy also indicates that waste should be prevented in the first instance (Defra, 2008). Prevention of waste is deemed to be the best option for managing waste and is seen as the most efficient and cost-effective option for waste minimisation (Poon, 2007; Peng *et al.*, 1997).

2.2.1.3 Construction waste minimisation

Construction waste minimisation has been proposed by the UK’s Environment Agency (1997), and Envirowise (1998), as reducing waste by preventive measures (prevention, reduction at source, and re-use) and waste management measures (quality improvement and recycling). This indicates priorities for waste minimisation in preventing and reducing at the source of construction waste for improving the quality of waste minimisation to encourage re-use, recycling and recovery (Poon and Jaillon, 2010). The adopted definition of construction waste minimisation is a process, which helps to prevent, eliminate or reduce waste at its source during design (Crittenden and Kolaczkowski, 1995; Riemer and Kristoffersen, 1999; Tam *et al.*, 2002; Osmani, 2013).

Prevention includes all activities that can reduce the amount of construction waste which includes minimising waste generation at source and reducing waste before it enters the waste stream (Osmani *et al.*, 2008; Defra, 2008; Baldwin *et al.*, 2009). In terms of waste reduction, Teo and Loosemore (2001) suggested two principles that should be followed: minimise the quantities of waste generated, and adopt an effective system to reduce unavoidable waste production.

2.2.2 Construction waste minimisation drivers

By and large, there are four thematic motivations during construction waste minimisation: environmental, business, economic and legislation drivers (Osmani *et al*., 2006).

2.2.2.1 Environmental drivers

Construction industry currently generates 120 million tonnes of waste (UK Green Building Council, 2013) including 13 million tonnes unused materials (Environment Agency, 2003). Construction waste that is sent to landfill causes contamination of waters, generation of fire hazards and damage to nature landscapes (Esin and Cosgun, 2007).

The large volume of construction waste also strains landfill capacities and causes environmental concerns. Landfill capacity within the UK will reach its limit by 2018 (LGA Media Office, 2007; Grice, 2010; Surrey county council, 2010). Therefore, the landfill issue encourages and pushes the construction industry to reduce, re-use and recycle waste materials, thereby slowing down the depletion of limited landfill capacities (Hao *et al*., 2008).

Thus, increasing construction waste activities raises serious environmental concerns in terms of benefits to the built environment. Environmental benefits of CWM include less dependence on raw materials (Greenwood, 2003). In addition, CIRIA (1995) indicated that the environmental benefits of CWM include prolonging the life of landfill sites and reducing primary resource requirements. Outcomes of these environmental benefits lead to social benefits, including avoidance of creating new and undesirable landfill sites, stemming potential environmental health risks associated with waste and their disposal and reducing the cost of construction (Lingard *et al*., 2000). Additionally, in terms of environmental issues, sending waste to landfill causes negative images linked to the construction industry by the public (Begum, 2006).

2.2.2.2 Business drivers

Construction waste minimisation implementation in construction projects is impeded by the unique nature of each project, the unpredictability of the production environment, the low level project management of building procurement and the pressures of intense project cost and time (Teo and Loosemore, 2001).

However, the business benefits in overcoming these problems are increasingly being recognised and considered important in driving construction waste minimisation. These benefits come in terms of better public relations and business position by obtaining ISO 14001 and eco-labelling certificates (Teo and Loosemore, 2001; Ball, 2002). Research conducted by CIRIA (1995) estimated that companies who integrate construction waste minimisation as part of their business strategy can have a 10% advantage in tendering for new construction projects. Business benefits are also driving design companies to achieve waste minimisation by seeking efficient waste reduction method, therefore maximising profit through design fee minuses the cost of implementing the waste reduction method (Rounce, 1998). Clients are also demanding improvements to the environmental performance of projects, including construction waste minimisation (Osmani *et al.*, 2006). Hence, implementing CWM promotes business image and secure long-term efficiency and profitability.

2.2.2.3 Economical drivers

Scarcity of landfill and high disposal costs of construction waste are driving down the waste production. These include the landfill tax, of which the standard rate of non-inert material sent to landfill increased from £32/tonne in 2008 to £80/tonne in 2014 (increasing by £8 per tonne each year from 1 April 2011 until at least 2014) (HM Revenue & Customs, 2013), and the aggregate levy cost rate at £2/tonne which encourages the use of recycled rather than virgin materials (HM Government, 2013). That indicates that the cost for that yearly landfill increased about two and half times during that time which is an enormous cost burden to the construction industry. Therefore, the cost of landfill tax is the key driver for construction waste minimisation. Indeed, the amount of construction waste going to landfill has reduced substantially since the introduction of the tax (Surrey county council, 2010). The Environment Agency (2008) has proved through case studies that the true cost of disposal is more than the cost of removing the construction waste from a construction site. Innes (2004) reported the true cost of material waste during construction is estimated to be around 20 times more than the disposal of the waste.

Moreover, costs of waste drive construction waste minimisation. The direct waste cost is not only the cost of the wasted material but also includes its removal and disposal cost (WRAP, 2008). Indirect waste is a type of payment or cost of the material which can be wasted partially or totally (Bossink and Brouwers, 1996), which can also be the difference between the cost of materials which could have been used and the cost of materials that were actually used (Skoyles and Skoyles, 1987). Indirect waste can be caused through following aspects (Soibelman *et al*., 1994):

- substitution: the use of a more expensive material than the specified material (e.g. the use of structural bricks in non structural walls);
- negligence: the excessive use of a material without reimbursement from the builder of the additional costs (e.g. thicker plaster due to problems occurring in the structure's geometry – this is commonly found); and
- production: occurrence of unpredicted situations without additional budgets (e.g. the additional use of concrete in foundations due to unexpected characteristics of the subsoil).

Furthermore, a number of studies have highlighted the economical benefits of implementing construction waste minimisation (e.g. Shen *et al*., 2004; Begum *et al*., 2006; Osmani *et al*., 2006; Tam *et al*., 2007). According to Ferguson *et al*. (1995), there are three main waste minimisation economical benefits:

- reduced cost for the transport and disposal of waste materials;
- reduced cost of using new materials; and
- increased returns from selling waste materials for re-use.

Although construction waste typically costs the UK construction industry up to 5% of turnover (BRE, 2006), the potential saving of 1% can be made through implementing a comprehensive waste minimisation programme (Osmani et *al*., 2006). Construction waste minimisation activities, e.g. re-using salvaged building materials and minimising packaging, will reduce material expense and cut waste disposal costs (Greenwood, 2003). Additionally, selling waste and re-using waste materials from construction sites with a reduced price is improving subsequent waste material reduction rather than sending it to landfill at a higher cost (Snook *et al*., 1995). The lower associated cost of landfill and purchasing raw materials are catalytic drivers that generate economical benefits for construction companies from the implementation of waste minimisation (Bossink and Brouwers, 1996).

2.2.2.4 Legislative and policy drivers

Construction waste related laws within the UK are from European Directives, such as the Landfill Directive aiming to minimise the negative effects of landfill on the environment and any resultant risk to human health through specifying technical standards at community level and setting out requirements for the design, management, engineering, and aftercare for landfill (Environment Agency, 2010). The EU directives provide the fundamental law for construction and demolition waste prevention, recycling, recovery and disposal which are stated in the EU Thematic Strategy on Waste Prevention and Recycling (2012).

Cost related waste controlling regulations, such as Landfill Tax and Site Waste Management Plans (SWMPs), are in place driving waste minimisation. Landfill Tax encourages waste producers to improve their waste reduction practice, waste recovery (e.g. through recycling or composting) and the use of more environmentally friendly methods for waste disposal. From the year 2008 onwards, SWMPs are compulsory for projects costing over £300,000 in England (Defra, 2008). It aims to reduce the amount of waste produced on construction sites through re-using, re-cycling and recovering, to improve material efficiency. It also intends to prevent fly-tipping (illegal waste dumping activity whereby waste is required to be disposed of appropriately in line with the waste duty of care provisions). It focuses on recording and measuring the amount and type of waste by setting out how building materials and resulting waste is going to be managed during the project. However, in response to the UK Government's Red Tape Challenge (HM Government, 2011), which was designed to remove unnecessary legislation to free-up businesses, Defra (2013b) recently conducted a public consultation on the proposed repeal of SWMPs and concluded that the repealing would come into effect on 1st December 2013. Reasons for the repealing is that waste prevention opportunities are being lost due to the lack of ownership from clients and engagement from the design community (e.g. architects, structural engineers and services engineers) to design waste prevention into construction projects rather than passing on the responsibility to contractors. Instead, more work will be done to engage architects and designers to ensure waste is designed out. This is because the design phase of construction is vital to achieve progress towards construction waste minimisation (Defra, 2013c).

Meanwhile, the UK government has introduced various policies to facilitate better CWM performance, such as Reducing and Managing Waste 2013 (including Packaging waste - producer responsibility regime and Review of Waste Policy in England 2011) and Sustainable Construction Strategy 2008. Packaging waste - producer responsibility regime aims to ensure a proportion of the packaging material is recoverable and recyclable. Review of the Waste Policy in England 2011 (Defra, 2011) targeted to recover more than 70% of construction and demolition waste by 2020 and confirmed the construction industry is on track, except for increased excavation waste, to meet the 2012 construction waste target which is Halving Waste to Landfill. It focused on waste reduction at the early design and design stages of construction projects as this is where the largest environmental and financial savings can be made (Defra, 2011).

Furthermore, the Strategy for Sustainable Construction (HM government, 2008) was a joint industry and government strategy that aims to promote sustainable construction by providing a clear policy framework, showing the roadmap towards achieving the aims of sustainable construction and introducing 50% reduction of construction, demolition and excavation waste by 2012 to landfill compared to 2008. Halving Waste to Landfill commitment by the end of 2012 was considered a great success by both Defra (2013c) and WRAP (2013b), claiming that more than 800 signatories prevented and reduced waste covering an estimated £43 billion worth of construction contracts. However, the excavation waste has increased due to changes in construction activity throughout a recessionary cycle, and changes in Environmental Permitting (England and Wales) Regulations (UK Legislation, 2010), which reduced opportunities to re-use soils (WRAP, 2013). As such, the Waste Subgroup of the Green Construction Board suggested that the excavation waste should be accounted separately when setting future landfill-associated waste reduction target (Green Construction Board, 2013).

2.2.3 Construction waste causes

It is notable that the terms of ‘causes’ of construction waste has been used to tackle waste generation in the reviewed literature. However, definitions of the term remained unclear until Osmani (2013) defined it as direct and/or indirect waste generators (e.g. design changes and unclear specification). A number of studies explored waste causes from different perspectives that are categorised into four categories to include material types, project activities, project stakeholders and project lifecycle stages, as listed in Table 2.1.

Studies aiming to identify wasteful construction material types have been conducted across the world: Australia (Forsythe and Marsden, 1999); Brazil (Pinto, 1989; Formoso *et al.*, 2002; Soibelman *et al.*, 1994); Dubai (Al-Hajj and Hamani, 2011); Hong Kong (Poon *et al.*, 2001); The Netherlands (Bossink and Brouwers, 1996); Nigeria (Babatunde, 2012); United Kingdom (Skoyles, 1976); United States (Franklin Associates, 1998). However, they did not reach a consensus on the severity and ranking of materials that appear to be most wasteful.

Table 2.1 Types of construction waste causes (compiled from literature)

Types			**Source**
Material types	Raw materials	Wood, cement, sand, mortar, concrete and asphalt, metal scrap, ceramic block/tiles, hydrated lime, brick, rubber, plastic and glass, etc	Spivey, 1974; Pinto, 1989; Soibelman *et al*., 1994
	Components	Steel reinforcement, premixed concrete, premixed mortar, ceramic tiles, pipes and wires, reinforcement bars, window glazing, ceramic sanitary appliances, plaster of paris ceiling, roof-tiles, etc	Formoso *et al*., 2002; Babatunde, 2012
Project activities	Design, material procurement, material handling, operation		Ekanayake and Ofori, 2000; Lingard *et al*., 2000; Osmani *et al*., 2006
Project stakeholders	Client, designer, contractor, supplier, manufacturer, site management, on-site worker		Keys *et al*., 2000; Al-Hajj and Hamani, 2011
Project lifecycle stages	(1) Design stages (2) Procurement stage (3) On-site construction (4) Residual (5) Others		Gavilan and Bernold, 1994; Ofori, 2000; Bossink and Brouwers, 1996; Osmani *et al*., 2008

The reason for this is that construction waste is most likely caused through various project activities and directly and indirectly influenced by stakeholders throughout the project lifecycle stages (Bossink and Brouwers, 1996; Keys *et al*., 2000; Osmani, 2013). A study of attitudes toward the causes of construction waste by project stakeholders namely, architects and contractors, indicates that construction waste is related to project activities such as design, site operation, procurement routes, and material handling (Osmani *et al*., 2006). Project stakeholders' attitudes towards waste minimisation are influenced by cultural issues of construction waste such as lack of awareness, lack of incentives, lack of support from senior management and lack of training (Lingard *et al*., 2000; Al-Hajj and Hamani, 2011). Osmani (2013) identified construction waste causes and in line with their sources (i.e. the project stakeholders) with compiling and grouping main sources of waste factors in terms of construction lifecycle stages from a construction lifecycle approach.

The above studies on types of construction waste causes endeavour to give a clear understanding of the causes of waste. Although several specific waste causes were highlighted, most of these are related to materials of waste generation processes (Skoyles, 1976; Soibelman *et al*., 1994; Al-Hajj and Hamani, 2011). Construction waste generation processes are illustrated in Figure 2.1 as material input-output throughout project lifecycle stages. The lack of construction waste minimisation knowledge is an important cause of waste (Agopyan *et al.*, 1998). Therefore, a holistic top-down relationship between the main causes of construction waste and the waste generated is important to project stakeholders for waste estimation and evaluation in order to achieve waste minimisation from a project lifecycle approach.

Past studies on construction waste causes in the construction project revealed that waste can arise from all stages of the construction lifecycle of which design, procurement and construction are considered to be the major processes (Spivey, 1974; Bossink and Brouwers, 1996; Keys *et al.*, 2000; Osmani *et al.*, 2008; Zakar, 2008).

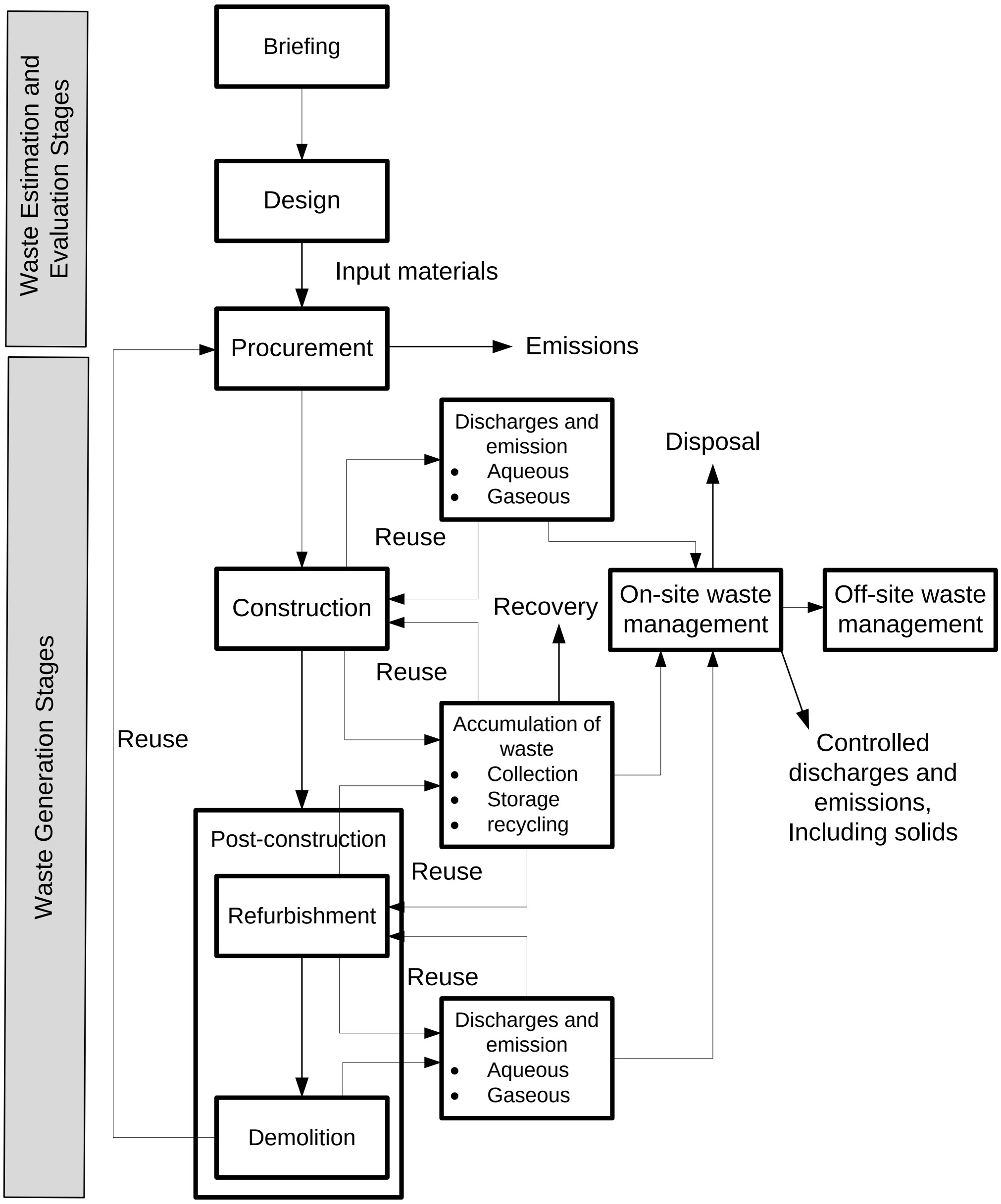


Figure 2.1 Conceptual construction waste material input-output (devised by the author based on the literature)

2.2.3.1 Construction waste causes during design stages

A significant portion of construction waste is caused by problems which occur in the early design stages (Bossink and Brouwers, 1996; Faniran and Caban, 1998; Rounce, 1998; Ekanayake and Ofori, 2000; Keys *et al*., 2000; Poon *et al*., 2004; Poon, 2007).

Around 33% of waste may be directly influenced by design concepts and decisions (Innes, 2004). In terms of avoiding and reducing waste from its causes, WRAP (2007a) indicated that there is a greater opportunity at the design stage than later stages (e.g. procurement and construction stages) from the waste reduction opportunity curve. This is because fundamental design decisions relating to building material, sharp, size and complexity, are more likely to have the greatest impact on waste. Design decisions initially impact on CW causes related to the design brief such as the lack of a waste feasibility study, failure to identify client needs, lack of early involvement by the contractor, lack of a clear waste minimisation goal, lack of waste responsibility and changing the design brief (Rounce, 1998; Lee *et al*., 1999; Osmani *et al*., 2008; Muhwezi *et al*., 2012; Panos and Danai, 2012; Osmani, 2012; 2013).

As shown in Table 2.2, construction waste during design is mainly related to design changes, material specification, design and construction detail errors, design and detailing complexity and ineffective coordination and communication. A number of studies indicate that design changes during the construction period, known as re-work, are the major factor of waste generation as it is primarily caused by client’s dissatisfaction of the design before commencing construction. Also, the cause of re-work is mainly due to poor communication (Love *et al*., 1999).

Osmani (2013) identified that incorrect work on standard dimensions and being unaware of design for construction waste minimisation issues, are significant design waste generators. Construction waste generation during design is primarily caused by inadequate coordination and communication, which result in unnecessary on-site off-cuts (Tam *et al*., 2002; WRAP, 2007a). The material waste off-cuts (due to the difference between market material sizes and design drawing sizes) are identified as one of the major waste streams during construction (Al-Hajj and Hamani, 2011; Babatunde, 2012).

Table 2.2 Design stage related waste causes (compiled from literature)

Construction waste causes	Source
Ineffective coordination and communication	Serpell *et al.*, 1995; Rounce, 1998; Keys *et al.*, 2000, Alwi *et al.*, 2002; Poon *et al.*, 2003; Osmani *et al.*, 2008; Osmani, 2012; 2013
Lack of waste feasibility study	Osmani *et al.*, 2008; Osmani, 2012; 2013
Lack of early involvement by the contractor	Bossink and Brouwers, 1996; Tam *et al.*, 2007; Osmani *et al.*, 2008; Gamage *et al.*, 2009; Osmani, 2012
Failure to identify client's needs	Rounce, 1998; Lee *et al.*, 1999; Muhwezi *et al.*, 2012
Lack of a clear goal of waste minimisation	Panos and Danai, 2012; Osmani, 2013
Lack of waste responsibility	Bossink and Brouwers, 1996; Lingard *et al.*, 2000; Osmani, 2013
Not fully evaluated design, leading to design changes during construction period (design decision)	Gavailan and Bernold, 1994; Bossink and Brouwers, 1996; Faniran and Caban, 1998; Ekanayake and Ofori, 2000; Alwi *et al.*, 2002; Polat and Ballard, 2004, Poon *et al.*, 2004; Kulatunga *et al.*, 2006; Osmani *et al.*, 2008; Nagapan *et al.*, 2012; Osmani, 2012; Panos and Danai, 2012
Difficulties in resolving design issues of architectural, structural and service design complexity	Keys *et al.*, 2000; Alwi *et al.*, 2002; Poon *et al.*, 2003; Osmani *et al.*, 2008; Osmani, 2012
Unclear outline specification of material purpose	Alwi *et al.*, 2002; Polat and Ballard, 2004; Muhwezi *et al.*, 2012; Osmani, 2012
Lack of attention paid to dimensional coordination	Bossink and Brouwers, 1996; Ekanayake and Ofori, 2000; Chen *et al.*, 2002; Polat and Ballard, 2004; Poon *et al.*, 2004a, Kulatunga *et al.*, 2006
Changing design brief	Keys *et al.* 2000; Osmani, 2013
Lack of buildability consideration	Keys *et al.*, 2000; Wong *et al.*, 2006
Limited design standardisation	Santos *et al.*, 2002; Polesie *et al.*, 2009
Lack of pre-fabrication design	Keys *et al.*, 2000; Tam *et al.*, 2007; Jaillon *et al.*, 2009; Osmani, 2013
Lack of considering design for deconstruction and flexibility	Papakyriakou & Hopkinson, 2012
Design and construction detail errors / lack of information on drawing / lack of coordination of detail design	Gavailan and Bernold, 1994; Bossink and Brouwers, 1996; Faniran and Caban, 1998; Ekanayake and Ofori, 2000; Alwi *et al.*, 2002; Poon *et al.*, 2003; Osmani *et al.*, 2008; Panos and Danai, 2012
Unclear specification of material	Bossink and Brouwers, 1996; Ekanayake and Ofori, 2000; Alwi *et al.*, 2002; Polat and Ballard, 2004; Osmani *et al.*, 2008; Osmani, 2012
Unclear specification of products and components	Bossink and Brouwers, 1996; Rounce, 1998; Alwi et al., 2002; Osmani *et al.*, 2008
Specification of material quantity (over specification)	Gavailan and Bernold, 1994; Bossink and Brouwers, 1996; Faniran and Caban, 1998; Ekanayake and Ofori, 2000; Keys *et al.*, 2000; Polat and Ballard, 2004; Osmani *et al.*, 2008; Panos and Danai, 2012
Inexperience in methods and sequence of construction	Bossink and Brouwers, 1996; Ekanayake and Ofori, 2000; Muhwezi *et al.*, 2012; Panos and Danai, 2012
Lack of standard sizes material knowledge available in market	Bossink and Brouwers, 1996; Ekanayake and Ofori, 2000; Muhwezi *et al.*, 2012
Unfamiliarity with alternative products	Bossink and Brouwers, 1996; Ekanayake and Ofori, 2000; Muhwezi *et al.*, 2012

Al-Hajj and Hamani (2011) argued that poor design related material off-cut waste is clearly outside the control of the contractors but that of the designers. A study conducted by Sinclair (2005) suggested that designers have a great deal of influence and control over construction waste generation during various project stages. However, there is a lack of understanding by designers on causes of design waste (Osmani, 2013).

A number of studies, as shown in Table 2.2, indicated that effective coordination and communication is vital to minimising construction waste at the design stage. Limited ‘know-how’ and incoherent coordination and communication between project members affect design waste (Osmani, 2013). Some studies suggested that coordination and communication of design decision making problems are partly influenced by the lack of early involvement by the contractor to provide consultation on waste reduction during design stages (Bossink and Brouwers, 1996; Tam *et al*., 2007; Osmani *et al*., 2008; Gamage *et al*., 2009; Osmani, 2012; 2013).

The results of both direct and indirect on-site waste are affected by associated causes related to the nature of the design process (Osmani, 2013). Direct waste is generated when the material is damaged and cannot be recovered and used, or wasted during construction, which can be prevented and involves the actual loss, removal or replacement of a material (Skoyles and Skoyles, 1987; Bossink and Brouwers, 1996). Such material waste could be: due to changes of design during construction stage, excess quantity of materials due to errors in procurement ordering or ordering wrong materials (Soibelman *et al*., 1994; Yahya and Boussabaine, 2006); or a consequence of vandalism, theft, or on-site management problems (e.g. transportation, unloading, stocking of the material or in production) (Soibelman *et al*., 1994). On the other hand, indirect waste is when materials are used for a purpose other than that for which they were ordered (Skoyles and Skoyles, 1987), as such materials are not physically lost (resulting in only a monetary loss) (Formoso *et al*., 2002).

As shown in Table 2.2, construction waste causes during design stages include lack of build-ability consideration, limited design standardisation, lack of pre-fabrication design, lack of design consideration for deconstruction and flexibility, inexperience in the methods and sequence of construction, lack of attention paid to dimensional coordination, unclear specification of material, products and components, lack of standard size material knowledge available in market, unfamiliarity with alternative products and over specification of material quantity.

Unclear, missing or incomplete design specifications presented to the contractor can lead to waste causes during construction (e.g. over ordering of materials, ordering the wrong materials or making mistakes in construction), which contributes to greater CW (Sinclair, 2005; Osmani, 2013). Moreover, design complexity problems such as design, detailing and construction detail complexity and errors, cause direct on-site waste (Keys *et al*., 2000; Alwi *et al*. 2002; Poon *et al*., 2003; Panos and Danai, 2012).

Rounce (1998), and Al-Hajj and Hamani (2011) believed that construction waste causes should be integrated and taken into consideration with better management of the design process at the design stage of the project.

2.2.3.2 Construction waste causes during procurement stage

During the procurement stage, there are three main waste causes related to tender and contract arrangements. These are errors in tender documents, incomplete tender documentation at the commencement of construction, and not being entrenched in tender documentation as indicated in Table 2.3. Osmani (2013) investigated waste causes (i.e. incomplete tender documentation at commencement of construction, not being entrenched in tender documentation and limited input by architect) in detail by identifying and adding sub causes as the following:

- Incomplete tender documentation at commencement of construction: detailing and specification under development; not fully coordinated design and detailing information; incomplete information from design team; incoherent information release schedule.
- Not entrenched in tender documentation: not issued and enforced in document control procedures for tender and contact; poorly defined construction waste minimisation responsibilities; lack of waste minimisation tender agreements; no target setting and implementation guidance; no financial costing of waste in bill of quantities.
- Limited architect input: lack of waste minimisation design intent; lack of architectural waste minimisation recommendations in tender documentation and action.

Table 2.3 Procurement stage related waste causes (compiled from literature)

Construction Waste Causes	Source
Errors in contract /tender documents	Bossink and Brouwers, 1996; Ekanayake and Ofori, 2000; Alwi *et al*., 2002; Osmani *et al*., 2008
Incomplete tender documentation at commencement of construction	Bossink and Brouwers, 1996; Ekanayake and Ofori, 2000; Kulatunga *et al*., 2006; Osmani *et al*., 2008; Osmani, 2013
Not entrenched in tender documentation	Skoyles and Skoyles, 1987; Osmani, 2013
Limited architect input	Osmani, 2013

2.2.3.3 Construction waste causes during construction stage

The body of literature identifies a large number of waste causes during the construction stage that can be classified into eight categories. These as listed in Table 2.4 are design changes and rework, material procurement, transit, material storage, material on-site handling on-site management and planning, site operation and residual. Material procurement is one of the major on-site waste causes (Ekanayake and Ofori, 2000); and a fourth of construction materials are wasted during site operation (Hamassaki and Neto, 1994). Lingard *et al.* (2000) and Al-Hajj and Hamani (2011) argued that waste causes can be influenced by culture related causes, i.e. lack of awareness, lack of incentives to minimise waste (including lack of contractual incentives), lack of support from senior management and lack of waste prevention training.

Most construction waste causes during the construction stage are mainly due to human error (Bossink and Brouwers, 1996; Graham and Smithers, 1996; Osmani *et al.* 2008). The site workforce has the most direct physical contact with materials being used and wasted, therefore occupying a critical position in the process of waste generation (Teo and Loosemore, 2001). Chen *et al.* (2002) further indicated that three main factors, namely skill, enthusiasm and collectivism, affect the amounts of waste generated by labour.

The most significant construction waste causes during the construction stage are design changes, material off-cuts, non-recyclable/re-useable packaging waste and design/detailing errors (Faniran and Caban, 1998). Design change and re-work can be caused by the client, architect or contractor and sub-contractor (Osmani, 2013). Design-led off-cuts are recognised as the major responsibility to material off-cuts (Al-Hajj and Hamani, 2011). Packaging waste is directly generated from material procurement process, and contributes to 10% - 15% of total waste volumes (Keys *et al*., 2000; Environment Agency, 2004; Han *et al*., 2010).

A recent study conducted by Osmani (2013) reported that design/detailing errors are related to design-led incoherent design information waste aspects, such as incomplete design information, inconsistencies between specification and drawings, detailing flaws and slow drawing revisions and distribution.

Furthermore, other construction waste causes associated with unpredictable factors are identified by a number of studies which include accidents, inclement weather and theft during construction stages (Gavailan and Bernold, 1994; Craven *et al*., 1994; Bossink and Brouwers, 1996; Lingard *et al.* 2000; Osmani *et al*., 2008). Interestingly, a study conducted by Babatunde (2012) in Nigeria indicated that theft and vandalism caused a high wastage (16.58%) of on-site waste.

Table 2.4 Construction stage related waste causes (compiled from literature)

Construction Waste Causes	**Source**
Design changes and rework	Gavailan and Bernold, 1994; Craven *et al.*, 1994; Bossink and Brouwers, 1996; Lingard *et al.*, 2000; Osmani *et al.*, 2008; Osmani, 2013
Material Procurement	
Over allowances (i.e. difficulties in ordering small quantities)	Gavailan and Bernold, 1994; Craven *et al.*, 1994; Bossink and Brouwers, 1996; Ekanayake and Ofori, 2000; Kulatunga *et al.*, 2006; Osmani *et al.*, 2008; Al-Hajj and Hamani, 2011; Osmani, 2013
Ordering errors (i.e. ordering items not in compliance with specification)	Gavailan and Bernold, 1994; Craven *et al.*, 1994; Bossink and Brouwers, 1996; Ekanayake and Ofori, 2000; Kulatunga *et al.*, 2006; Osmani *et al.*, 2008
Inadequate planning for required quantities of materials, components or products (resulting in over-ordering)	Bossink and Brouwers, 1996; Ekanayake and Ofori, 2000; Kulatunga *et al.*, 2006; Osmani *et al.*, 2008; Osmani, 2013
Purchase of inadequate materials or products	Bossink and Brouwers, 1996; Ekanayake and Ofori, 2000; Lingard *et al.*, 2000; Al-Hajj and Hamani, 2011
Supplier errors	Gavailan and Bernold, 1994; Craven *et al.*, 1994; Osmani *et al.*, 2008
Poor quality of materials	Lingard *et al.*, 2000; Al-Hajj and Hamani, 2011
Poor advice from suppliers	Lingard *et al.*, 2000; Al-Hajj and Hamani, 2011
Shipping errors	Gavailan and Bernold, 1994
Delivery schedules	Lingard *et al.*, 2000
Delivery methods	Lingard *et al.*, 2000
No take-back schemes	Lingard *et al.*, 2000
Poor supply chain management	Lingard *et al.*, 2000
Transit	
Damage during transportation to site/on site	Gavailan and Bernold, 1994; Craven *et al.*, 1994; Bossink and Brouwers, 1996; Ekanayake and Ofori, 2000; Lingard *et al.*, 2000; Kulatunga *et al.*, 2006; Osmani *et al.*, 2008; Al-Hajj and Hamani, 2011
Insufficient protection during unloading	Bossink and Brouwers, 1996; Osmani *et al.*, 2008
Inefficient methods of unloading	Bossink and Brouwers, 1996; Osmani *et al.*, 2008
Difficulties for delivery vehicles accessing construction sites	Osmani *et al.*, 2008
Material storage	
Inappropriate site storage space leading to damage or deterioration	Gavailan and Bernold, 1994; Craven *et al.*, 1994; Bossink and Brouwers, 1996; Enshassi, 1996; Ekanayake and Ofori, 2000; Kulatunga *et al.*, 2006; Osmani *et al.*, 2006; 2008
Materials stored far away from point of application	Bossink and Brouwers, 1996; Osmani *et al.*, 2008
Inadequate storing methods	Lingard et al. 2000; Osmani *et al.*, 2008
Material on-site handling	
Inadequate material handling	Enshassi, 1996; Gavailan and Bernold, 1994;Lingard *et al.*, 2000; Osmani *et al.*, 2008
Onsite transportation methods from storage to the point of application	Enshassi, 1996; Ekanayake and Ofori, 2000; Osmani *et al.*, 2008
Material supplied in loose form	Kulatunga *et al.*, 2006; Ekanayake and Ofori, 2000; Osmani *et al.*, 2008
Unpacked supply	Bossink and Brouwers, 1996

On-site management and planning	
Delays in passing information on types and sizes of materials, components or products to be used	Bossink and Brouwers, 1996; Ekanayake and Ofori, 2000; Osmani *et al.*, 2006; 2008
Lack of on-site material control	Gavailan and Bernold, 1994; Craven *et al.*, 1994; Kulatunga *et al.*, 2006; Osmani *et al.*, 2008
Lack of on-site waste management plans	Gavailan and Bernold, 1994; Craven *et al.*, 1994; Bossink and Brouwers, 1996; Osmani *et al.*, 2008
Lack of supervision	Enshassi, 1996; Osmani *et al.*, 2008
Inadequate or no thorough check of project information (including design information) prior to commencing construction	Enshassi, 1996; Osmani, 2013
Site operation	
Use of incorrect materials resulting in requiring replacements, even their disposal	Gavailan and Bernold, 1994; Craven *et al.*, 1994; Bossink and Brouwers, 1996; Ekanayake and Ofori, 2000; Kulatunga *et al.*, 2006; Osmani *et al.*, 2008; Osmani, 2013
Poor craftsmanship	Gavailan and Bernold, 1994; Craven *et al.*, 1994; Bossink and Brouwers, 1996; Lingard *et al.* 2000; Kulatunga *et al.*, 2006; Osmani *et al.*, 2008; Al-Hajj and Hamani, 2011
Equipment malfunction	Gavailan and Bernold, 1994; Craven *et al.*, 1994; Bossink and Brouwers; 1996; Ekanayake and Ofori, 2000; Kulatunga *et al.*, 2006; Osmani *et al.*, 2008
Damage to work completed caused by subsequent trades	Gavailan and Bernold, 1994; Craven *et al.*, 1994; Bossink and Brouwers, 1996; Ekanayake and Ofori, 2000; Kulatunga *et al.*, 2006
Accidents due to negligence	Gavailan and Bernold, 1994; Bossink and Brouwers, 1996; Ekanayake and Ofori, 2000; Kulatunga *et al.*, 2006
Poor working attitude of on-site project team (e.g. labour) towards waste minimisation	Ekanayake and Ofori, 2000; Kulatunga *et al.*, 2006; Osmani *et al.*, 2008; Al-Hajj and Hamani, 2011
Poor communication and coordination between project members	Ekanayake and Ofori, 2000; Lingard *et al.* 2000; Kulatunga *et al.*, 2006
Time restraint	Lingard et al. 2000; Osmani *et al.*, 2008; Al-Hajj and Hamani, 2011
Method to lay the foundation	Bossink and Brouwers, 1996
Unused materials and products	Osmani *et al.*, 2006; 2008
Residual	
Waste from application process (i.e., over preparation of mortar)	Gavailan and Bernold, 1994; Craven *et al.*, 1994; Bossink and Brouwers, 1996; Kulatunga *et al.*, 2006; Osmani *et al.*, 2006; 2008; Babatunde, 2012
Off-cuts from cutting materials to length	Gavailan and Bernold, 1994;Craven *et al.*, 1994; Bossink and Brouwers, 1996; Osmani *et al.*, 2008; Al-Hajj and Hamani, 2011; Babatunde, 2012
Conversion waste from cutting uneconomical shapes	Gavailan and Bernold, 1994; Craven *et al.*, 1994; Bossink and Brouwers, 1996; Enshassi, 1996; Osmani *et al.*, 2006; 2008
Throwaway packaging	Gavailan and Bernold, 1994; Craven *et al.*, 1994; Enshassi, 1996; Bossink and Brouwers, 1996; Osmani *et al.*, 2008; Al-Hajj and Hamani, 2011
Lack of knowledge of material or product requirements (e.g. over-mixing of materials)	Gavailan and Bernold, 1994; Craven *et al.*, 1994; Bossink and Brouwers, 1996; Lingard *et al.* 2000

2.2.4 Current construction waste minimisation practices

A review of current construction waste minimisation approaches, techniques and tools is discussed in the section below.

2.2.4.1 Construction waste minimisation approaches

As shown in Table 2.5, current construction waste minimisation approaches are associated with design, supply chain management and on-site waste activities. However, the bulk of approaches are mainly related to construction stage, with very few approaches looking into Briefing and Design stages.

Designing out waste approach outlines the causes of physical waste generated from the construction process through design, and the principal strategies for waste reduction (Keys *et al*., 2000; Osmani, 2005; WRAP, 2009). Additionally, WRAP (2009) provided designing out waste guidance for designers, clients and contractors to adopt construction waste minimisation in their projects. Furthermore, a Standard BS 8895 Part 1 (Principles and Framework for Building Design Briefing) has recently been published, which provides the principles and implementation framework for CW prevention and minimisation during Briefing stages (BSi, 2013). A project life cycle approach for design waste mapping to assist project stakeholders in identifying design waste causes has recently been developed by Osmani (2013).

Table 2.5 Current construction waste minimisation approaches (compiled from literature)

Current construction waste minimisation approaches	**Briefing stages**		**Design stages**				**Procurement stages**		**Construction stages**			**Post-construction stages**			**Source**
	Appraisal	Design Brief	Concept	Design Development	Technical Design	Production Information	Tender Documentation	Tender Action	Mobilisation	Construction to Practical Completion	Post Practical Completion	In use /Facility Management	Renovation	Demolition	
Designing out waste		√	√	√											Keys *et al.*, 2000; Osmani *et al.*, 2008; WRAP, 2009; BSi, 2013
Procurement guidance							√		√	√					WRAP, 2013c
Material Logistic Plans									√	√				√	WRAP, 2007b
Reverse logistics									√	√				√	Leite, 2003; Nunes *et al.*, 2009
Construction supply chain management									√	√					Ofori, 2000; Akintoye *et al.*, 2000; Briscoe *et al.*, 2001; Saad *et al.*, 2002; Dainty and Brooke, 2004
On-site sorting of construction waste										√				√	Poon *et al.*, 2001
On-site waste mapping										√					Shen *et al.*, 2004
On-site waste control										√					Formoso *et al.*, 1999
Financial waste management										√					Mills *et al.*, 1999
On-site waste behaviour / attitude										√					Teo and Loosemore, 2001; Begum *et al.*, 2009; Qi *et al.*, 2010; Kulatunga *et al.*, 2006
Implementation of environmental management										√					Shen and Tam, 2002

Studies related to construction waste minimisation logistical issues are mainly focused on supply chain management approaches, such as greening supply chain management (Ofori, 2000), supply chain collaboration and management (Akintoye *et al*., 2000), skills, knowledge and attitudinal requirements of construction supply chain partnerships (Briscoe *et al*., 2001), the progress towards adoption of supply chain management relationships within construction (Saad *et al*., 2002), and improved supply chain integration (Dainty and Brooke, 2004).

A number of on-site waste minimisation approaches have been proposed from different perspectives such as waste control (Formoso *et al*., 1999), construction waste financial planning and management (Mills *et al*., 1999), waste sorting (Poon *et al*., 2001), waste associated environmental performance management (Shen and Tam, 2002), waste mapping (Shen *et al*., 2004), and the attitude and behaviour of the project team towards construction waste minimisation (Teo and Loosemore, 2001; Kulatunga *et al*., 2006; Begum *et al*., 2009; Qi *et al*., 2010). It is evident that current construction waste minimisation approaches relate primarily to improvement of on-site waste management.

Attitudes and practices of contractors towards improving on-site waste management are currently driven by the direct economic benefits of implementing construction waste minimisation and are influenced by an increasing awareness of waste impact during construction, an understanding of the quality of recycled products, and effectiveness of on-site supervision (Qi *et al*., 2010; Al-Sari *et al*., 2012).

2.2.4.2 Construction waste minimisation techniques

As shown in Table 2.6, current construction waste minimisation techniques are mainly concerned with on-site and off-site construction issues. These techniques are focused on the construction stage, of which low-waste techniques facilitated off-site construction affects both design and construction stages.

Table 2.6 Current construction waste minimisation techniques (compiled from literature)

Current construction waste minimisation techniques	**Briefing stages**		**Design stages**				**Procurement stages**		**Construction stages**			**Post-construction stages**			**Source**
	Appraisal	Design Brief	Concept	Design Development	Technical Design	Production Information	Tender Documentation	Tender Action	Mobilisation	Construction to Practical Completion	Post Practical Completion	In use /Facility Management	Renovation	Demolition	
On-site recycling construction and demolition wastes										√				√	CIRIA, 2001
Waste source evaluation systems										√					Bossink and Brouwers, 1996
Materials flow analysis system							√		√	√					Bertram *et al.*, 2002
Ready-mixed concrete waste management										√					Sealey *et al.*, 2001
Dynamic modelling of construction and demolition waste management processes										√				√	Hao *et al.*, 2007; 2008; 2010
Integrated GPS and GIS technology										√					Li *et al.*, 2005
Geographical Information System (GIS) and Life Cycle Assessment (LCA) mix for supply chain										√				√	Blengini and Garbarino, 2010
Use of off-site technique: prefabricated / precast concrete elements			√	√	√	√				√					Baldwin *et al.*, 2008; 2009b; Tam *et al.*, 2007
Low-waste design technologies			√	√	√	√				√					Tam and Tam, 2006; Esin and Cosgun, 2007
Low-waste technologies for implementation of advanced construction material and components			√	√	√	√				√					Poon *et al.*, 2003; Zhang *et al.*, 2012
Modern methods of construction (MMC)			√	√	√	√				√					WRAP, 2007c

Current on-site waste minimisation techniques are based on identifying waste management and decision making process. Bertram *et al*. (2002) proposed a construction materials flow analysis system to estimate budgets in waste management. Hao *et al.* (2007; 2008; 2010) developed a dynamic model of construction and demolition waste to assist with on-site waste forecasting for better waste minimisation decision making. Moreover, new techniques such as Global Position System (GPS) and Geographical Information System (GIS) are being integrated with the development of on-site waste minimisation techniques. Li *et al.* (2005) established an integrated GPS and GIS technology developed from automatic data-capture systems (e.g. bar-coding system) for on-site construction material and equipment management. Similarly, Blengini and Garbarino (2010) developed a combined GIS and Life Cycle Assessment (LCA) mixed model that uses site-specific data and concerns land use, transportation and landfill, which are critical issues for waste reduction planning and management.

Currently, off-site construction technique enabled Modern Methods of Construction (MMC), which includes volumetric modular, pre-fabricated kitchen and bathroom pods, pre-cast structural panels, hollow-core flooring, concrete cladding and insulating concrete formwork, offers significant opportunities for minimising on-site waste (WRAP, 2007c; Baldwin *et al.*, 2008; Silva and Vithana, 2008; Jaillon *et al*., 2009). Tam *et al.*, (2007) introduced a pre-fabrication implementation for project parties to consider construction methods before project commencement on site and improve project constructability at the early design stage. Baldwin *et al*., (2008) used modelling information flows to facilitate pre-fabricated and precast elements in the design process for reducing waste. Baldwin *et al*. (2009b) further developed the information modelling with Design Structure Matrix techniques for design to pre-cast to assist decision making in the design detailing process. The above off-site construction techniques are typically facilitated by low-waste technologies that assist efficient consumption of construction materials to reduce waste generation during the construction process (CIRIA, 1995; 1999). These low-waste technologies include low-waste design techniques and implementation of advanced construction materials and components. The low-waste design techniques include design for reducing foundation size, design for re-use and recycling and design for deconstruction or sequential demolition (Poon *et al*., 2003; Zhang *et al*., 2012). The advanced construction materials and components can be implemented by a variety of techniques, such as advanced formwork (e.g. composite foundation formwork and large panel formwork) and pre-fabricated and pre-casted elements (Tam and Tam 2006; Esin and Cosgun, 2007).

2.2.4.3 Construction waste minimisation tools

As indicated in Table 2.7, current CWM tools mostly focus on the Construction stage and Post-construction stages, with few that deal with Briefing and Design stages. The widely used construction waste minimisation tools were mainly developed by organisational bodies such as BRE and WRAP. A significant number of tools are used for on-site waste management and auditing such as construction Waste Management Plan (WMP), Site Methodology to Audit and Target Waste (SMARTWaste).

Construction WMP has been implemented as a strategic tool for minimising waste generation from the construction process (McDonald and Smithers, 1998). WRAP (2010) developed an online tool called SWMP Tracker. This concerns the planning and implementation of waste reduction and recovery by using on-site WMP templates to collate and analyse data from multiple projects.

On-site waste controlling tools which include waste monitoring and auditing have been suggested for collection of construction activity information to establish patterns of building products and materials usage on site (Formoso *et al.*, 1999). BRE (2001) brought it further and focused on developing a software tool for on-site waste management (i.e. Site Methodology to Audit and Target Waste: SMARTWaste) to audit, classify, and reduce on-site waste generation. As indicated in Table 2.7, the SMARTWaste related tools are being developed into a series of interdependent construction waste minimisation instrument, namely waste cost calculator and key environmental performance. It would also appear that the development of waste minimisation online applications embedding more integrated techniques, such as GIS, have increased in recent years.

Table 2.7 Current construction waste minimisation tools (compiled from literature)

Current construction waste minimisation tools	**Briefing stages**		**Design stages**				**Procurement stages**		**Construction stages**			**Post-construction stages**			**Source**
	Appraisal	Design Brief	Concept	Design Development	Technical Design	Production Information	Tender Documentation	Tender Action	Mobilisation	Construction to Practical Completion	Post Practical Completion	In use /Facility Management	Renovation	Demolition	
Waste forecasting tool (online tool)			√	√											WRAP, 2011
Building waste assessment score: design-based tool			√	√	√	√									Ekanayake and Ofori, 2004
On-site waste auditing: SMARTWaste										√			√	√	BRE, 2001
Waste management planning										√			√	√	McDonald and Smithers, 1998
On-site waste control tools										√			√	√	Formoso *et al.*, 1999
SWMP Tracker										√			√	√	WRAP, 2010
ConstructCLEAR (online tool)										√			√	√	BlueWise, 2010
True cost of waste calculator (online tool)										√					BRE, 2010
SMARTAudit										√			√	√	BRE, 2008
BreMap (online GIS tool)										√			√	√	BRE, 2009
SMARTStart										√			√	√	BRE, 2007
Material bar-code system										√					Chen *et al.*, 2002
BIM based structural analysis tool					√	√									Porwal and Hewage, 2012
BIM to demolition and renovation waste													√	√	Cheng and Ma, 2013
Webfill (online tool)										√			√	√	Chen *et al.*, 2006

Construction waste forecasting tools have been introduced to aid design. Ekanayake and Ofori (2004) developed a building waste assessment score model for waste forecasting based on scores of design waste causes and on-site material wastage within building projects. It helped facilitate the designer in delivering the most viable design and the project management team to formulate guidelines for the project as well as monitor the construction process in terms of minimising on-site waste generation. In addition, WRAP (2011) launched a new package of online tools for waste forecasting based on designing out waste for Concept and Design Development stages. These contain two designing out waste tools, one for building projects and another for civil engineering projects. These are applied at Concept Stage construction waste forecasting and the net waste tool is engaged in the Design Development Stage. These tools aim to capture live data on construction waste and provide a comprehensive method to improve resource efficiency in terms of waste minimisation.

Online tools are being used for managing and minimising construction waste. Chen *et al.* (2006) developed an online e-commerce simulation tool, Webfill, to provide an online construction waste exchange platform for reducing waste between waste minimisation players, consisting of contractors, property managers, material manufacturers and recyclers, and landfill managers. An online tool called ConstructCLEAR was designed by BlueWise (2010) to assist both construction and waste management sectors by streamlining and integrating the process of site WMP, carbon reporting, waste management procurement and regulatory compliance.

Emerging BIM visualisation and simulation tools have been developed recently for handling of construction and demolition waste. BIM has been introduced for analysis of the design of structural reinforcement to minimise rebar waste during Technical Design stage (Porwal and Hewage, 2012). A BIM-based Application Programming Interface (API) system has been used for demolition and renovation waste estimation and planning, waste disposal charging fee, and pickup truck requirements through the BIM as-built model at Post-construction stages (Cheng and Ma, 2013).

As mentioned in this section, current construction waste minimisation approaches, techniques are dominated endeavours to manage on-site waste, yet Briefing and Design stages of the greatest opportunities for waste reduction (Bossink and Brouwers, 1996; Keys *et al.*, 2000; Poon *et al.*, 2004; Osmani *et al.*, 2008; WRAP, 2007a). Although design related construction waste issues have caught the attention of the industry, few approaches, techniques and tools have been established to help with the issue. There is a recent trend to develop online and integrated waste minimisation techniques and tools (e.g. GIS and GPS). However, integrated BIM-enhanced construction waste minimisation during design stages is absent from literature.

2.3. Building information modelling (BIM)

2.3.1 Definitions

There is still no single, widely-accepted definition of BIM. BIM has been developed from computer-aided design (CAD) research over several years. This is because BIM is defined in different terms through modelling and design data to construction management. From a three-dimensional (3D) parametric modelling perspective, BIM encompasses 3D parametric modelling of buildings for design and detailing along with computer-intelligible exchange of building information not only between project stakeholders but also project lifecycle stages (Sacks *et al*., 2010a). In relation to design and project data management, BIM acts as a set of interacting policies, processes and technologies that generates a methodology to manage the essential building design and project data in digital format throughout the life-cycle of a building (Penttilä, 2006). Within the context of construction management, BIM is an intelligent simulation of architecture that enables integrated delivery achievement (Eastman *et al*., 2008). In the context of this research, BIM is defined as a collaborative communication and coordination platform to assist architects' decision making to attain CWM throughout design.

2.3.2 BIM development

2.3.2.1 History of BIM development

The 3D solid modelling was first developed in the late 1970s and was widely adopted during the early 1980s (Eastman *et al*., 2008). This was particularly driven by ISO STEP (Standard for the Exchange of Product Data) standardisation project (STEP Tools, 2010), as well as CAD systems such as RUCAPS, TriCAD, Calma and GDS (Bozdoc, 2003). Meanwhile, the concept of the semantic model was established to connect logical and physical information into a machine engineering domain (Grabowski and Eigner, 1979). This concept was adapted for the earlier established generic building description systems to fit the demand of the building construction industry (Eastman, 1976). Based on this semantic model concept, Fruchter *et al*. (1996) developed the Interdisciplinary Communication Medium model for collaborative conceptual building design. At a later date, a building description system was developed as a building product model (Bjork, 1989). Studies have since investigated components and consequences of the building product modelling for several years prior to the term 'BIM' being introduced into the market (Eastman, 1999). The foundations for object-oriented building product modelling for BIM were introduced to the industry throughout the 1990s (Gielingh, 1988; Kalay, 1989; Eastman, 1992). Since 2002, BIM has been widely adopted after being adapted by major CAD developers within the industry (Laiserin, 2010), and treated as a new CAD paradigm (Ibrahim *et al*., 2004).

There are three types of information data within a BIM model, these being geometric, semantic, and topological. Geometric information data directly links to the building form in 3D; semantic information data states the component properties, whilst topological information data captures the dependency of components (Schlueter and Thesseling, 2009).

The information data is also called form-behaviour relations to parts and assemblies within the BIM model (Eastman, 1999). Additionally, BIM ontology has been developed. The two main uses of BIM ontology are to generate a language for communication between project members (Uschold, 1996; Studer *et al.*, 1998) and interoperability to transfer data seamlessly between applications and systems (Uschold, 1996). This added communication and interoperability feature to the relations through the use of a BIM model.

BIM technology continues to develop rapidly as it has done from 2D drawings, 3D (object-oriented and AEC-specific CAD), 4D (3D + time sequencing), 5D (4D + cost) (Popov *et al*., 2010; Forgues *et al*., 2012; Udhayakumar and Karthikeyan, 2014), 6D (Sustainability analysis) (O'Keeffe *et al*., 2009; O'Keeffe, 2012; Bryde *et al*., 2013; Ganah and John, 2013; Udhayakumar and Karthikeyan, 2014), and 7D (Facility management) (Ganah and John, 2013; Kulasekara *et al*., 2013; Udhayakumar and Karthikeyan, 2014), to nD (Aouad *et al*., 2005). Some researchers use the 6th or 7th dimension for health and safety (McKinney and Fischer, 1998; Autodesk, 2002; CITA, 2012). Eastman *et al.* (2008) argued that the concept of development of technology-driven BIM will renew the vision of future buildings by emphasising workflow and construction practices. Eastman (2008) proposed a clear vision of the future development of BIM, which is thought to provide significant enhancements in the following areas:

- improved import and export capabilities applying protocols such as IFC (Industry Foundation Classes);
- one-stop solution: each BIM authoring tool will expand its repertoire of applications, enabling increasingly complex buildings to be designed and built using a family of related tools built on the same platform without the need for data translation and

exchange;

- lighter but efficient BIM tools for specific building types to help client understand actual design and construction;
- move from desktop application to internet-based interaction that employs BIM and integrates web-based content from service to building element models and analysis tools, known as cloud BIM; and
- support building products involving complex layout and detailing.

Kymmell (2008) argued that although BIM technology and software application development tools will continue to change, the concepts and underlying processes of collaboration, communication, understanding, and visualisation, are likely to remain the same. However, Krygiel and Nies (2008) stated that integration with other techniques and simulation of design performance are the future of BIM. The trend in functionality of building design and construction is heading towards sustainability (BRE, 2009; USGBC, 2010; HM government, 2013). Hence, further development of BIM has the direction to improve sustainable building design and construction performance such as integrated computational fluid dynamics analysis, energy analysis, acoustic simulation and water analysis, etc (Azhar *et al*., 2008; Braun *et al*., 2010). In order to facilitate the uptake of BIM, industry and government bodies have issued a number of BIM standards and guidelines.

2.3.2.2 BIM standards and guidelines

BIM standards

BIM standards represent the rules allowing users to apply BIM efficiently and consistently (McGraw-Hill, 2008). Furthermore, BIM standards are critical when communication takes place among different project teams, specialists, and suppliers during the duration of a project (Howard and Björk, 2008). Therefore, BIM standards are key factors in the successful implementation of BIM. Existing BIM standards include:

- Protocol level standards:
  - PAS 1192-2:2013: Specification for information management for the capital/delivery phase of construction projects using building information modelling.
  - IDM: Information Delivery Manuals (ISO/FDIS 29491-1:2009) for creating guidance on how and when to provide information during a project.
  - IFD: International Framework Dictionary (ISO 12006-3: 2007) for creating uniform

object libraries.

  - BS 1192:2007: Collaborative production of architectural, engineering and construction information - Code of practice.
  - NBIMS from National Institute for building Sciences, US.
  - Open Standards Consortium for Real Estate (OSCRE) standards.
  - Open BIM standards.

- Model level standards:
  - IFC: Industry Foundation Class.
  - gbXML: The Green Building XML (Extensible Markup Language) scheme.
  - COBie: Construction Operations Building Information Exchange for facility management.

There are five that are widely adopted by the UK's construction industry in recent years, namely PAS 1192-2:2013, BS 1192:2007, IFC, gbXML and COBie (HM Government, 2012; NBS, 2013).

PAS 1192-2:2013: The Publically Available Specification (PAS 1192-2:2013) was developed in line with BS 1192:2007 to specify requirements in achieving BIM Level 2 through focusing on the project delivery (BSi, 2013). These include the majority of graphical data, non-graphical data and documents, known collectively as the project information model (PIM), which are accumulated from design and construction activities.

BS 1192:2007: BS 1192:2007 was published by the British Standards Institution to provide guidelines to support collaboration and implementation of BIM by defining the rules for modelling, publishing and sharing information (BSi, 2008). These apply to all parties who are involved in the preparation and use of the information throughout the construction project lifecycle, such as design, construction, operation and deconstruction. It is also a guide for software developers in the development of applications through the provision of configuration files or application add-ons.

IFC: BIM models should be distinguished between proprietary models established by software companies and open non-proprietary models. IFC is one of the most distinguished formats which has been developed by the International Alliance for Interoperability (IAI), recently renamed building SMART (IAI, 2010). The IAI collaborates with over 600 companies around the World including industry practitioners, software vendors and researchers. They work to support interoperability throughout building design and construction and the information technology community by developing IFC towards the standard for model information exchange within the building industry (BLIS, 2004). IFC is defined as using STEP description methods and can be shared and exchanged in the three implementation levels of a BIM model, dictionary, and process (IAI, 2008). The IFC model presents as a high-level object-oriented, comprehensive and universal data model of building. It contains various types of building design and construction project information such as stages of building, the geometry and material properties of building components, project costs, schedules, organisations and suppliers (Froese, 2003; Bazjanec, 2004; Arayici, 2008).

The structured data information in relation to building design and construction projects from most computer applications can be mapped into IFC data files (Arayici, 2008). Based on that, the IFC data model has been used by a number of CAD tools as an export and import option for exchanging requirements (IAI, 2010; ISG, 2010). Commercial BIM platforms such as Autodesk's Revit, Graphisoft's Archicad, Bentley Architecture, Gehry Technologies' Digital Project, and Nemetschek's Allplan have undergone many major releases offering commercial software tools for the building design and construction industry and implementing IFC import/export for exchange capabilities (Froese, 2003; Eastman *et al.*, 2008, Jeong *et al.*, 2009). Furthermore, several case studies have shown applicability of the IFC model in the design process and 3D object-based data transfer (Dayal and Timmermans, 2004; Plume and Mitchell, 2007; Jeong *et al*., 2009).

However, IFC translators have limitations and implementation errors, which still require correct development (Froese, 2003). According to Froese (2003), the IFC product model had limitations in terms of attempting to address very broad coverage of design, construction and product data. For example, it does not fully support different types of fabrication-level products including precast concrete structures. Although geometric shape information for building is clearly defined by IFC classes, the complex geometric shapes are quite often transferred incorrectly (Jeong *et al.*, 2009). Additionally, IFC product model has a problem in supporting several complex geometric entities provided by ISO/STEP Part 42: 1997, such as B-Spline surfaces cited in Jeong *et al.* (2009), this was successfully addressed in ISO 10303 (Steptools, 2013).

gbXML: An alternative way to exchange building model information data is through gbXML developed by Green Building Studio, Inc (gbXML, 2014). It is developed to facilitate the transfer of building information stored within building information models, and enable integrated interoperability between building design models and a wide range of engineering analysis and simulation tools (gbXML, 2013). The gbXML standard has the ability to carry building environmental information. It is simple and easy to facilitate the implementation in the extension of schema for different design analysis and simulation purposes that facilitates productivity for energy analysis model generation in particular (Dong *et al*., 2007; Ali, 2010).

COBie assists the management of information for new or existing facilities, which provides an information exchange specification for documenting building design and construction and operation over the building's lifetime, delivering information required by facility managers (East, 2012; BIM Task Group, 2013).

The BIM standards provide information in relation to modelling, coordination, communication and collaboration for delivery when applying BIM at standardised level. BIM guidelines suggest certain roadmap of using BIM during various stages whereby users can easily understand and apply.

BIM guidelines

There are a number of academic studies and government bodies that issue the current guidelines for the process of BIM implementation within the UK, as shown in Figure 2.2.

The most efficient way to understand and implement BIM at the process guideline level is to follow the widely adopted Bew and Richards's maturity diagram of BIM. This diagram attempts to summarise the BIM evolutionary process originally presented by Mark Bew and Mervyn Richards in 2008 and updated in 2012 in line with the UK Construction Strategy 2012. According to Bew and Underwood (2010), as known further developed Bew and Richards' 2008 BIM maturity level, 95% of UK BIM users are currently sitting in Level 0 by using 2D drawings or working without CAD drawings. However, developing evidence suggested that the construction industry is slowly moving up the 'ramp' as results of the UK national BIM Survey studies conducted by National Building Specification (NBS) (2011; 2012; 2013) indicate that the use of Level 0 BIM in the industry has dropped from 75% in 2011 to 61% in 2013. The adoption of Level 1 BIM has increased from 13% in 2011 to 35% in 2013. Furthermore, the maturity levels (Level 0, 1, 2 and 3) are widely referred to in the construction industry to the extent of BIM implementation phased in by the Government Construction Strategy 2011. This requires public projects to implement Level 2 BIM from summer 2012 and all public projects have to fully collaborate with BIM-associated asset information, documentation and data being electronic by 2016.

Although the latest data of achievement of using BIM for public projects from 2012 has not been published, the latest UK Government Construction Strategy towards 2025 (HM Government, 2013) demand all central government departments' projects, irrespective of project size, implementing at least Level 2 BIM from 2016.

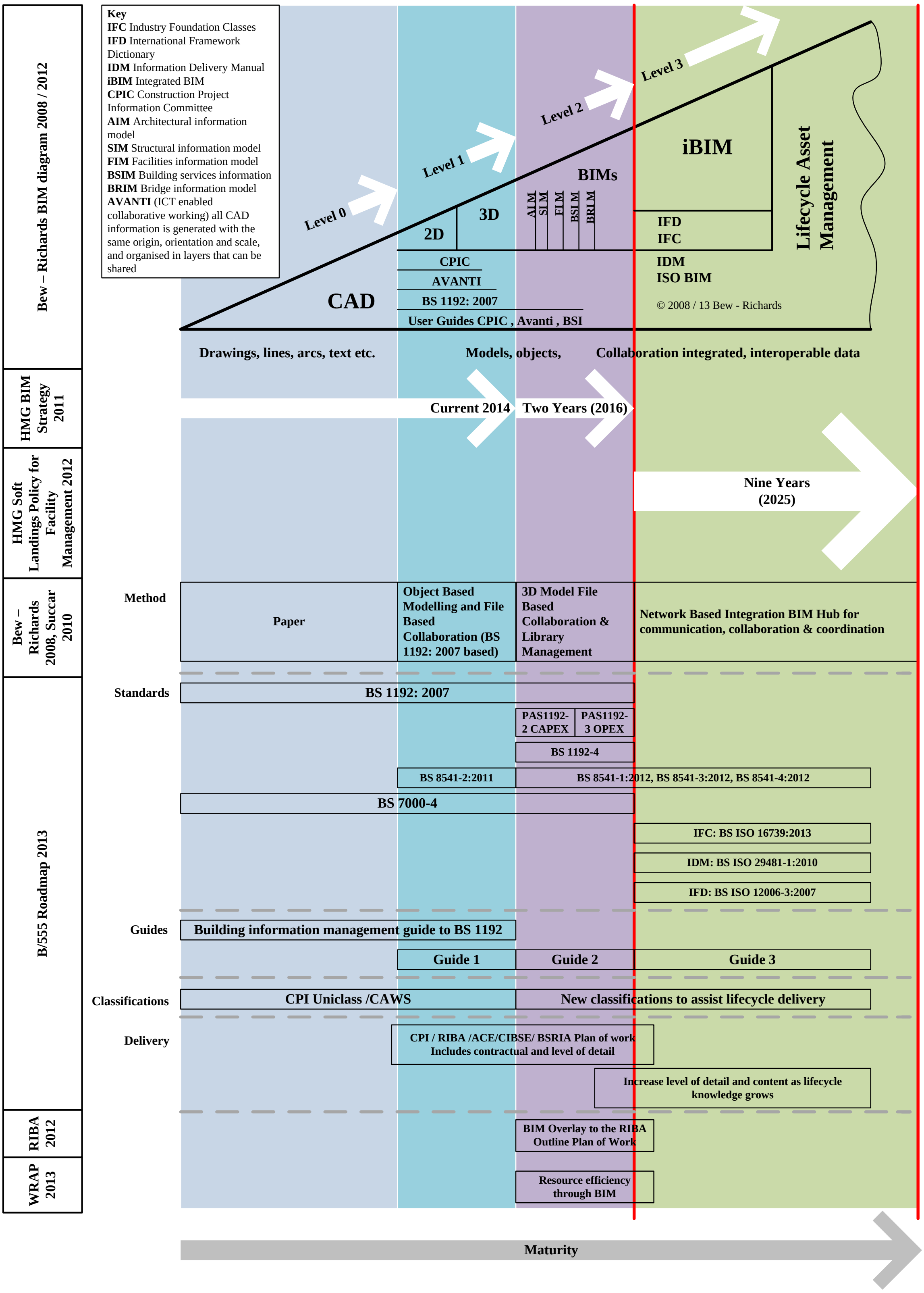


Figure 2.2 Diagram of current UK's BIM guidelines (compiled from literature)

In order to comply with the BIM maturity diagram, BSi (2012) introduced the updated B/555 Roadmap 2012 to illustrate the process. This entails that all standards in the immediate past, present and future have to be planned to ensure clear representation of the standards and guidance, their relationship to each other and how they can be applied to projects in line with the BIM maturity diagram. Additionally, RIBA published a BIM Overlay to the RIBA Outline Plan of Work, edited by Sinclair (2012), in response to the B/555 Roadmap 2012 and Government Construction Strategy 2011. The BIM Overlay provides stage-by-stage guidance for assisting architects to design and manage construction projects through the use of BIM, and suggests data drops at the end of each design stage for Soft Landings.

The Government Soft Landings framework aims to improve client and end user experiences by reducing revisits, and to provide a way in which building asset management meets client expectations. It has been developed by the UK Government Property Unit in the light of Construction Strategy 2011 and aligned with the principles and stages recommended by the BIM Task Group to facilitate facility management through the implementation of BIM. The process applies COBie as the data management protocol which forms a key part to Government plans to achieve Level 2 BIM 2016 onwards. Additionally, according to UK Government Construction 2025 (HM Government, 2013), it was expected that both the UK Government and construction industry will move to a new era of implementing Level 3 BIM from 2016 to 2025 to save cost, reduce carbon emission, build more sustainable buildings, and establish Digital Built Britain. Furthermore, the use of BIM for resource efficiency has been released by WRAP (2013a) to provide a strategic guideline for the user to manage the material resource in general to meet sustainability needs.

Current BIM standards and guidelines can provide methods for implementation of BIM, which have to be applied in real life BIM practices to validate their reliability.

2.3.3 Current BIM practices

The current BIM practice within the construction industry is implemented through approaches that are associated with a number of techniques and tools.

2.3.3.1 BIM approaches

Current BIM approaches can be summarised across five domains. These are ‘3D parametric modelling’, ‘simulation and analysis’, ‘enhanced coordination and communication for collaborative working’, ‘lifecycle information assessment and management', and 'information management across project lifecycle stages'. Based upon 3D parametric modelling, these BIM approaches support improving performance of construction lifecycle stages as illustrated in Figure 2.3. This indicates that the 3D parametric modelling is a core enabler for BIM knowledge integration within BIM approaches. In other words, the outcome of the 3D parametric modelling, the 3D parametric model, is the common object to embed expertise in a reusable form which allows the assigning of different complex relationships and rules (Cavieres *et al*., 2011). Therefore, all current BIM approaches comply with Level 2 BIM and Level 3 BIM. They allow 3D model based collaboration and library management along with network based integration, through the use of a collaborative BIM hub for coordination and communication.

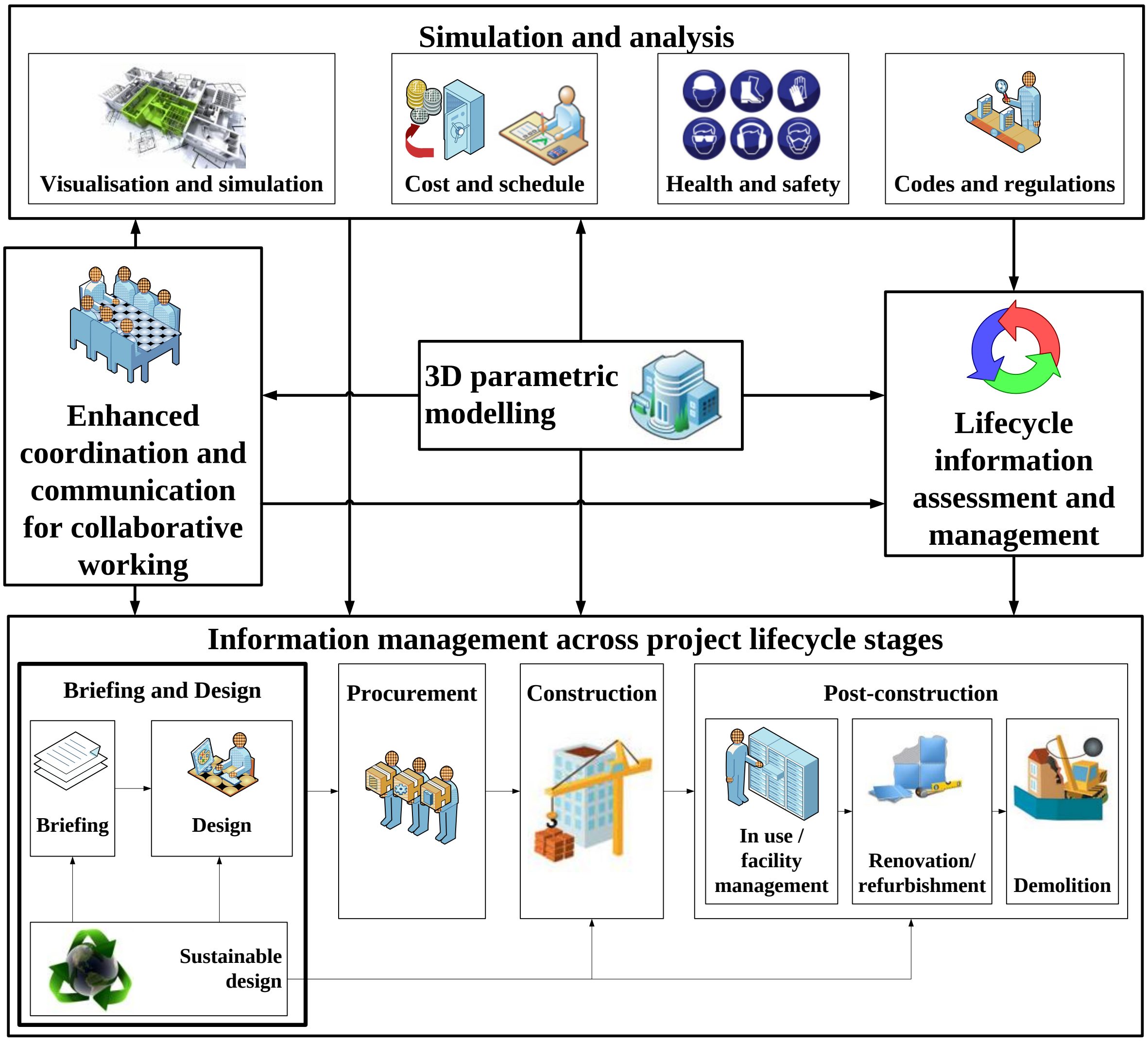


Figure 2.3 Current BIM approaches' conceptual framework (devised by the author based on the literature)

3D parametric modelling allows the user to parameterise different properties of model creation and modification, so that the design as a whole can be modified by a simple adjustment of parameter to the modification (Steel *et al*., 2012). In this view, the readjustment can interactively operate all parts of the building model through parametric relations. For example, if a piece of external wall is moved by the re-adjustment, then all the vertical walls connected to the original wall will be moved correspondingly and all related objects will also be affected. This underlines the significant 3D parametric modelling performance for solving the problem of complexity within building design. Different models of architectural, structural and services parts within the building models as a unit differ from each other. They incorporate large numbers of parts in the assembly, coordinate relationships between the model parts that are restricted to each other and predetermine the sequence of re-evaluation in response to parametric changes (Sacks *et al*., 2004). Furthermore, there are different model types used at different levels of complexity, namely, level of detail (LOD). This is utilised by parametric modelling in facilitating the various purposes of BIM approaches (Gruen *et al*., 2009). Hence, the current 3D parametric modelling aims to support the data required for other BIM approaches such as simulation and analysis, lifecycle information assessment and management, coordination and communication and performance of construction lifecycle stages. According to the NBS (2013) national survey, the most used BIM packages for 3D parametric modelling are Autodesk Revit, Tekla Structures, Bentley Architecture, Graphisoft ArchiCAD and Nemetschek Vectorworks.

The latest BIM techniques and tools have been developed to facilitate these approaches and are discussed in the following sections.

2.3.3.2 BIM techniques and tools

As shown in Figure 2.3, there are currently four main approaches in the current use of BIM alongside their supporting techniques and tools. These are simulation and analysis, enhanced coordination and communication for collaborative working, lifecycle information assessment and management, and information management across project lifecycle stages.

I. Simulation and analysis

Simulation and analysis through BIM includes four main aspects, such as visualisation and simulation, cost and schedule, health and safety, and codes and regulations.

Visualisation and simulation

As presented in Table 2.8, current visualisation and simulation within BIM has been used for design, construction, and post-construction, health and safety, co-ordination and communication, lifecycle information assessment and management. It is clear from Table 2.8 that design and construction stages are more likely to gain benefit by implementing BIM-related visualisation and simulation techniques and tools.

These techniques and tools are implemented through the 3D parametric BIM model, which is exchanged via standards, such as IFC, or schema for various applications. These applications are Augmented Reality (AR), 4D, Radio Frequency Identification (RFID), Virtual Reality (VR), Virtual Prototype (VP) for user experience analysis, building spatial analysis, constructability analysis in design, on-site construction process control and management, health and safety management and coordination and communication. The proven benefits of these visualisation and simulation techniques are the improvement to working experience, increase spatial cognition and better reliance on past experience (Keller and Tergan, 2005; Bowman *et al*., 2006). It is important for project team members to evaluatate the design via various perspective views thoughout visualisation and simulation in BIM during early design stages (Yan *et al*., 2011). However, there are few challenges related to 3D parametric BIM model to the use of BIM for visualisation and simulation, such as time-consuming processes for both preparation of inputting model for simulation (Wellel *et al*., 2011) and conducting analytical model simulation (Hong *et al*., 2008), and inaccurate and inconsistent exchange of architectural model to analytical models (Bazjanac and Kiviniemi 2007; Wellel *et al*., 2011; Kovacic *et al*., 2013).

Table 2.8 Current visualisation & simulation for simulation and analysis BIM approach (compiled from literature)

Current visualisation & simulation in BIM	**Briefing**		**Design**				**Procurement**		**Construction**			**Post-construction**			**Source**
	Appraisal	Design Brief	Concept	Design Development	Technical Design	Production Information	Tender Documentation	Tender Action	Mobilisation	Construction to Practical Completion	Post Practical Completion	In use /Facility Management	Renovation	Demolition	
3D models and Augmented Reality representations for imagining the scene of non-existing buildings in an existing environment <**AR**>		√													Shin *et al.*, 2013
Occupant flow in building spaces <**IFC**>			√												Nassar, 2010
A knowledge-based framework for automated space-use analysis < **Knowledge database**>			√												Kim *et al.*, 2013
Integrating BIM and gaming for real-time interactive architectural visualization <**Game**>			√	√											Yan *et al.*, 2011
User activity simulation and evaluation <**Game**>			√	√											Shen *et al.*, 2012a
Simulation of the user experience for design optimisation <**SMART Move**>			√	√											Sharma and Fisher, 2013
Topological information extraction model <**IFC**>			√	√											Jeong & Ban, 2011
IFC space database for automated design review <**IFC**>			√	√											Lee *et al.*, 2012a
Querying BIM model for construction-specific spatial analysis <**IFC**>			√	√											Nepal *et al.*, 2012
Virtual Prototyping technology to prefabricated construction <**VP**>			√	√	√	√									Li *et al.*, 2008
Set-based design to structural analysis <**IFC**>					√	√									Lee *et al.*, 2012b
Safety management and visualization system <**Game, RFID, AR**>										√					Park and Kim, 2013
4D visualisation for safety management in metro construction <**4D**>										√					Zhou *et al.*, 2013
4D object-based system for visualizing the risk information of construction projects <**4D**>										√					Kang *et al.*, 2013
4D visualisation system for field monitoring data <**4D**>										√					Hsieh and Lu, 2012
Integrates AR and BIM associated with radio frequency identification (RFID) for on-site construction <**AR, RFID**>										√					Wang *et al.*, 2013
AR with BIM for construction defect management <**AR**>										√					Park *et al.*, 2013
AR-based site inspection <**AR, camera**>										√					Shin and Dunston, 2010
BIM-based serious game for fire safety evacuation simulations <**Game**>												√			Rüppel and Schatz, 2011
4D, BIM model, AR and VR visualisation for health and safety in Table 2.10										√					
Pre-occupancy evaluation simulation; virtual reality simulation; building performance simulation; AR on site communication in Table 2.12			√	√	√	√				√		√			
Virtual project development simulation; PIIM in Table 2.13		√	√	√	√	√				√		√	√	√	
Lean production management systems for construction by visualisation; 4D visualisation of work flow to lean construction; information visualisation for multi-system construction in Table 2.18										√					
AR method for facility management techniques Table 2.19												√			

Cost and schedule

Cost and schedule known as 5D and 4D applications within BIM have been heavily used for technical design, tender and procurement and onsite construction, through quantity takeoff from the BIM model, supply chain management and lifecycle assessment, as shown in Table 2.9. The 4D model, through inclusion of the schedule can help to improve many areas. Improvement areas include: coordination and communication of construction processes related to construction timing, material lead times, labour involvements, and equipment implementation. It also eliminates problems associated with schedule misinterpretation through enhanced visualisation by merging the schedule into the virtual construction process (Koo and Fischer, 2000; Hardin, 2009). Currently, most construction scheduling techniques and tools use the critical path method or the project evaluation and review technique for planning analysis (Mikulakova *et al.*, 2010). Through linking the building components and construction processes in 4D, the 5D cost management is more effective (Cheung *et al.*, 2012). There are many tools within the market to assess the cost performance of design such as DProfiler. This estimates the cost based on a schematic BIM model at the conceptual design stage. The Vico Cost Planner allows users to plan and estimate building cost as the design evolves and updates automatically with reference to imported building models.

Health and safety

Table 2.10 indicates that the current use of BIM within health and safety management issues focuses on the construction stage. Health and safety issues facilitated by BIM techniques and tools are summarised into the following four themes:

- implementation of visualisation technology within construction safety management such as 4D visualisation, VR, AR, animation, 3D walk through and rendering;
- application of advanced tracking and navigation techniques for safety management, such as GIS and RFID;
- cloud based information/knowledge management system for safety management; and
- game simulation of human behaviour for safety management.

Codes and regulations

Codes and regulations through BIM range from building codes and safety to the techniques of fabrication and assembly, to comply with acoustic standards, fire safety regulations and energy performance requirements (Eastman *et al.*, 2009; Pauwels *et al.*, 2011). BIM allows both automatic parametric generation of designs that respond to various criteria and the prospect of computer-interpretable models with automated design checking after they are generated (Eastman *et al.*, 2008). The code and regulation based automated compliance checking is the quality guarantee of design and construction that reduces quality inspection errors. Consequently, it improves quality compliance and reduces violation to the regulations that govern the construction process (Zhong *et al.*, 2012). Hence, the current use of BIM for code and regulation checking is focused on both design and construction stages, as shown in Table 2.11. These code and regulation based assessment tools within BIM are implemented across various platforms, which consist of an embedded application within a design tool that allows checking whenever the designer wishes, or cloud based applications for design retrieving guidance from a variety of sources.

Furthermore, the code and regulation based checking within BIM is enabled by usage of IFC. This was described by Eastman *et al.* (2009) as a design tool having independent and neutral data model representation that is supported by most BIM design tools, which is being used as the building model representation in most of the efforts reviewed here (Table 2.11).

Table 2.9 Current cost and schedule for simulation and analysis BIM approach (compiled from literature)

Current cost and schedule in BIM	Briefing		Design				Procurement		Construction			Post-construction			Source
	Appraisal	Design Brief	Concept	Design Development	Technical Design	Production Information	Tender Documentation	Tender Action	Mobilisation	Construction to Practical Completion	Post Practical Completion	In use /Facility Management	Renovation	Demolition	
Early stage multi-level cost estimation for schematic BIM models <**IFC**>			√												Cheung *et al*., 2012
Cost estimation for tendering based on IFC data of design model <**IFC**>							√								Ma *et al*., 2013
Cost of design error for design validation					√	√									Lee *et al*., 2012
Work breakdown system (WBS) <**IFC**>					√	√	√			√					Song *et al*., 2012
FReMAS (Functional Requirement Model for Automatic Sequencing)					√	√	√			√					Chua *et al*., 2013
MD (multi-dimensional) CAD model for development of the time-cost integrated schedule					√	√	√			√					Feng *et al*., 2010
Knowledge-based schedule generation and evaluation					√	√	√		√	√	√	√	√	√	Mikulakova *et al*., 2010
4D techniques for visualisation and simulation in Table 2.8										√					
4D techniques for health and safety in Table 2.10					√	√				√					
PIIM in Table 2.13				√	√	√	√		√	√	√	√	√	√	
Early stage multi-level cost estimation; IPD design error management 4D in Table 2.14		√			√	√									
4D visualization of work flow to lean construction; automated construction progress measurement using a 4D building information model and 3D data; An automated construction progress tracking system using 4D modelling and 3D laser scanning in Table 2.18										√					

Table 2.10 Current health and safety for simulation and analysis BIM approach (compiled from literature)

Current health and safety in BIM	Briefing		Design				Procurement		Construction			Post-construction			Source
	Appraisal	Design Brief	Concept	Design Development	Technical Design	Production Information	Tender Documentation	Tender Action	Mobilisation	Construction to Practical Completion	Post Practical Completion	In use /Facility Management	Renovation	Demolition	
Associated with Geographical Information System for site selection and fire response management <**GIS**>		√													Isikdag *et al.*, 2008
8D BIM modelling tool for accident prevention through design <**nD**>					√	√									Kamardeen, 2010
BIM-based site layout and safety planning <**4D**>										√					Sulankivi *et al.*, 2009
Communicating and implementing a construction site safety plan <**4D, 3D rendering & walk through**>					√	√				√					Azhar and Behringer, 2013
4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction <**4D**>										√					Hu and Zhang, 2011
Web-based system for safety risk early warning in urban metro construction <**Web-based**>										√					Ding and Zhou, 2013
GIS based navigable 3D animation in safety planning process < **GIS, 3D animation**>										√					Bansal, 2011
Real-time resource location data collection and visualization technology for construction safety and activity monitoring applications <**VR, RFID**>										√					Cheng and Teizer, 2013
BIM based information displays for construction site safety communication <**4D**>										√					Kiviniemi *et al.*, 2011
Safety management and visualization system (SMVS) <**RFID, AR, Game**>										√					Park and Kim, 2013
BIM-based serious game for fire safety evacuation simulations <**Game**>												√			Rüppel and Schatz, 2011
BIM and safety code checking in Table 2.11										√					

Table 2.11 Current code and regulation for simulation and analysis BIM approach (compiled from literature)

Current code and regulation in BIM	**Briefing**		**Design**				**Procurement**		**Construction**			**Post-construction**			**Source**
	Appraisal	Design Brief	Concept	Design Development	Technical Design	Production Information	Tender Documentation	Tender Action	Mobilisation	Construction to Practical Completion	Post Practical Completion	In use /Facility Management	Renovation	Demolition	
Knowledge-based parametric tools for conceptual design and preliminary structural analysis <**IFC**>			√												Cavieres *et al.*, 2011
Automatic rule-based checking of building designs				√	√	√							√		Eastman *et al.*, 2009
Semantic web rule checking environment for building performance checking <**Web-based**>					√	√									Pauwels *et al.*, 2011
Model checking in building design <**XML, LING**>				√	√	√									Nawari, 2012
Semantic modelling of regulation constraint for automated construction quality compliance checking <**IFC**>										√					Zhong *et al.*, 2012
Semantic organisation of conformance requirements in construction <**IFC**>										√					Yurchyshyna and Zarli, 2009
Share architectural drawing information and document information for automated code checking system <**STEP, XML**>					√	√	√			√					Choi and Kim, 2008
BIM and safety										√					Zhang *et al.*, 2013
LicA: automated code-checking application for water distribution										√		√			Martins and Monteiro, 2013
4D visualisation for safety code checking in Table 2.8										√					
Consistency checking for coordination in Table 2.12				√	√	√									
PIIM in Table 2.13				√	√	√	√		√	√	√	√	√	√	

II. Enhanced coordination and communication for collaborative working

BIM-enhanced coordination and communication for collaborative working are fundamental features offered by BIM (Eastman *et al.*, 2008). They influence all aspects of construction projects across all lifecycle stages and have a huge impact on design and construction stages in particular, as shown in Table 2.12. BIM helps to streamline processes that use 3D parametric models and facilitates communication among disparate members of the project stakeholders such as client, design team and contractor, to achieve a better understanding and speed of decision making (Greenwood *et al.*, 2008; Shelden, 2013). This decision making requires effective coordination and communication to be delivered without any interoperability problems at company level, design team level and project level. Enhanced coordination and communication for collaborative working via BIM is achieved through enhanced human communication, innovative visualisation, a rich knowledge database and parametric 3D interaction. This transforms the current BIM practice into being more competitive, productive and creative (Grilo and Jardim-Goncalves, 2010).

The efficacy of enhanced coordination and communication for collaborative working processes within BIM can determine the success of the project if effective coordination through BIM is implemented to manage conflict between project participants' models, known as clash detection (Kim and Grobler, 2009). The current use of BIM for coordination is not only to ensure design-phase coordinated 3D models, but also in monitoring the scale and speed of construction and retain responsibility for site management and work coordination (Davies and Harty, 2013).

Table 2.12 Current enhanced coordination and communication for collaborative working through BIM (compiled from literature)

Current enhanced coordination and communication for collaborative working through BIM	**Briefing**		**Design**				**Procurement**		**Construction**			**Post-construction**			**Source**
	Appraisal	Design Brief	Concept	Design Development	Technical Design	Production Information	Tender Documentation	Tender Action	Mobilisation	Construction to Practical Completion	Post Practical Completion	In use /Facility Management	Renovation	Demolition	
Pre-occupancy evaluation method (UPOEM)			√												Shen *et al.*, 2013
Decision-making in a model-based design process			√												Schade *et al.*, 2011
Networked geometry for communication for multidisciplinary design				√	√	√									Shelden, 2013
Virtual Reality <**VR**>			√												Greenwood *et al.*, 2008
Building performance simulation (BPS) through building simulation visualization <**IFC**>			√	√	√	√				√		√			Hamza and DeWilde, 2014
BIM + AR on site communication <**AR**>										√					Wang and Love, 2012
i-Booth onsite information management kiosk <**VR**>										√					Ruwanpura *et al.*, 2012
Virtual workspaces enhanced communication and collaboration in design review				√	√	√									Bassanino *et al.*, 2013
Social e-business and the satellite network model PLAGE platform <**Web-based, IFC**>										√					Costa and Tavares, 2012
Construction collaborative networks for business interoperability quotient measurement model (BIQMM) <**IFC**>					√	√	√			√					Grilo *et al.*, 2013
A cloud AR for construction <**AR, Cloud BIM, Web 3D**>										√					Jiao *et al.*, 2013a
3D object models based interdisciplinary coordination and collaboration			√	√	√	√									Moum, 2010
Building information model-based synchronous collaboration				√	√	√									Isikdag & Underwood, 2010
Consistency checking				√	√	√									Kim and Grobler, 2009
Site BIM for coordination										√					Davies and Harty, 2013
nD modelling for collaborative working		√	√	√	√	√	√		√	√	√	√	√	√	Aouad *et al.*, 2005
Knowledge-based framework for automated space-use analysis communication; user activity simulation communication; Simulation of the user experience communication in Table 2.8			√	√											
A 3D analyzer for BIM-enabled Life Cycle Assessment communication; IFC and building lifecycle management in Table 2.13		√	√	√	√	√				√		√	√		
Services design coordination through LOD; 3D model based collaboration and communication in Table 2.14				√	√	√									
Integrated construction supply chain collaboration in Table 2.17		√	√	√	√	√	√								

However, there are a few concerns regarding BIM aided coordination and communication. Neff *et al.* (2010) reported that there is sometimes difficulty in overcoming the lack of interpretive flexibility through the use of digital coordination and communication tools, even when those tools are designed to encourage interdisciplinary collaborative working which really depends upon BIM skills of team members and organisational status. In addition, Dossick and Neff (2011) found that BIM technologies made the design, fabrication and construction processes more efficient in terms of data exchange and coordination and communication of problems or issues between project participants. Nonetheless, representations of structured meeting conversations in BIM do not necessarily make the process of finding a solution more efficient or effective. On the other hand, a recent study conducted by Bassanino *et al.* (2013) stated that BIM can be further utilised to enhance team coordination and communication during design review meetings to make them more productive in reducing time and costs; therefore, increasing the quality of the final product by integrating real-time collaborative workspace.

Therefore, current BIM techniques and tools for enhanced coordination and communication for collaborative working as shown in Table 2.12, include (1) using stakeholders' integrated 3D parametric models for coordination and communication of design intent by providing 3D views of BIM models through improved visualisation, such as AR, VR, and Web 3D; (2) avoiding gaps and overlaps; therefore, achieving results efficiently when coordinating and communicating within a complex project. This is through coordinating all parts of the project model within a compiled model, and any existing conflicts can be detected and resolved by clash detection and cloud BIM applications via IFC; (3) setting collaborative joint goals and responsibilities for the development of innovative solutions. This results in a 3D parametric BIM model as a common method to ensure enhanced coordination and communication for collaborative working by the various project team members on most relevant briefing, design and construction issues. Associating 3D parametric BIM models with on-line tools, such as a cloud BIM server and forums, would help achieving better interoperability performance (Redmond *et al*., 2012).

III. **Lifecycle information assessment and management**

BIM enhanced lifecycle information assessment and management is to generate, assess, store, manage, exchange and share building information in an interoperable and reusable method that enables users to integrate and reuse building information domain knowledge throughout the lifecycle of a building (Lee *et al.*, 2006; Vanlande *et al.*, 2008). As shown in Table 2.13, building lifecycle information assessment and management in BIM considers the entire impact of building lifecycle. As such, building designers can select products and processes that have the least impact on the environment through environmental assessment by applying IFC based BIM whilst considering the whole lifecycle information of the building and integrating technologies to provide an efficient analysis which supports 3D visualisation and user interaction (Kulahcioglu *et al*., 2012; Basbagill *et al*., 2013). Through the information assessment, the complete building lifecycle information within BIM is able to assist in simulating the project on the basis of the project 3D parametric model via IFC. This calculates the precise resource demand, determines the time scale of project implementation, and effectively assesses alternatives for the decision making through 4D and 5D applications (Popov *et al*., 2010; Wu and Hsieh, 2012). Furthermore, the building lifecycle assessment and management information within BIM is to be implemented when representing a virtual organisation by the cloud-based service platform acting on a layered multi-model based environment. It supports a well-directed application of design and construction information for decision making by project stakeholders on all technical and management levels and lifecycle stages (Scherer and Schapke, 2011; Wu and Hsieh, 2012; Jiao *et al*., 20013b; Kulahcioglu *et al*., 2012).

IV. **BIM assisted information management across project lifecycle stages**

A computer database model of building design information contains information through BIM regarding building design, procurement, construction and post-construction, i.e. in use operation and maintenance (facility management), renovation and demolition (Howell and Batcheler, 2005).

Table 2.13 Current lifecycle information assessment and management through BIM (compiled from literature)

Current lifecycle information assessment and management through BIM	Briefing		Design				Procurement		Construction			Post-construction			Source
	Appraisal	Design Brief	Concept	Design Development	Technical Design	Production Information	Tender Documentation	Tender Action	Mobilisation	Construction to Practical Completion	Post Practical Completion	In use /Facility Management	Renovation	Demolition	
Life-cycle assessment to early stage building design for reduced embodied environmental impacts <**IFC**>			√	√											Basbagill *et al.*, 2013
A 3D analyzer for BIM-enabled Life Cycle Assessment of the whole process of construction <**IFC**>			√	√	√	√				√					Kulahcioglu *et al.*, 2012
Virtual project development (VPD) <**5D**>		√	√	√	√	√				√		√	√		Popov *et al.*, 2010
PIIM Framework (Project Information Integration Management Framework) <**IFC, 4D, 5D**>				√	√	√	√		√	√	√	√	√	√	Wu and Hsieh, 2012
The 'role and life-cycle information model' (RIM/LIM) for exchange of relevant information				√	√	√	√		√	√	√	√	√	√	Hjelseth, 2010
IFC and building lifecycle management <**IFC, Active 3D**>		√	√	√	√	√				√		√	√	√	Vanlande *et al.*, 2008
Multi-model-based Management Information System for simulation and decision-making <**IFC, Web-based**>	√	√	√	√	√	√	√		√	√	√	√	√	√	Scherer and Schapke, 2011
A cloud approach to unified lifecycle data management by Integrating BIMs and SNS <**IFC, Cloud-based**>	√	√	√	√	√	√	√		√	√	√	√	√	√	Jiao *et al.*, 2013b
Virtual collaborative life cycle tools in Table 2.17		√	√	√	√	√						√	√		

Briefing and Design

Briefing and Concept Design are critical in determining the success of a project throughout its lifecycle. BIM applications would help capture the needs of the client such as costs, building functions, visual impact and other more general factors (Eastman, 2009). As such, BIM currently has been used for site selection and site planning (Isikdag *et al.*, 2008), spatial planning (Lee *et al.*, 2008), multi-level cost estimation (Cheung *et al.*, 2012), integrated design and analysis (Thuesen *et al.*, 2010) and early-design lifecycle analysis (Basbagill *et al.*, 2013). The early design results provide a set of assessments from BIM applications to ensure that the same criteria is used for different variations and development of the same concept design within the developed and technical design (Penttila, 2007). As shown in Table 2.14, during the developed and technical design stage, current BIM techniques and tools are used to assist following design related activities:

- coordinate and communicate design of multiple disciplines (architectural, structural and services designs) and identify design conflicts (clash detection) prior to construction (Sebastian, 2010; Leite *et al.*, 2011; Love *et al.*, 2011).
- enable precast/prefabrication of components (modern methods of construction) prior to construction (Sacks *et al.*, 2010b);
- attain accurate geometric representation of all parts of the facility (CAD output) (Alwisy *et al.*, 2012);
- estimate the cost and schedule (5D, 4D) for supporting the decision making of design usability and constructability (Feng *et al.*, 2010; Song *et al.*, 2012); and
- assess the sustainability issues (e.g. energy, carbon, and material) (Welle *et al.*, 2012; Irizarry *et al.*, 2013a; Basbagill *et al.*, 2013).

At the Design stages, the sustainability issues are achieved through the use of a shared and coordinated common BIM model. This focuses on the finally completed and fully detailed 3D parametric model comprising of all design parts covering a geometrical model of the building, physical properties (e.g. materials) and functional peculiarities of components (Hoekstra, 2003; Gabbar *et al.*, 2004; Popov *et al.*, 2010). The common BIM model has the LOD to facilitate the aforementioned design activities throughout each design stage (Leite *et al.*, 2011). It allows users to define detailing and layout by characterising building model components with data for analysis, such as quantity take-off and specifications, to achieve sustainable design requirements (Xie *et al.*, 2010). CHAPTER TWO: Literature Review

BIM makes efficient achievement of design possible and more sustainable design in particular (Wong and Fan, 2013).

Sustainable design: Clients are putting a much greater emphasis on sustainable design by demanding energy efficiency, reduced carbon emissions, material efficiency, less water usage, and waste reduction (Malkin, 2010). Through the use of BIM, these sustainable design intents can be achieved more effective (Azhar and Brown, 2009).

Energy efficiency

According to the UK Department of Finance and Personnel (DFP, 2011), buildings contribute almost 50% of the UK's energy consumption and carbon emissions in total. This suggests that even minor changes to the energy performance of buildings would have a significant effect in reducing energy consumption and carbon emissions.

As shown in Table 2.15, issues relating to building energy efficiency through BIM facilitated simulation at the design stage are highlighted. These issues cover the size of the building and its Heating, Ventilation, Air-conditioning system (HVAC), building massing, building envelope, window locations, building orientation and other parameters.

By simulating energy performance using BIM during the design stages, the creation of a virtual energy performance model assists in predicting the energy demands and overall energy performance. This allows for scoping the appropriate solutions for reduction in energy loads in lighting and heating/air-conditioning (Krygiel and Nies, 2008). Once these energy systems have been established, changes to the design BIM model can be made. This will optimise the energy performance of each energy system to facilitate the selection of energy efficiency options, such as using renewable energy and reducing energy needs. Currently, there are various BIM technologies and tools available for energy efficiency such as the Green Building Studio, eQUEST, IES, Ecotect, Virtual environment, Virtual construction suite 2008, EnergyPlus and Radiance Wrapper (Yoon *et al.*, 2009; Osello *et al.*, 2011). An integrated energy analytical tool built into the BIM modelling platform can run the analysis, so the information of the 3D parametric model is exported out of the model in a standard file format, IFC or gbXML (Azhar and Brown, 2009; Lagüela *et al.*, 2013).

BIM-assisted energy efficiency design also potentially facilities simulation modelling for other sustainable design intents, such as carbon, material, and water (Malkin, 2010; Basbagill *et al.*, 2013; Kulahcioglu *et al.*, 2012).

Table 2.14 Current use of BIM for Briefing and Design (compiled from literature)

Current use of BIM for Briefing and Design	**Briefing**		**Design**				**Procurement**		**Construction**			**Post-construction**			**Source**
	Appraisal	Design Brief	Concept	Design Development	Technical Design	Production Information	Tender Documentation	Tender Action	Mobilisation	Construction to Practical Completion	Post Practical Completion	In use /Facility Management	Renovation	Demolition	
BIM for Briefing space planning		√													Lee *et al*., 2008
Early stage multi-level cost estimation for schematic BIM models		√													Cheung *et al*., 2012
Architectural precast facades evaluation at conceptual design stage <**IFC**>			√												Sacks *et al*., 2010b
MCMPro (Automated Drafting and Design) for modular construction manufacturing					√	√									Alwisy *et al*., 2012
Design error reduction					√	√									Love *et al*., 2011
IPD design error management <**4D, 5D**>					√	√									Love *et al*., 2013a
Services (mechanical, electrical and plumbing (MEP)) design coordination through LOD				√	√	√									Leite *et al*., 2011
Occupant flow in building spaces			√	√											Nassar, 2010
An integrated approach for design and analysis			√	√	√	√	√			√	√	√	√		Sanguinetti *et al*., 2012
3D model based integrated design and engineering collaboration and communication				√	√	√									Sebastian, 2010
3D model based integrated design and delivery	√	√	√	√	√	√	√		√	√	√	√	√	√	Prins and Owen, 2010
Integrated design and delivery process	√	√	√	√	√	√	√		√	√	√	√	√	√	Rekola *et al*., 2010
3D models and AR for site plan; VP technology to prefabricated construction; set-based design to structural analysis; knowledge-based parametric tools for conceptual design; user activity simulation; simulation of the user experience; space-use analysis; topological information extraction model; IFC space database for automated design review in Table 3.8		√	√	√	√	√									
Early stage multi-level cost estimation; cost of design error in Table 2.9			√	√	√	√									
Associated with GIS for site selection in Table 2.10		√													
LCA to early stage building design in Table 2.13			√	√											

Table 2.15 Current use of BIM for energy efficiency (compiled from literature)

Current use of BIM for energy efficiency	**Briefing**		**Design**				**Procurement**		**Construction**			**Post-construction**			**Source**
	Appraisal	Design Brief	Concept	Design Development	Technical Design	Production Information	Tender Documentation	Tender Action	Mobilisation	Construction to Practical Completion	Post Practical Completion	In use /Facility Management	Renovation	Demolition	
Automatic HVAC fault detection and diagnosis system <**IFC**>				√	√	√									Zimmermann *et al.*, 2012
HVAC Design				√	√	√									Knight *et al.*, 2010
BIM-centric daylight profiler for simulation (BDP4SIM) <**IFC**>												√			Welle *et al.*, 2012
Visualisation of impact of time on the internal lighting <**VRML**>			√	√	√	√									Khosrowshahi and Alani, 2011
ThermalOpt: automated BIM-based multidisciplinary thermal simulation <**IFC**>			√	√	√	√									Wellel *et al.*, 2011
Semantic material name matching system for building energy analysis (BEA) <**IFCXML**>					√	√									Kim *et al.*, 2013b
Visual ratio of equivalent transparency (Req) calculation tool for green building evaluation <**gbXML**>					√	√									Wu and Chang, 2013
Evolving database structure for optimal design		√	√	√											Diao *et al.*, 2011
Automatic thermographic and RGB texture of as-built BIM for energy rehabilitation <**gbXML, 3D laser scan**>												√			Lagüela *et al.*, 2013
3D thermography and energy efficiency evaluation <**Infrared image, 3D laser scan**>												√			González-Aguilera *et al.*, 2012
Building operation and energy performance: monitoring, analysis and optimisation toolkit <**IFC**>												√			Costa *et al.*, 2013
Holistic system architecture for energy efficient building operation <**Wired/wireless sensor**>												√			Gökc and Gökc, 2013
Energy/exergy performance assessment in early design stages <**IFC, API**>		√	√												Schlueter and Thesseling, 2009
Systems modelling for sustainable building design		√	√	√	√	√						√	√		Geyer, 2012
Virtual collaborative life cycle tools to improve the energy performance of the built environment		√	√	√	√	√						√	√		Crosbie *et al.*, 2011

Carbon, material, water, and waste reduction

Table 2.16 indicates that current use of BIM techniques and tools in construction projects for carbon, material, water, and waste is focused mainly on construction stage.

The 3D parametric BIM model based carbon quantification (Mah *et al.*, 2011) and VP integrated BIM for visualisation of carbon prediction (Wong *et al.*, 2012) have been used for on-site carbon reduction.

BIM has the ability to assist material resource efficiency through effective scheduling and accurate material quantities (Hardin, 2009). Currently, BIM has provided information on when a portion of work is scheduled to begin and be completed, the amount of materials required, with timely controlled delivery of materials for on-site materials planning and tracking. To achieve that, BIM has been integrated with several techniques and tools, such as RFID and GPS (Razavi and Haas, 2010), Enterprise resource planning (ERP) (Babič *et al.*, 2010), and GIS (Irizarry *et al.*, 2013a). Because fewer materials are stored on the construction site, less material will be damaged before its use (Razavi and Haas, 2010). However, this also raises a challenge to ensure the right amount of materials is available on-site when needed; while reducing on-site material storage through controlled 'in-time' delivery (Babič *et al.*, 2010). This challenge could be addressed by using BIM tools, such as Navisworks, to simulate the construction processes to find redundancies in the schedule and revise it manually (Hardin, 2009).

Currently, there is limited published evidence on the current use of BIM for water and waste reduction.

An IFC BIM model database enabled code-checking system has been developed by Martins and Monteiro (2013) for monitoring water usage and distribution during construction and post-construction stages.

As mentioned in section 2.2.4.3, BIM has currently been used for structural analysis to reduce metal bar waste (a part of bar material efficiency) by applying the as-planned 3D parametric model in technical design; and provided the estimation of renovation and demolition waste for landfill via an IFC-model-based API application which exchanges as-built 3D parametric model information during post-construction stages, such as renovation/refurbishment, and demolition.

Table 2.16 Current use of BIM for carbon, material, water, and waste reduction (compiled from literature)

Current use of BIM for carbon, material, water, and waste reduction	**Briefing**		**Design**				**Procurement**		**Construction**			**Post-construction**			**Source**
	Appraisal	Design Brief	Concept	Design Development	Technical Design	Production Information	Tender Documentation	Tender Action	Mobilisation	Construction to Practical Completion	Post Practical Completion	In use /Facility Management	Renovation	Demolition	
Carbon															
Carbon emissions quantification in housing construction process										√					Mah *et al.*, 2011
Visualisation of predicted onsite carbon emission control via virtual prototyping technology										√					Wong *et al.*, 2012
Material															
Multi-sensor data fusion for on-site materials tracking in construction <**RFID, GPS**>										√					Razavi and Haas, 2010
Integrating resource production and construction <**IFC, ERP**>										√					Babič *et al.*, 2010
Integrated BIM-GIS system for visualizing the supply chain process <**GIS**>					√	√	√			√					Irizarry *et al.*, 2013a
Water															
Code-checking application for water distribution in Table 2.11										√		√			
Waste															
BIM to demolition and renovation waste in Table 2.7													√	√	
BIM based structural analysis tool for metal bar waste reduction in Table 2.7					√	√									

All information generated from the design stages must be processed and retained in a common format which all project participants can share. This can be achieved through the use of object-oriented attributes and meta-data within the BIM model for later project lifecycle stages, namely, procurement, construction and post-construction (Lee *et al.*, 2008).

<u>Procurement stage</u>

Table 2.17 shows BIM techniques and tools during procurement are currently used for tender, supply chain management and e-procurement solutions.

By using BIM enhanced semi-automatic and specification-compliant cost estimation based on IFC data from the 3D parametric design model, tendering documentation can be coordinated without errors that are commonly caused by working with traditional 2D representation of design in a complex project environment (Ma *et al.*, 2013). It appears that cloud based and API enabled BIM is being developed for the next generation BIM-aided procurement, e-procurement. London and Singh (2013) created a cloud based BIM model server (IFC enabled) for virtual team collaboration to facilitate integrated construction supply chain management throughout the design and procurement stages. Grilo and Jardim-Goncalves (2013) further developed the concept as an e-platform (cloud-market), which is a BIM model driven and service oriented API for interoperable communities during procurement.

<u>Construction stage</u>

Each construction project is a complex and dynamic system that raises considerable complexity and difficulties to construction design and planning, site management and construction management (Zhang and Li, 2010). BIM has been used to solve these difficulties by achieving goals in construction such as reduction in requests for information and change of orders, satisfaction through visualisation, improved productivity in scheduling, faster and more effective construction management with easier information exchange (Leite *et al.*, 2011). As shown in Table 2.18, current BIM techniques and tools are applied for these goals through on-site coordination and communication, through the implementation of on-site BIM applications. There are various state-of-the-art techniques being integrated into BIM applications such as cloud computing, AR, RFID, GPS, 3D laser scanning, and nD. These facilitate on-site construction management through monitoring of the construction quality, schedule and material efficiency during the construction.

Post-construction stages

Post-construction comprises three stages: in use, renovation/refurbishment and demolition.

In use (facility management)**:** BIM has provided an environment through which any related information regarding a 3D entity can be retrieved and updated by facility managers during the whole project lifecycle (Tse *et al.*, 2005). This 3D entity model (as-built model) contains integrated information from the construction activities associated with design, therefore facilitating the use of BIM for facility management. On the other hand, the process of knowledge transfer from building facility management feedback to building design through BIM knowledge database facilitates better building design for new projects (Jensen, 2009). Current usage of BIM for facility management focuses on building product lifecycle information management, interior utility management and re-survey of buildings to as-built models for further use. This is shown in Table 2.19. Cloud based BIM information and role-based RFID techniques and tools have been used for building product lifecycle information management (Shen *et al.*, 2012b). Moreover, there are a number of techniques and tools associated with BIM that have been developed to assist the management of facilities such as GIS (Hijazi *et al.*, 2012), CityGML (Hijazi *et al.*, 2011), RFID (Costin *et al.*, 2012a), AR enhanced mobile application (Irizarry *et al.*, 2013b) and fieldwork support (Lee and Akin, 2011). Furthermore, it seems that 3D laser scanning is the preferred solution in the re-survey of buildings to generate an as-built model for further use by creating point clouds, verifying the models based on images and video clips (Brilakis *et al.*, 2010; Tang *et al.*, 2010; Murphy *et al.*, 2013; Xiong *et al.*, 2013)

Table 2.17 Current use of BIM for Procurement (compiled from literature)

Current use of BIM for Procurement	**Briefing**		**Design**				**Procurement**		**Construction**			**Post-construction**			**Source**
	Appraisal	Design Brief	Concept	Design Development	Technical Design	Production Information	Tender Documentation	Tender Action	Mobilisation	Construction to Practical Completion	Post Practical Completion	In use /Facility Management	Renovation	Demolition	
PLAGE Platform for e-procurement management <**IFC, Cloud-based**>							√								Grilo and Jardim-Goncalves, 2011
Cloud-Marketplaces based BIM for e-procurement <**Cloud-based**>							√								Grilo and Jardim-Goncalves, 2013
Integrated electronic commerce material procurement and supplier performance management system							√								Ren *et al.*, 2012
Integrated construction supply chain <**Cloud-based**>			√	√	√	√	√			√					London and Singh, 2013
Cost estimation for tendering based on IFC data of design model in Table 2.9							√								
Integrated BIM-GIS system for visualizing the supply chain process in Table 2.16					√	√	√			√					

Table 2.18 Current use of BIM for Construction (compiled from literature)

	Briefing		**Design**				**Procurement**		**Construction**			**Post-construction**			
Current use of BIM for Construction	Appraisal	Design Brief	Concept	Design Development	Technical Design	Production Information	Tender Documentation	Tender Action	Mobilisation	Construction to Practical Completion	Post Practical Completion	In use /Facility Management	Renovation	Demolition	**Source**
Lean production management systems for construction										√					Sacks *et al.*, 2010
4D visualisation of work flow to lean construction <**4D**>										√					Sacks *et al.*, 2009
nD technology to an integrated construction management system for city rail transit construction <**nD**>										√					Ding *et al.*, 2012
Information visualisation for multi-system construction										√					Kuo *et al.*, 2011
Object-based 3D walk-through model interior construction progress monitoring <**Photo matching**>										√					Roh *et al.*, 2011
Automated construction progress measurement using a 4D building information model and 3D data <**4D, Remote-sensing**>										√					Kim *et al.*, 2013
A semi-automated plane-based coarse registration approach for as-built model generation onsite <**4D, 3D laser scan**>										√					Bosché, 2012
An automated construction progress tracking system using 4D modelling and 3D laser scanning <**4D, 3D laser scan**>										√					Turkan *et al.*, 2012
A graph-based model for the identification of the impact of design changes										√					Isaac and Navon, 2013
AR with BIM for construction defect management; 4D visualisation system for field monitoring data; 4D object-based system for visualizing the risk information of construction projects; integrates AR and BIM associated with RFID for construction on-site; AR-based site inspection in Table 2.08										√					
4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction; safety management and visualization system (AR) in Table 2.10										√					
Site BIM for coordination; i-Booth onsite information management; BIM + AR on site communication; A cloud AR for construction in Table 2.12										√					
Integrating resource production and construction; Multi-sensor data fusion for on-site materials tracking in construction in Table 2.16										√					

Table 2.19 Current use of BIM for Post-construction (compiled from literature)

Current use of BIM for Post-construction	Briefing		Design				Procurement		Construction			Post-construction			Source
	Appraisal	Design Brief	Concept	Design Development	Technical Design	Production Information	Tender Documentation	Tender Action	Mobilisation	Construction to Practical Completion	Post Practical Completion	In use /Facility Management	Renovation	Demolition	
In use / Facility management															
3D GIS for representing and analysing interior utility networks <**GIS**>												√			Hijazi *et al.*, 2012
An integrated framework for representing the relation among building structure and interior utilities <**IFC, CityGML**>												√			Hijazi *et al.*, 2011
RFID and a BIM model for real-time resource location tracking <**RFID**>												√			Costin *et al.*, 2012a
Integration approach for decision support in facility management <**RFID, Web-based**>												√	√	√	Shen *et al.*, 2012b
A knowledge-based BIM system for building maintenance												√			Motawa and Almarshad, 2013
InfoSPOT: a mobile AR method for facility management <**AR, Mobile-based**>												√			Irizarry *et al.*, 2013b
AR based computational fieldwork support for equipment operations and maintenance <**AR**>												√			Lee and Akin, 2011
Laser and image based surveys of historic building information modelling <**3D laser scan**>												√			Murphy *et al.*, 2013
Automatic reconstruction of as-built building information models from laser-scanned point clouds <**3D laser scan**>												√			Tang *et al.*, 2010
Imaged-based verification of as-built documentation of operational buildings < **Imaged-based**>												√			Klein *et al.*, 2012
Automatic creation of semantically rich 3D building models from laser scanner data <**3D laser scan**>												√			Xiong *et al.*, 2013
Automated generation of parametric BIMs based on hybrid video and laser scanning data <**3D laser scan, Video-image-enhanced**>												√			Brilakis *et al.*, 2010
Code-checking application for water distribution in Table 2.11										√		√			
Automatic thermographic and RGB texture of as-built BIM for energy rehabilitation; building operation and energy performance: monitoring, analysis and optimisation toolkit in Table 2.15												√			
Renovation and demolition															
RFID technology for construction resource field mobility and status monitoring <**RFID**>													√		Costin *et al.*, 2012b
Workflow information management in BIM													√		Roorda and Liu, 2008
4D model based renovation planning framework <**4D**>													√		Ho and Fischer, 2009
BIM to demolition and renovation waste in Table 2.7													√	√	

Renovation/refurbishment: three BIM associated techniques and tools currently have been dedicated to the purpose of renovation, namely, 4D modelling, 3D laser scanning, and RFID. The former has been established as an effective tool for construction schedule visualisation and coordination within renovation projects, of which 4D model based analysis enables users to analyse schedules for a variety of design and construction issues such as workspace requirements, construction specifications and work in progress checks (Boukamp and Akinci, 2007; Ho and Fischer, 2009). Many existing buildings do not currently have an as-built model. 3D laser scanning integrated with BIM has been used for creating the as-built model for renovation purposes as mentioned above. Furthermore, RFID tags integrated within BIM analysis has been implemented for renovation resources tracking onsite. This offers a full automation of the data transfer process from the jobsite to a database for site operation and scheduling (Costin *et al.*, 2012b).

Demolition**:** Although there are a number of BIM-assisted techniques and tools that have the potential use for demolition in terms of information management across project lifecycle, such as 4D and 5D enhanced project information integration (Wu and Hsieh, 2012), role-based lifecycle information model exchange system (Hjelseth, 2010), and web-cloud hosted BIM and business social networking services integration (Jiao *et al*., 2013), there is currently one BIM techniques and tools has been used focusing on demolition.

2.3.3.3 Functional level of BIM practices

As shown in Figure 2.4, current BIM practice appears to contribute to building design and construction throughout the project lifecycle through the process of five functional levels. These are: model level, exchange level, dimension level, integration level, and implementation level with regard to various approaches, techniques and tools. Currently, a BIM model created by 3D parametric modelling with certain LOD at the model level is exchanged, if needed, by several standard formats at exchange level. The standard formats such as IFC and gbXML before passing for modelling purposes (e.g. 2D, 3D, 4D, 5D, 6D, 7D and nD) at dimension level. During this process, the modelling information can be integrated with various techniques (e.g. AR, GIS, and cloud computing) and tools (e.g. RFID, and 3D laser scanning) at integration level to facilitate BIM implementation. These functional levels are connected and shared through interoperability. Many BIM 3D model applications that measure the impact of sustainable design issues (e.g. energy efficiency) within the applications themselves are limited (Krygiel and Nies, 2008). Hence, exporting building information data to another application or imported from a data source could lead to the interoperability problem when data is used for other communication and collaborating purposes. Also, technical concerns over interoperability of various BIM packages and the availability of bandwidth to allow large volumes of data to flow smoothly are ongoing concerns, but are being addressed by major BIM developers, such as Autodesk (Emmitt, 2010). Therefore, interoperability is the barrier and essential facet for BIM success within building projects (Baldwin *et al*., 2009a; Jardim-Goncalves and Grilo, 2010). However, the path to interoperability may not come from a single BIM standard but a set of open standards (McGraw-Hill, 2007; Smith and Tardif, 2009). Over time, capabilities of interoperability will grow as will the ability to support better and more extensive techniques (Eastman *et al*., 2008).

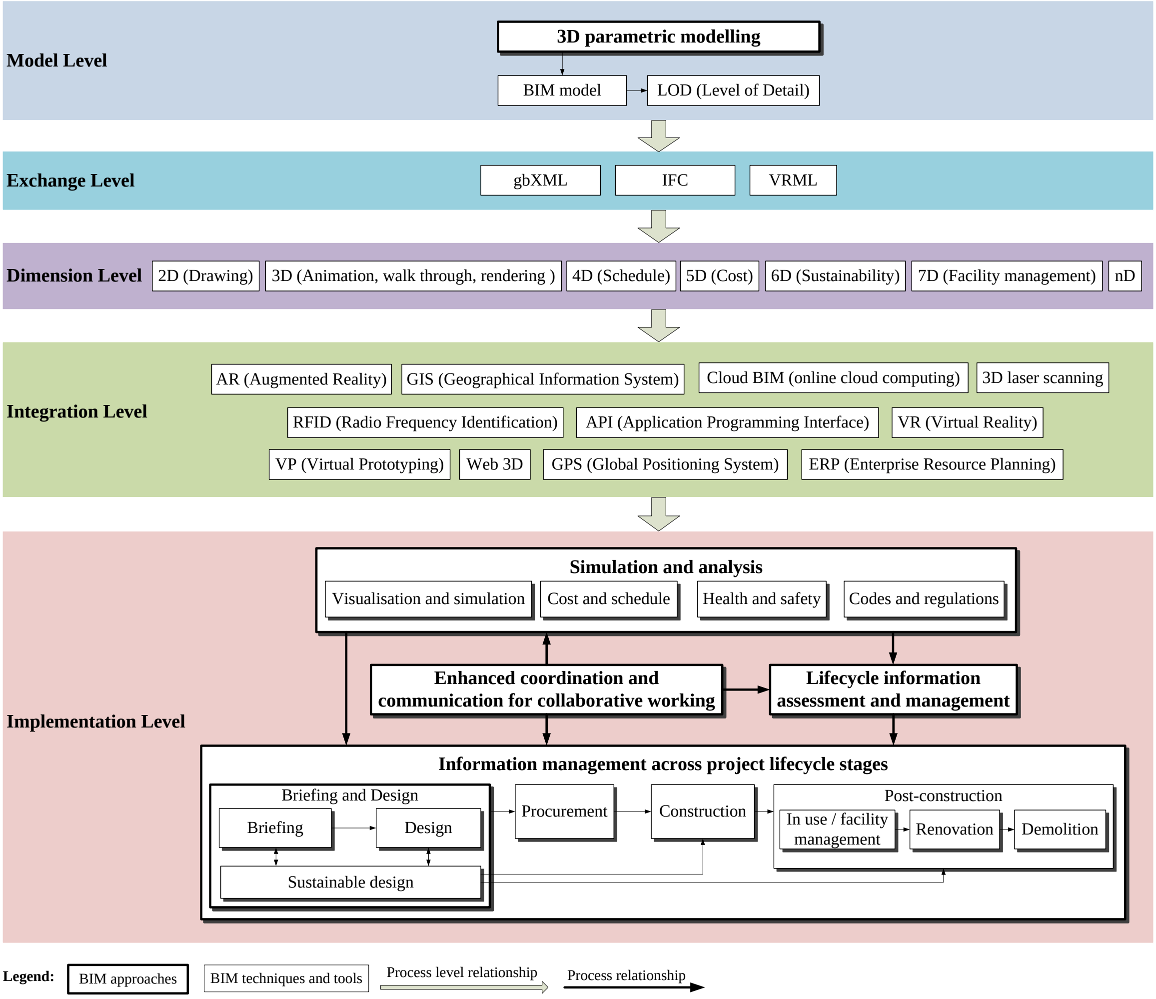


Figure 2.4 Current BIM practices (devised by the author based on the literature)

2.3.4 BIM adoption barriers and incentives

There are several barriers to the adoption of BIM (Bernstein and Pittman, 2004; Howard and Bjoïrk, 2008; Arayici *et al*., 2011; Ku and Taiebat, 2011; RICS, 2013), such as:

- Overcoming the resistance to change by getting project stakeholders to understand the potential and value of BIM.

- Insufficient standards and protocols for the required collaboration, integration and interoperability between project players.
- Lack of a framework/roadmap to outline the effective strategy and methodology of implementing BIM, training or finding project stakeholders to use and understand BIM.
- Unbalanced BIM adoption and implementation between project partners (e.g., architects, engineers, subcontractors).
- Lack of BIM model-related legal / contractual agreements.

There has recently been a rising legal concern over ownership of the BIM model, right to rely, shifting of risk, standard of care and compensation for BIM implementation (Arensman and Ozbek, 2012; Porwal and Hewage, 2013). Interestingly, the most recent survey conducted by RICS (2013) indicates that the lack of client demand is the biggest barrier to BIM adoption.

On the other hand, there are five main incentives that currently drive the use of BIM, namely, client driven, project manager interest (e.g. efficient communication and project management), increase in staff production due to easy retrieval of information, uptake at project level (cost efficiencies and increase in delivery speed) and UK Government Construction Strategy (in terms of mandatory implementation of BIM) (Mihindu and Arayici, 2008; NBS 2011, 2012, 2013). There are several project benefits to the incentives (Eastman *et al*., 2008; Azhar, 2011):

- Client, design team and contractor get faster and more effective processes through more easily shared information which can be value-added and reused.
- Better client satisfaction by better understanding through accurate visualisation and simulation.
- Quick first response in the early stages of design can contribute to the design and make building more efficient.
- Better design through rigorous analysis, quickly performed simulation, and benchmarked performance for enabling improved and innovative solutions.
- Better view of facilities for better decision making.
- Efficient control of whole-life costs and environmental data for more predictable environmental performance and better understanding of lifecycle costs.
- Better production quality by flexible output of documentation and automation of

exploits.

- Quicker automated assembly enabled by exploitation of digital product data in downstream processes and used for manufacturing and assembly.
- Rich lifecycle data of requirements, design, construction and operational information for facility management.

Therefore, BIM adoption process can be slower than imagined by the industry and government body, as the BIM is inclusive and engaged with people. Arayici *et al*. (2011) argued that BIM adoption can be successful through support from the top management, as people can be encouraged to use BIM through ‘learning by doing’. This is because BIM adoption and implementation is as much more about people and processes than it is about technology (Brewer and Gajendran, 2012). For individuals to engage in BIM adoption, they must believe that it helps them enhance their skills and understanding and increase their knowledge capacity (Davis, 2008). This can only be achieved through applying successful change management strategies and diminishing any potential resistance to change (Arayici *et al.*, 2011). Therefore, effective BIM implementation requires significant changes in how the construction industry works at almost every level within the building lifecycle process. This indicates that it does not only require that project team members learn new BIM techniques and acquire the necessary tools, but also how to reinvent the workflow through the use of BIM; how to train and assign responsibilities to the team members; and change how the design, construction and operation processes are managed (Bernstein and Pittman, 2004; Eastman et *al.*, 2008; Roorda and Liu, 2008; NBS, 2012).

2.4. The potential use of BIM for construction waste minimisation

These comprise: BIM-CWM focused investigation involving data collection and analysis (see section 2.4.1); and related studies that highlighted the potential of BIM to assist CWM without undertaking research actions (see section 2.4.2). These two clusters are discussed separately below.

2.4.1 BIM related construction waste researches

By and large, the current research on BIM related CWM on four key processes: 1) BIM-enhanced coordination for CWM, 2) BIM-enhanced design waste minimisation, 3) BIM-enhanced on-site waste management, and 4) BIM-enhanced demolition waste management, as shown in Table 2.20.

Table 2.20 Construction waste related current BIM studies (compiled from literature)

Construction waste related BIM topic	**Briefing stages**		**Design stages**				**Procurement stages**		**Construction stages**			**Post-construction stages**			**Research method**	**Source**
	Appraisal	Design Brief	Concept	Design Development	Technical Design	Production Information	Tender Documentation	Tender Action	Mobilisation	Construction to Practical Completion	Post Practical Completion	In use /Facility Management	Renovation	Demolition		
A BIM-based system for demolition and renovation waste estimation and planning														√	Case study	Cheng and Ma, 2013
Construction waste management at source: a building information modeling based system dynamics approach										√					Case study	Porwal, 2013
BIM utilisation to achieve resource efficiency in construction: Leeds Arena			√	√											Case study	WRAP, 2013a
BIM perspectives on construction waste reduction	√	√	√	√	√	√	√	√	√	√	√	√	√	√	Literature review	Ahankoob *et al.*, 2012
Sustainable construction: an information modelling approach for waste reduction										√					Literature review	Hewage and Porwal, 2012
Using BIM as a tool for cutting construction waste at source			√	√	√	√									Questionnaire	O'Reilly, 2012
BIM–Based analysis to minimise waste rate of structural reinforcement					√	√									Case study	Porwal and Hewage, 2012
Use of Lean and BIM in the construction process										√					Interviews	Ningappa, 2011
The interaction of lean and BIM in construction										√					Literature review	Sacks *et al.*, 2010

1) BIM-enhanced coordination for construction waste minimisation

Based on literature review results, Ahankoob *et al.* (2012) reported that, in general, BIM could potentially act as a coordination tool to support project team with construction waste reduction throughout project lifecycle stages. However, up-to-date methodes have not been developed or suggested to facilitate waste reduction through BIM-enhanced coordination throughout project stages.

2) BIM-enhanced design waste minimisation

WRAP (2013a) conducted a case study on the implementation of BIM to achieve resource efficiency for the Leeds Arena project, which suggested that BIM could assist reducing material wastage rates through its adoption at the early design stages. Nonetheless, there was a lack of efficient guidelines or instructions, which have been produced for the BIM implementation on material wastage reduction during design.

Similarly, based on a case study, Porwal and Hewage (2012) developed a BIM-assisted tool for structural engineers to use in reducing bar material usage in Technical Design. Although, the study has developed BIM-assisted tool for material waste reduction, the tool was focused on the reduction of a specific structural material (i.e. bar metal) and for structural engineer to use in Technical Design stage. Moreover, the study has not investigated impacts on the material waste reduction, which are affected by BIM-enhanced design activities during early design stages, such as Concept and Design Development.

Further, O'Reilly (2012) conducted a study via a questionnaire survey and reported that the BIM could help architects with minimising waste by making informed design decisions especially during Concept and Design Development stages.

3) BIM-enhanced on-site waste management

Hewage and Porwal (2012) proposed a potential conceptual BIM approach for on-site construction waste management based on a literature review, which is through BIM modal driven system for dynamics modelling by using information of material quantities. Based on the above study, Porwal (2013) developed a cost-oriented system dynamic approach through BIM by using three case studies, which focuses on specific on-site waste causes, such as design changes owned by design and construction engineers. However, the study only explored specific on-site waste causes which BIM could help with addressing, and has not explored other various on-site waste causes (e.g. client-led design changes) influenced during design, which could potentially be addressed by the use of BIM.

Based on literature review, Sacks *et al*. (2010) suggested that waste could be reduced by adopting BIM-integrated lean in construction. Similarly, Ningappa (2011) conclude from results of interviews that BIM has the potential to assist on-site project team with waste reduction. However, nothing has been developed so far based on the studies to facilitate on-site waste management by the use of BIM.

4) <u>BIM-enhanced demolition waste management</u>

Based on a case study, Cheng and Ma (2013) developed a BIM-based waste estimation and planning system via an API-enhanced online application for managing construction waste by waste estimation and planning at Demolition stage. The study was focused on demolition waste, but failed to provide suggestions for using such waste estimation system for other project stages, such as design.

2.4.2 BIM potentials for construction waste minimisation

The second cluster is discussed in sections below.

These BIM potentials to CWM are mainly focused on improvement of design, specification, coordination, and project performance, as shown in Table 2.21.

Baldwin *et al.* (2008) and McGraw-Hill (2010) argued that BIM-enhanced design promotes the construction project to take advantage of modern construction by extracting modelling information from the BIM system such as prefabrication, preassembly and modularisation, which can make the construction project faster and more efficient through avoiding the use of raw material and on-site generation of construction waste. Moreover, efforts relating to construction waste involved during the design stage could reduce on-site re-work which is one of the main causes of waste (see section 2.2.3.1 and section 2.2.3.2). Baldwin *et al*. (2008; 2009b) claimed that this could be achieved through a 3D capacity enhancement within BIM whereby 3D information analysis improvements mainly store, retrieve and analyse in-depth building feature information, such as walls, windows and doors. In addition, BIM was being able to consider building performance in the early design stages facilitated by an access to all information that defines a building, such as its form, material, and system, through a integrated view of the building (Schlueter and Thesseling, 2009). As such the use of BIM helped to increase the ability to rapidly test numerous design options of varying complexity (Eastman *et al.*, 2008; Hardin, 2009); increase the ability to quantify and test variables (Eastman *et al.*, 2008; Hardin, 2009); increase decision making quality (Eastman *et al*., 2008; Hardin, 2009; Nisbet and Dinesen, 2010; Love *et al.*, 2013b); increase reliability of specifications (Krygiel and Nies, 2008;

Love et al., 2013b); and increase satisfaction of client design requirements (Eastman *et al.*, 2008; Hardin, 2009; Schlueter and Thesseling, 2009; Nisbet and Dinesen, 2010)

Table 2.21 Potential construction waste minimisation through BIM (compiled from literature)

Potential CWM through BIM		**Source**
Design	Increase the ability to rapidly test numerous options of varying complexity	Eastman *et al.*, 2008; Hardin, 2009
	Increase the ability to quantify and test variables	Eastman *et al.*, 2008; Hardin, 2009
	Increase quality of knowledge service for decision making	Eastman *et al.*, 2008; Hardin, 2009; Nisbet and Dinesen, 2010; Love *et al.*, 2013b
Specification	Reduce material waste	Eastman *et al.*, 2008; Krygiel and Nies, 2008; Hardin, 2009; Nisbet and Dinesen, 2010
	Reduce rework	Baldwin *et al.*,2008; 2009b; Eastman *et al.*, 2008; Krygiel and Nies, 2008; Hardin, 2009; Nisbet and Dinesen, 2010; Love *et al.*, 2013b
	Increase reliability of specifications	Krygiel and Nies, 2008; Love *et al.*, 2013b
Coordination	Reduce conflicts between disciplines	Eastman *et al.*, 2008; Krygiel and Nies, 2008; Hardin, 2009; Love *et al.*, 2013b
	Reduce information/intent loss in translation between designer and fabricator for pre-fabrication/pre-cast	Baldwin *et al.*,2008; Eastman *et al.*, 2008; Krygiel and Nies, 2008; Hardin, 2009; McGraw-Hill, 2010
	Reduce errors by clash detection	Eastman *et al.*, 2008; Krygiel and Nies, 2008; Hardin, 2009; Love *et al.*, 2013b
	Increase communication and integration.	Eastman *et al.*, 2008; Krygiel and Nies, 2008; Hardin, 2009; Lancaster and Tobin, 2010; Nisbet and Dinesen, 2010
Project performance	Increase satisfaction of client design requirements	Eastman *et al.*, 2008; Hardin, 2009; Schlueter and Thesseling, 2009; Nisbet and Dinesen, 2010; Lancaster and Tobin, 2010

Moreover, BIM-enhanced coordination through clash detection enabled inspection of conflicts before construction, as such on-site waste raised from the consequence of the conflicts will be avoided (Eastman et al., 2008; Krygiel and Nies, 2008; Hardin, 2009; Love et al., 2013b).

Furthermore, the BIM-based project delivery tended to maintain high project value for all project stakeholders through effective coordination and communication for collaborative working to reduce waste throughout project lifecycle (Eastman *et al.*, 2008; Krygiel and Nies, 2008; Hardin, 2009; Lancaster and Tobin, 2010; Nisbet and Dinesen, 2010).

The current CWM practices (see section 2.2.4) are focused on managing on-site waste with limited efforts to reduce waste through design stages, and the current BIM practices (see section 2.3.3) are implemented across project stages and towards sustainability. However, as discussed above, only two studies have developed BIM-aided tools for waste management in specific project lifecycle stages, such as reducing bar material usage in Technical Design and Production Information stages (Porwal and Hewage, 2012), and managing waste during Demolition stage (Cheng and Ma, 2013); and one study explored the BIM potential to help architects with CWM during design without providing any method for the use of BIM to drive out waste (O'Reilly, 2012). Hence, there is a need for a comprehensive investigation of BIM as a platform to aid CWM, and development and validation of a BIM-aided CWM Framework throughout design stages.

In addition, although waste cost and materials waste could be reduced by implementing BIM during design and construction stages is widely accepted (AIA, 2007; Krygiel and Nies, 2008; Hardin, 2009; Smith and Tardif, 2009; Nisbet and Dinesen, 2010; Hamil, 2013; Porwal, 2013; Gurevich and Sacks, 2014), there are no comprehensive BIM decision support tools available to support designers to minimise waste during design stages. Krygiel and Nies (2008) and McGraw-Hill (2010) suggested that architects should consider environmental performance criteria (e.g. water, energy and waste) under an effective platform, such as BIM. Furthermore, UK Construction Strategy towards 2050 (HM Government, 2013a) and Hamil (2013), who is a BIM expert and director of design and innovation at RIBA Enterprises, believed that BIM potentially could reduce waste during design and construction.

Therefore, there is a consensus in the literature that BIM could effectively drive CWM. However, findings of existing studies in the field are mainly related to its potential in specific stages across Design and Construction stages, such as Technical Design. As such, there was a lack of efforts that have been made to develop integrated BIM-aided CWM decision making tools and methodologies throughout all design stages, which is the focus of this research.

2.5. Summary

This chapter shows that the most preferred methods in which to manage construction waste is avoidance and reduction at the early stages of a construction project lifecycle, namely design, through which the control of material consumption and waste reduction can be exerted.

Therefore, this chapter classified and discussed construction waste causes and current construction waste minimisation practices during every stage of the construction project lifecycle in seeking opportunities for waste minimisation. Most current waste minimisation practices, including approaches, techniques and tools, focus on the construction stage for handling on-site waste, rather than design stages which holds the greatest waste reduction opportunities. Furthermore, the effective decision making coordination and communication within design was deemed critical for avoiding and reducing on-site waste.

The literature review indicates that current BIM techniques and tools have been used to enhance planning and construction related issues during design, including improvements to sustainable project performance strategies, such as energy efficiency. The current process in implementing BIM-based techniques and tools through different phases of a project lifecycle can be summarised as:

- Briefing and conceptual design: capture client needs by an early analysis of functional, financial, and environmental targets.
- Design development and technical design: management and verification of requirements fulfilment (e.g. usability, constructability, and sustainability) prior to the construction, interface (communication, coordination and collaboration) between models within multi-disciplinary design and construction schedule and cost.
- Construction: on-site management of resources, process and schedules interface (communication, coordination and collaboration) between different designs, production and as-planned model to as-built models.
- Post-construction: asset management, management of lifecycle information, as-built model based space management, maintenance and services, BIM-based renovation processes.

The most significant finding that stems from the literature review is that although there was an emphasis on the need to explore the use of BIM for construction waste minimisation, particularly within building design, there are no previous attempts to devise BIM-related frameworks to reduce waste during design stages. Hence, this research sets out to develop a BIM framework to aid CWM. The next chapter presents the discussion of the adopted research methodology.

CHAPTER THREE

Research Methodology

3.1. Introduction

The aim of this chapter was to examine key research methodology concepts and principles and present the adopted research methodology for this research. The following aspects related to the research methodology were investigated in the following sections: research philosophy, research strategies/approaches, research design and methods. Justification of the adopted research methodology is explained.

3.2. Research philosophy

Philosophy is the study of general and fundamental problems related to the knowledge and understanding of nature, the meaning of the universe and human life (Grayling, 1998; Teichmann and Evans, 1999). It also provides a framework of thinking, which facilitates the development and improvement of alignment between what people think and what people do (Paul, 1993; Honderich, 1995). Hence, philosophy is the foundation of scientific research that provides the way for exploring research leading to knowledge development.

Research philosophy is related to the nature and development of knowledge containing the key assumptions that lead to the views of the research study (Saunders *et al.*, 2007). It provides guidelines in the selection of a research approach containing a different subject or knowledge structure to support research design decisions (Easterby-Smith *et al.*, 2002). Therefore, failure to consider issues related to research philosophy can seriously affect the research quality and its respective design (Easterby-Smith *et al.*, 2002).

There are two major research philosophy aspects that are related to social research and most construction management research, which are ontology and epistemology (Crotty, 1998; Walliman, 2006; Bryman, 2008; Dainty, 2008).

3.2.1 Ontology

Ontology is related to the nature of reality and its characteristics and describes assumptions about reality and what knowledge is (Tan, 2002; Creswell, 2007; Bryman, 2008; Dainty, 2008). It considers two views: objectivism and constructionism, to the nature of social entities (Bryman, 2008).

Objectivist ontology asserts social phenomena and their meanings as the independent existence of social actions; whereas constructivist ontology affirms that social phenomena and their meanings are produced through social interaction which is constantly changing (Bryman and Bell, 2007). Similarly, Fitzgerald and Howcroft (1998) argued that realism and relativism are two types of ontology positions. Realist ontology sees the external world as comprising and tangible structures that pre-exist independently. The latter relates to the individual's ability to acquire knowledge and is considered practical and unconcerned with the abstract or idealistic view of life; whereas relativist ontology observes reality as being directed by socially-transmitted terms and varies according to language and culture (Fitzgerald and Howcroft, 1998). However, Walliman (2006) argued that realism (particularly social realism) is a type of epistemology approach as it maintains structures that underpin social events and discourses, but does not prevent them being used in action to change the society. Furthermore, Bryman (2008) indicated that realism (particularly critical realism) is another philosophical position of epistemology that purports to provide an account of the nature of scientific practice.

Although the debate regarding the nature of social research is ongoing, all philosophical positions and their attendant methodologies hold a social reality view, which will determine what can be regarded as legitimate knowledge (Walliman, 2006).

3.2.2 Epistemology

Epistemology describes how knowledge should be achieved and accepted (Tan, 2002; Bryman, 2008). It is concerned with questions of what should be regarded as acceptable knowledge within a discipline (Dainty, 2008). There are two types of epistemology, namely, positivism and interpretivism (Love *et al.*, 2002; Dainty 2008). The major characteristics and key assumptions of positivism and the constructivism paradigm are summarised in Table 3.1.

The positivist paradigm is the method of natural science which can be applied to the study of social phenomena (Walliman, 2006; Bryman, 2008; Dainty, 2008). It is close to rationalism and empiricism, and objectively recognises only the observed non-metaphysical facts and phenomena (Fellows and Liu, 2008). Therefore, positivism has a strong relationship with the quantitative approaches.

On the other hand, the interpretive paradigm sees a difference between the objects of natural science and people within those phenomena that have different subjective meanings for those studied actors (Walliman, 2006; Dainty, 2008). It is mainly useful to social research including management, by indicating reality conducted by the people involved. This is derived through observations and perceptions that are different to those of others and modified by socialisation (Pickering, 1992; Tauber, 1997; Walliman, 2006; Fellows and Liu, 2008). In terms of epistemological assumption, the researcher should get as close as possible to the participants being studied and stay in the study field as long as possible to understand their issues (Creswell, 2007). Hence, interpretive paradigm is more likely to feature in qualitative approaches.

Table 3.1 Characteristics and assumptions of positivism constructivism (often combined with interpretivism) (source: Crotty, 1998; Phillips and Burbules, 2000; Easterby-Smith *et al*., 2002; Walliman, 2006; Creswell, 2009)

	Positivism	**Constructivism (often combined with Interpretivism)**
Major Characteristics	Determination	Understanding
	Reductionism	Multiple participant meanings
	Empirical observation	Social and historical construction
	Theory verification	Theory generation
	Experimental or quasi-experimental validation of theory research	The research for meaningful relationships and the discovery of their consequences for action
	Abstraction of reality, especially through mathematical models and quantitative analysis	The representation of reality for purposes of comparison, such as analysis of language and meaning
Key Assumptions	1. Knowledge is conjectural and anti-foundational that absolute truth can never be found (Hypothesis will not be proved) 2. Research is the process of making claims and then refining or abandoning some of them for other claims more strongly warranted. (Most quantitative research, i.e. starts with the test of theory) 3. Data, evidence, and rational considerations shape knowledge. (Recorded observation in practice) 4. Research seeks to develop relevant, true statements, ones that serve to explain the situation of concern or that describes the causal relationships of interest. (Questions or hypotheses in quantitative studies) 5. Being objective is essential to competent inquiry and methods and conclusions must be examined for bias. (Within quantitative research, standards of validity and reliability are important)	1. Meanings are constructed by participants engaged in the study. (Open-ended questions used in qualitative research to share views) 2. Participants' views are based on their historical and social perspectives. (Seeking to understand the context of participants by visiting and gathering information in person in qualitative research) 3. Constructed and imposed understanding through interpretation is limited by the frames derived from researcher's experience in these situations. 4. The basic generation of meaning is always social and arising in and out of interaction with a human community. (Qualitative research process is mainly inductive by inquirer generating meaning from the data collected in the field)

Understanding the influence of competing paradigms that research is based upon is fundamental to understanding the contribution that the research adds to knowledge (Dainty, 2008). Hence, the selection of adopted paradigm will fundamentally affect the methods of data collection and analysis and the nature of the knowledge produced (Kuhn, 1996; Dainty, 2008; Fellows and Liu, 2008; Creswell, 2009).

3.2.3 Philosophical position of this research

This research investigated current construction waste minimisation (CWM) and BIM practices including approaches, techniques and tools, to develop and validate a BaW Framework for the use of BIM as a vehicle to facilitate waste minimisation. As such, the research aimed to prove the reality nature of BIM and waste minimisation, also their meaningful relationship and consequences for action (a BIM-aided CWM framework). Hence, theoretical generation of that relationship based on ontological constructivism combined with interpretivism leads to theory verification from epistemological positivism, providing the philosophical position of the research. This relationship can be indicated as a triangulation of combined paradigms, whereby a mixed positivist and constructivist (combined with interpretivism) philosophy was adopted.

This research explored construction waste causes and examines current CWM practices and industry BIM practices. This process constructed phenomena of CWM and BIM, and their meanings through gathering information from industry experts, leading the research towards constructivist ontology. However, data related to the extent of BIM current usage and the effect of potential use of BIM to aid CWM for abstraction of reality, should be collected and analysed quantitatively (Leedy and Ormrod, 2005; Fellows and Liu, 2008). This provided a potential positivist epistemology route to the research. When exploring the relationship between BIM practices and the causes of construction waste, the research represented architects' perspective based on their own experiences. Therefore, this drove the research towards interpretivist epistemology in terms of constructing meanings from participants engaged within the research (open-ended questions used in qualitative research to obtain shared views from participants).

Previous research studies have widely explored the knowledge areas of CWM and BIM individually, and the relationship of CWM and BIM has not been investigated yet, as such the previous researches would not affect the investigation conducted by the research.

Hence, a literature review was undertaken to find out the needs of the study and how to conduct it. This positioned the research within realism of constructivist ontology. However, the research was further investigated and developed by consideration of the human community, allowing contribution of their own beliefs and experiences. This enabled open-ended questions to be used for data collection. This led the research towards the interpretivist epistemology position.

3.3. Research strategies/approaches

Research strategies are broadly categorised as qualitative, quantitative, or mixed method research. Table 3.2 summarises the terms of contrast between the three methodological research strategies which are discussed in the following sections.

3.3.1 Qualitative research

Qualitative research is defined as an inquiry of understanding based on distinct methodological traditions that explores a social or human experience (Creswell, 2007). Many qualitative oriented researchers subscribe to a research philosophy known as constructivism (often combined with interpretivism) and its variants, which are seen as approaches to qualitative research (Howe, 1988; Mertens, 1998; Travers, 2001; Silverman, 2010). Qualitative research studies social phenomena within their natural setting, attempting to make sense of, or to interpret the phenomena in terms of the meanings it brings to them (Denzin and Lincoln, 2003). It involves the use and collection of a variety of empirical materials such as a case study, personal experience, introspective, life story, interview, observational, historical, interaction and visual text, which describes routines, problematic moments and meanings in the life of an individual (Denzin and Lincoln, 1994). Hence, data from qualitative research is defined as the detailed description of situations, events, people, interaction, observed behaviour and direct quotations from people about their experiences, attitudes, beliefs and thoughts; and excerpts or entire passages from documents, correspondence, records and case histories (Patton, 1990). Qualitative data is naturally suitable in extracting meanings from people involved in the events, processes and structure of their lives in terms of perception, assumptions, pre-judgements and pre-suppositions (Amaratunga *et al.*, 2002). Similarly, qualitative data can be gathered from a hermeneutic study and interpretation of biblical text, where the theory and practice of interpretation and understanding are in a different type of human context (Odman, 1988).

Therefore, qualitative research requires careful thought at the outset, demanding mental agility, flexibility and alertness during data collection, calling for advanced skills in data management and text-driven creativity during the analysis and write-up (Davies, 2007). It attempts to deduce answers as to how and why questions are explored within nature (Perry, 1994). Perry (1994) argued that a major issue is to identify the variables involved in the question.

Table 3.2 Terms of contrast between the three research strategies (Neuman, 2006; Bryman and Bell, 2007; Bryman, 2008; Creswell, 2009; Teddlie and Tashakkori, 2009)

Terms	Qualitative Strategy	Quantitative Strategy	Mixed Strategies
Methods	Qualitative methods	Quantitative methods	Mixed methods
Researchers	Qualitative methodologists	Quantitative methodologists	Mixed methodologists
Paradigms	Constructivism (combined with interpretivism)	Positivism	Pragmatism; transformative perspective
Research questions	Qualitative research questions	Quantitative research questions	Mixed research questions
Form of data	Narrative	Numeric	Narrative plus numeric
Purpose of research	(Often) exploratory plus confirmatory	(Often) Confirmatory plus exploratory	Confirmatory plus exploratory
Role of theory	Inductive; Grounded theory	Deductive (hypothetical); Rooted in conceptual framework or theory	Mixed inductive and deductive (inductive-deductive research cycle)
Progress	None-linear	Rarely linear	Concurrent
Research design	Ethnographic research designs and others (case study)	Correlational; survey; experimental; quasi-experimental	Mixed research designs, such as parallel and sequential ones
Sampling	Mostly purposive	Mostly probable	Probable, purposive, and mixed
Data analysis	Thematic analysis: categorical and contextualising	Statistical analysis: descriptive and inferential	Integration of thematic and statistical analysis; data conversion
Quality and validity	Trustworthiness; credibility; transferability	Internal validity; external validity	Inference quality; inference transferability
Advantage	1) Natural data collection methods 2) Being able to change process over time 3) Being able to understand meanings from participants 4) Benefit to theory generation	1) Being quick and economical 2) Covering wide range of situations 3) Capability to manage a large number of samples	Combined strength from both qualitative and quantitative research
Disadvantage	1) Limited generalisation capability 2) Subjectivity 3) Difficulty of replication 4) Lack of transparency 5) Data collection could be tedious and require more resources 6) Difficulties in data analysis and interpretation 7) Difficulties in controlling research process	1) Sampling limitation 2) Non-response limitation 3) Data collection errors 4) Data processing errors 5) Failure to distinguish between people and social institutions from the natural world 6) Referring to artificial measurement process 7) Relying on instruments and procedures 8) Creation of a static view of social life	Need for clear vision of research process

Creswell (2007) indicated situations whereby the qualitative method is selected as the research method. These are:

- when the problem or issue needs to be explored.
- needs for a complex, detailed understanding of the issue.
- the need to empower individuals to share their story, hear their voice and minimise the strong relationship between researcher and participants involved in the study.

- to write in a literary, flexible style that conveys stories without the restrictions of formal, academic structured methods of writing.
- to understand the context or setting where the study participants address problems and issues;
- to follow up quantitative research and help explain the mechanisms or linkage to the causal theories or models.
- to develop theories when partial or inadequate theories exist for certain populations and samples or existing theories do not adequately capture the complexity of the problem that is being examined.
- quantitative research methods and statistical analyses simply do not fit the research problem, whereas qualitative methods fit better.

Bryman (2008) further simplified the situations when:

- there is no existing research data on the topic and the most appropriate unit of measurement is not certain, or
- the research concept is assessed on a nominal scale with no clear demarcation involved in exploring behaviour or attitudes.

As shown in Table 3.2, qualitative research has a limited capability of sampling methods to generalise the research findings. Within the context of this research, it is too subjective to limit confidence in the results which may not represent the fundamental truth regarding CWM and BIM. However, qualitative research is flexible in changing the process over time, is of benefit to theory generation when the issues of CWM and BIM need to be explored and helps understand meanings from participants. Hence, qualitative research was applied to follow up the quantitative research (as discussed in the following section) to examine CWM and BIM. It allowed facilitation of a further explanation to the mechanism and linkage of CWM and BIM, and to develop and validate the BaW Framework.

3.3.2 Quantitative research

Quantitative research is defined as an investigation related to positivism (Davies, 2007). It seeks to gather factual data and to study the relationship between facts and how such facts and relationships accord with the theories and findings of previously executed research (Fellows and Liu, 2008). It is frequently referred to as a tenet of positivism (Atkinson and Hammersley, 1994) hypothesis-testing research (Kerlinger, 1964; Fitzgerald and Howcroft, 1998; Naoum, 2002) being deductive in nature (Newman and Benz, 1998). Hence, the purpose of quantitative research is to discover answers to questions through the application of scientific procedures, which have been developed in order to increase the likelihood that the information gathered will be reliable and unbiased and relevant to the question asked (Selltiz *et al.*, 1965). In other words, quantitative research is used to answer questions about relationships between measured variables with the purpose of explaining, predicting and controlling phenomena (Leedy and Ormrod, 2005).

Therefore, quantitative research requires imagination, patience and discipline at the planning and design stages; data collection may present technical problems and require tenacity but is often straightforward; the task of data analysis and write-up is largely, although not entirely, determined by the way the research was set up (Davies, 2007).

As shown in Table 3.2, quantitative research can be implemented to cover a wide range of samples and to obtain a static view of CWM and BIM. This research was independent of the lives of respondents when analysing the relationship between those variables with precision and accuracy to test the theory of BIM potential as a platform to aid CWM. However, quantitative research is too linear and statistical in that the respondents' explanation of the mechanism and linkage to CWM and BIM was hard to investigate and attain. As such, as discussed in above section 3.3.1, qualitative research was used as part of this research for obtaining information of further investigation on the relationship of CWM and BIM.

3.3.3 Mixed methods/triangulation research

The term of mixed methods research is widely used nowadays to refer to methods that combine both quantitative and qualitative research (Axinn and Pearce, 2006; Creswell, 2009; Teddlie and Tashakkori, 2009). Another term, triangulation, is much concerned with triangulating data sources, which is a means in seeking convergence across quantitative and qualitative methods (Jick, 1979; Flick, 2002; Fellows and Liu, 2008). Mixed method research is defined as a type of research design in which quantitative and qualitative approaches are used within types of questions, research methods, data collection and analysis procedures, and/or inference (Tashakkori and Teddlie, 2003). These quantitative and qualitative approaches are used to make multiple measurements, adopt multiple methods and to investigate at multi-level analysis (Love *et al.*, 2002). It manages the combination of these two approaches to gain the most advantage from their respective advantages (Teddlie and Tashakkori, 2009). In other words, mixed method research offers the opportunity for researchers to benefit from the multiple advantages of both approaches and avoid any possible defects of one approach by using the strengths of the other (Jick, 1979).

The mixed method research drives the interaction between qualitative and quantitative methods to line out the research. Newman and Benz (1998) indicated this interaction as a conceptual model as shown in Figure 3.1. This represents the interrelationship between qualitative and quantitative methods as the approach to mixed method research. Indeed, qualitative research is the pre-cursor to quantitative research. This is because an exploration of the subject is undertaken without prior formulation whereby the objective is to gain an understanding and to collect information and data to develop theories (Fellows and Liu, 2008). The approach to mixed method research integrates or connects the qualitative and quantitative data, being triangulating data (Creswell, 2009). Fellows and Liu (2008) pointed out that triangulation, the process to generate triangulating data, can be a very useful and powerful approach to acquire insight and results, to facilitate inference making and drawing conclusions, as illustrated in Figure 3.2.

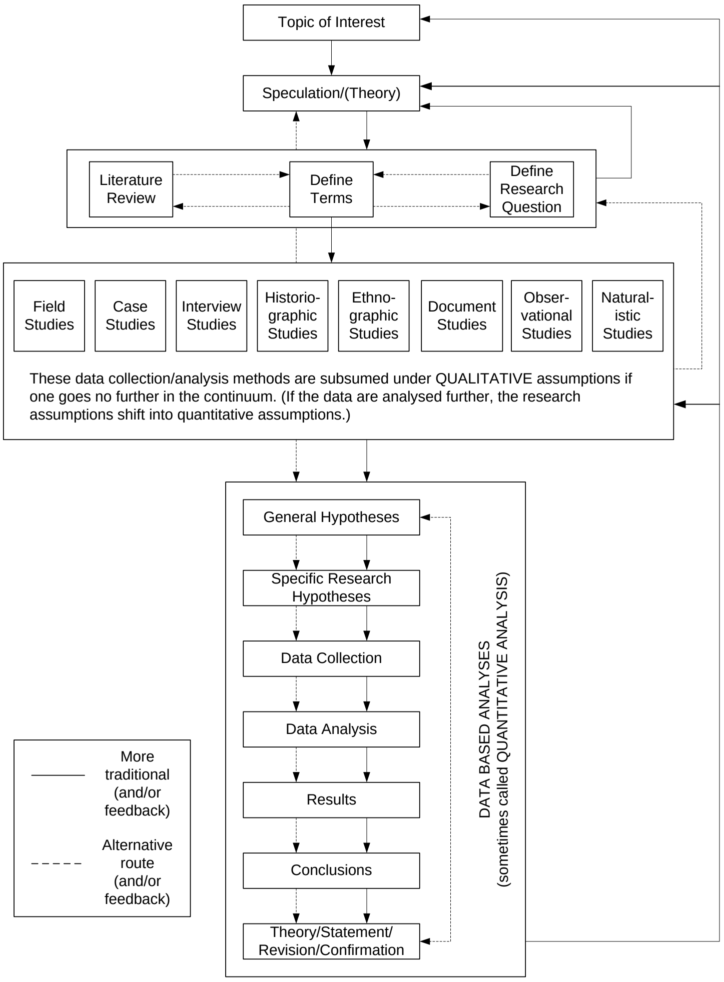


Figure 3.1 Qualitative-quantitative interactive continuum (source: Newman and Benz, 1998)

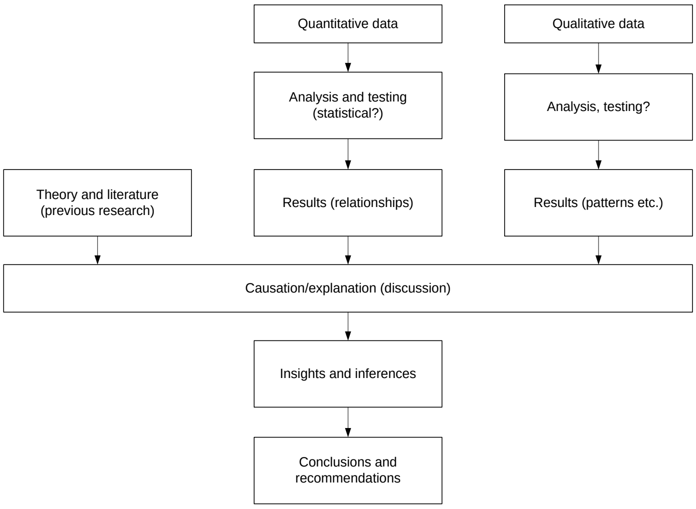


Figure 3.2 Triangulation of quantitative and qualitative data (source: Fellows and Liu, 2008)

There are two fundamental advantages of the mixed method research approach (Love *et al.*, 2002). Firstly, the capability of providing the knowledge in a combined form is increased and the congregation of findings can provide greater confidence for the researcher in the reliability and/or validity of the results. Secondly, divergence can lead to greater definition and theoretical elaboration as the researcher attempts to think about different aspects of the phenomena to get a clear coherent image of it. In addition, mixed method research can improve the precision of both the measurement and description of the problem, in terms of formalising the problem along the lines of qualitative and quantitative research (Baumard and Ibert, 2001).

However, Yin (2008) mentioned that there are two problems when research is conducted through mixed methods:

- cost: collecting data from a single source could be less expensive than from many sources; and
- techniques for data collection: the researcher needs to know the methods in conducting a variety of data collection techniques.

Mixed method research is becoming more popular within social research since it was introduced by Jick in 1979 (Creswell, 2009). The study conducted by Dainty (2008) revealed that overall, 11.2% of research papers applied the mixed method research within the construction management research community, and argued that through the implementation of a powerful multi-strategy or multi-methodology research design, it can make a radical contribution to construction management research to better understand the complex phenomena.

As mentioned in section 3.2.3, this study adopted a mixed positivist and constructivist (combined with interpretivism) philosophy to generate and test the theory which leads the research to mixed research strategies. By implementing mixed research strategies, the BIM-aided waste minimisation Framework was developed and validated, whereby the qualitative strategy became the major item for theory testing. Additionally, the research questions drive the research strategy.

The initial stage of this study (see Figure 3.3) explored the relationship between the use of BIM and CWM to identify what BIM can offer to reduce waste and how. The direction of this study was suggested through the research literature. It proved that a clear relationship between BIM and CWM was hightlighted but has not yet been established allowing knowledge gaps within the body of available literature (see section 2.4). Hence, to generate the theory for this study, the research adopted quantitative and qualitative research strategies. As such, the research investigated and indentified the nature of relationships between the use of BIM and CWM. A Framework development which obtained narrative data for the use of BIM for CWM was the second stage of the research. The last stage was to validate the BAC Framework through the qualitative data obtained.

3.4. Research design and methods

3.4.1 Research design

Research design is defined as the plan to identify research questions and the means of drawing conclusions (Tan, 2002). It provides a framework for the collection and analysis of data and subsequently indentifies which of the research methods are appropriate for the study (Royer and Zarlowski, 2001; Walliman, 2006; Bryman, 2008). Research questions which determine the required data and indicate appropriate method for analysis, must be taken into consideration for research design in terms of maximising the opportunity to realise research objectives (Fellows and Liu, 2008). Royer and Zarlowski (2001) argued that research design leads the course of research process and assists the avoidance of barriers that emerge in later stages of the research process. There are extensive types of research design having different terms that are available within the social research domain (Walliman, 2006; Creswell, 2009; Bryman, 2008). However, according to Fellows and Liu (2008), there are five major powerful types of research design within construction management, namely action research, ethnographic research, experiments, case studies and surveys.

3.4.1.1 Action research

Action research is whereby the research tends to effect a change which then creates knowledge about the process and the consequences of the change within a social system (Lewin, 1946). The stages of action research are social problem information, action of hypotheses, implementation, interpretation and diagnostic cycles (Guffond and Leconte, 1995). It is used to generate and test solutions to particular social problems, whilst the process of identifying the problems and alternative methods of action may lie within the qualitative and quantitative research (Fellows and Liu, 2008). However, this research does not intend to investigate changes within a social system. Hence, the action research is unsuitable.

3.4.1.2 Ethnographic research

Ethnography outlines the interpretation of the social world by observing the behaviour of participants and statements to obtain meanings of ‘what’, ‘how’ and ‘why’ their patterns of behaviour occur (Saunders *et al.*, 2007; Fellows and Liu, 2008). It is based on techniques designed by researchers to study social life and the cultural practice of communities by involving themselves in the day-to-day life of research subjects (Walliman, 2006). Fellows and Liu (2008) suggested that an initial period of questioning and discussion between the researcher and group participants can assist in obtaining their understanding of perspectives in making the world meaningful to themselves and to others. However, Walliman (2006) argued that the ethnographic research design is a difficult design for beginners as it requires special research techniques and specialist knowledge of social culture concepts. It is also a time consuming research process. However, the behaviour of participants is not related to this research. Thus, the ethnographic research design is inappropriate.

3.4.1.3 Experiments

Experimental research is undertaken on a certain sample of the population and within a controlled environment to test whether there is a causal relationship between the variables under investigation (Baker, 2001). It indicates that experimental research is thus relatively narrow in the type of information it produces, but can provide more definitive answers regarding causal links than other types of research can (Hakim, 1987). Hence, the most important characteristic of experimental research is that it deals with the phenomenon of cause and effect (Walliman, 2006). Although experimental research can be suited to specially built laboratories and dynamically social, industrial, economic, and political arenas (Fellows and Liu 2008), it is not suitable for many management studies. This is due to several factors such as ethical reasons, willingness to participate in experiments, difficulties in obtaining representative samples, complexity and cost (Saunders *et al*. 2007). Walliman (2006) argued that there are also problems in laboratories such as faulty randomisation, lack of validity, ethical issues, lack of control and the types of experiments. Therefore, experimental research is unsuitable for this research.

3.4.1.4 Case studies

Case study research is concerned with the complexity and particular nature of the 'case' in question (Stake, 1995). It is conducted via generalisation of theory for experiments rather than empirical/statistical generalisation (Fellows and Liu, 2008) and associated with a location, such as a community or organisation (Bryman, 2008). The process of the case study involves intensive investigation into one or a few cases to generate and test theory using both inductive and deductive approaches (Walliman, 2006). However, Bryman (2008) argued that case studies are frequently employed by both qualitative and quantitative researchers. In other words, mixed method research and multiple data collection techniques can be applied to case studies. Thus, one case or a small number of cases can be studied in detail using whatever the appropriate research methods to develop an understanding of that case as fully as possible; whilst there may be a variety of specific research questions and purpose (Punch, 1998).

However, as shown in Table 3.3, there are challenges when conducting case studies such as lack of rigour, difficulties in data analysis, difficulties in assessing where the context begins and ends, and difficulties in generalising findings. In addition, the main concern of the case study is that it is not interested in theoretical inference. These challenges and the concern will affect obtaining accuracy of findings in relation to CWM and BIM, which may lead to research bias.

Table 3.3 Key specifications of case studies, surveys and research design (Hammersley and Gomm, 2000; Tan, 2002; Saunders *et al*., 2007; Bryman, 2008; Gibson and Brown, 2009; Blaxter *et al*., 2010; C.S.U, 2011a; C.S.U, 2011b)

Terms	Case studies	Surveys	
		Questionnaire	**Interview**
Amount of investigation	• A small number of cases (sometimes just one)	• A large number of cases	• A small number of cases
Amount of data collection and analysis	• A large number of features of each case	• A small number of features of each case	• A large number of features of each case
Sample control	• Naturally occurring or in 'action research' form • Study of cases created by the actions of the research but where the primary concern is not controlling variables to measure effects	• Naturally occurring • To maximise the representativeness of samples in relation to a larger population	• Naturally occurring
Priority of data	• Qualitative data is prior • Both qualitative and quantitative data involved	• Quantitative data is prior	• Qualitative data is prior
Main concern	• Understanding the case studied in itself • No interest in theoretical inference or empirical generalisation, but they may attempt one or the other, or both • Alternatively, the findings may be conceptualised in terms of the provision of vicarious experience, as a basis for 'naturalistic generalisation' or 'transferability'	• Empirical generalisation from a sample to a finite population • As a platform for theoretical inference	• Generation of theory • Social and cultural phenomena study • To describe and explain • To explore and interpret
Advantages	• Being easy to start and flexible • Multi-perspective analyses • Triangulated research strategy • Multiple data collection methods are often applied	• Relatively less expense • Being of use in describing the characteristics of a large population • Administration from remote locations using mail, email or telephone • Very large samples are feasible • Making the results statistically significant even when multiple variables are analysed • Many questions can be asked about a given topic with considerable flexibility to the analysis • Flexibility at the creation phase in deciding how the questions will be administered • Standardised questions make measurement more precise • Standardisation ensures that similar data can be collected from groups and then interpreted comparatively • High reliability is easy to obtain	• Data gathering methods seen as natural rather than artificial • Flexibility for changing process over time • Enable to understand people's meaning • Contribute to generate theory
Disadvantages	• Lack of rigour • Generating too long and massive results • Difficulties in analysing data • Difficulties in assessing where context begins and ends • Difficulties in generalising findings • Difficulties in writing up case studies	• Accuracy of findings due to difficulties in checking first hand understanding of respondent • Progress could be delayed due to dependency on others' responses • Inability to demonstrate causality mainly in survey for opinion • Requiring the initial study design to remain unchanged throughout the data collection • Ensuring a large number of the selected sample will reply • Relying on standardisation of question development	• Expensive • Data collection could be time consuming and need more resources • Data analysis and interpretation may be difficult

3.4.1.5 Surveys

Survey research is related to data collected primarily by questionnaires or structured interviews at a certain period of time. The aim is to collect a body of quantitative or quantifiable data in connection with two or more variables, which are examined to detect patterns of association (Bryman, 2008). Axinn and Pearce (2006) argued that a survey could be used for collecting both quantitative and qualitative data depending on the data collection technique employed. The main survey data collection techniques are through the questionnaire, interview, and observation (Fellows and Liu, 2008). Fellows and Liu (2008) suggested that it is important that the study subject matter must be introduced to the participants in terms of data quality. Survey design research is widely used for the deductive research approach. This is whereby data can be obtained from a sample based on a systematic method. It only considers a particular case in depth but also captures the major characteristics of the population at any instant or monitors changes over time (Tan, 2002).

The research was set to investigate and indentify the nature of relationships between the use of BIM and CWM though the mixed methods research that requires both quantitative and qualitative data. As shown in Table 3.3, survey contains questionnaire and interview, in which quantitative and qualitative data can be obtained and the relationships between the use of BIM and CWM can be investigated. Hence, the survey was adopted to conduct the research.

3.4.2 Research methods

As previously mentioned, quantitative and qualitative survey has been adopted as the research design for the research. Therefore, the commonly used data collection techniques of questionnaires and interviews have been adopted (as shown in Table 3.4), because they can assist this study in achieving its objectives as follow:

- questionnaires assist the obtaining and generation of reliable, accurate and a general image of the research issues from a large number of experts and professionals, which can help build a good general image of the potential use of BIM to aid CWM;
- questionnaires and interviews enable the researcher to organise the questions and have the flexibility to collect data in a variety of different circumstances;
- questionnaires and interviews completed by respondents allow extraction of information associated with CWM and BIM (the recent phenomenon in particular) through both quantitative and qualitative methods that can assist to gather the most consistent information in developing and validating the BIM-facilitated Framework to

aid CWM; and

- questionnaires is less expensive and easy to administrate.

Table 3.4 Characteristics of questionnaires and interviews (source: Domingo, 2008; Gibson and Brown, 2009)

Methods	Questionnaires	Interviews
Types	• Self-administrative questionnaires • Questionnaires by post, email, and telephone	• Structured interviews • Semi-structured interviews • Unstructured interviews • Door-to-door/face-to-face interviews • Telephone interviews • Computer interviews • Group interviews
Advantages	• Less expensive than interviews • Large amount of anonymity	• Appropriate for complex situations • Useful for collecting in depth information • Supplemented information • Explained questions • Suitable for wider applications • Controlled questions
Disadvantages	• Low response rates • Self-selecting bias • Unsuitable to all situations • Lack of opportunity to clarify issues • Spontaneous responses are not allowed	• Expensive and time consuming • Data quality relies on interaction and interview qualities • Researcher’s bias could be involved • Interviewer could be bias • Unequally articulate and perceptive in respondents

3.5. Adopted research methodology

This section presents the adopted methodology approach for the research following the determined aspects: literature review, data collection, data analysis, and the BaW Framework development and validation.

3.5.1 Literature review

The literature review which is discussed in Chapter 2 covers the following topics: CWM, CWM drivers, current CWM practices, BIM definition, BIM development, current BIM practice, BIM adoption and managing CWM through BIM. The relevant literature, available exclusively in English, was carried out through the search of publications (e.g. books, reports, journals, conference proceedings and theses etc.) in both printed and electronic format. It was obtained from a variety of database information (e.g. Loughborough University library Meralib database, ScienceDirect, Taylor and Francis online, ASCE Journals, SAGE Journals, etc.) and online search engines (e.g.

Loughborough University library catalogue, Zetoc search, Google Scholar, etc.). This review essentially served its purpose in three major areas: provide a solid foundation for this study by exploring all relevant issues; identify knowledge gaps within the body of literature; and act as the basis in design and development of the BIM-aided waste minimisation Framework. The literature suggested that there is no clear evaluation, nor research studies, which have developed BIM-aided CWM strategies and methodologies during design for CWM (see section 2.4).

3.5.2 Data collection

3.5.2.1 Questionnaire survey

The questionnaire is one of the tools used to carry out a survey and intended to facilitate communication driven by the researcher's own agenda (Davies, 2007). Thus, the role of the questionnaire is to draw both quantitative and qualitative information from people, which is required to enable the researcher to answer the objective of the questionnaire (Walliman, 2006; Brace, 2008). Using a questionnaire survey enables the researcher to organise questions and have the flexibility to collect data in a variety of different circumstances without actually having to talk to every respondent (Walliman, 2006; Moore, 2000). However, sometimes questionnaires are unlikely to gain a great depth of information because respondents usually tend to fill them in quickly, giving an immediate rather than a considered response (Brace, 2008). Hence, questionnaires assist in generating the general image of the research issues rather than exploring issues in depth (Moore, 2000).

There are some factors that need to be taken into consideration within the questionnaire design, such as sample size, type of questions, number of questions, characteristics of respondents, availability of time, financial implications and ease of data analysis (Moore, 2000; Walliman, 2006; Brace, 2008). There are two forms of questions (Walliman, 2006; Fellows and Liu, 2008):

- ■ Closed-ended questions, whereby the respondents must choose from provided answers.
  - advantages: the questions are quick to answer and easy to code, requiring no special writing skills from the respondents.
  - disadvantages: the questions limit the range of possible answers and are impossible to qualify.
  - types of question: single answer (yes/no), multiple answers (select from list), and rank order (number items on a list by preference).

- Open-ended questions, where the respondents are free to answer in their own words and style.
  - advantages: the questions permit freedom of expression; bias is eliminated because the respondents are free to answer in their own way; and the respondents can qualify their responses.
  - disadvantages: the questions are more demanding and time-consuming for respondents, being difficult to code; answers by respondents are open to the interpretation of the researcher.

Fellows and Liu (2008) argued that all questionnaires should initially be tested via a pilot study, because it can test whether the questions are intelligible, easy to answer or unclear. Also, there will be an opportunity to improve questionnaires based on feedback by the respondents.

The aim of the questionnaire was to explore the BIM potential for construction waste minimisation during design. The questionnaire objectives were: explore the current use of BIM in building design; investigate BIM as a potential tool to minimise waste during design; and identify barriers and incentives to the use of BIM in building design.

Questionnaire design and development

The questionnaire was divided into seven sections comprising 14 different types of questions (see Table 3.5), background (two questions), BIM in building design (two questions), BIM as a potential platform to minimise waste during design (three questions), BIM barriers in building design (two questions), BIM incentives in building design (two questions), further comments (three questions). The final version of the four-page questionnaire was based on four revisions (see Appendix 2.1.2) and a pilot study.

Table 3.5 Type of questions

Question type	Questions' population
Open - ended	3
Category	6
Rating	5
Total	14

Questionnaire piloting

Piloting is a small-scale trial before the main investigation that is intended to assess the adequacy of the research design (Sapsford and Jupp, 1996). It is useful in refining the questionnaire, eliminating problems in answering and recording data, and enables the researcher to obtain the assessment on validity of questions and reliability of data (Saunders *et al.*, 2007).

The following issues are highlighted for consideration during questionnaire piloting: clarity of instructions, length of questionnaire, significant topic omissions, unclear or ambiguous questions, questions whereby a respondent is uneasy to answer or comment on and any other comments (Kvale and Brinkmann, 2009). There are three well established methods for piloting, namely, a peer review, cognitive interview, and focus group discussion (Forza, 2002). A peer review involves in-house people or research colleagues who are familiar with the questionnaire subject or the questionnaire. The cognitive interview is concerned with how respondents respond to questions and the questionnaire, and whether they can answer it correctly. Focus group discussions are similar to the cognitive interview but designed in a group (five to eight participants) environment and managed by a discussion leader and dedicated note-taker.

The study adopted the peer review method for questionnaire piloting due to time constraints, and difficulty in organising cognitive interviews and focus group discussions with industry experts. Hence, a draft pilot questionnaire was given to six (in total) researchers and academic staff at the Civil and Building Engineering School at Loughborough University. Feedback on the draft questionnaire was received from the selected participants and subsequently refinements were made to improve it. Three questions were re-worded to enhance clarity and answer space was increased for all open-ended questions to allow for more written comments.

Questionnaire sampling

As discussed in section 3.4, the survey methods (i.e. questionnaire and interviews) were used for collecting quantitative and qualitative data. It is difficult and impractical that the data concerned could be collected from the entire population for the research (Conway, 1967). Hence, sampling of the survey needs to be considered prior to the data collection process. Sampling can be defined as a manageable part of a chosen population (a sample of individuals) for making conclusions that concern the whole population drawn from a study of the sample (Conway, 1967). A sampling frame is essential to the sampling process, which is a list of references that clearly defines every element or unit in the study population from which the sample is taken (Stopher and Meybury, 1979). By use of the probability sample, selection bias can be avoided and statistical theory can be used to derive properties of the survey estimators. This compares the subjective non-probability sampling that adds uncertainty when the sample is used to represent the entire population for the study (Kalton, 1983; Henry, 1990). As shown in Table 3.6, there are four types of probability sampling techniques commonly used in the research field, namely, simple random sampling, systematic sampling, stratified sampling, and cluster (multistage) sampling.

The sampling technique selection involves selecting a unit of analysis for the questionnaires and interviews through chronological and purposeful sampling methods, i.e. quantitative to qualitative, or vice versa (Tashakkori and Teddlie, 2009). The quantitative to qualitative process is a common sampling process which has been used for data collection in mixed method research (Kemper *et al.*, 2003; Bryman, 2008), where the sequential data collected from a first sample is usually required to draw a second sample obtained from a purposive sampling procedure.

This research required respondents who have knowledge and experience related to construction waste minimisation, BIM, and sustainability issues in building design. Thus, the experienced architects (i.e. partners and associates) from the UK top 100 architectural practices listed in Building Magazine (2010), as shown in Appendix 2.1.3, were selected as the sample for the research to capture their views on the potential use of BIM to reduce construction waste at design stage. Building Magazine’s ranking of architectural practices was based on the number of qualified architects in the firms and turnover, profit, growth and staff employed. The largest architectural practices in the UK were selected for the survey, as their abilities have been considered to have sufficient resources in place. Compared to small and medium-sized enterprises (SMEs), these companies should potentially have implemented holistic sustainable and waste minimisation strategies and BIM at company, design team and project levels. Partners and associates were targeted in these companies due to they rich experience of managing a significant number of projects and leading decision-making process across strategic, design and communication levels (Osmani *et al.*, 2006). The cluster (multistage) sampling method was adopted for this research by using both quantitative and qualitative sampling methods in multiple stages. The sequence of sampling methods used is discussed in the following sections (see Table 3.11: sample distribution of respondents).

Table 3.6 Characteristic of sampling techniques (source: Stopher and Meybury, 1979; Kalton, 1983; Henry, 1990)

Methods	Sampling frame	Selection strategies	Benefits	Drawbacks
Simple random	Random or listing	● assumes every part of the sample has an equal and calculable probability of being selected	● ease of selection ● ease of use of the data ● no extra information needed for population once sampling frame is assembled ● useable with no adjustments or recalculation by statistical software	● Long and tedious process ● Requires an explicit sampling frame (a complete list of stay population) ● Involves site visits and interviews ● Visits across the geographic spread of the population ● High cost, such as travel ● Inefficient in terms of standard error per unit sampled as stratified sampling
Systematic	Physical representation or listing	● Advanced random sampling by either assembling or listing each of the study population ● Requires a random start	● ease of selection of field settings ● a sample is selected automatically by determining the sample size or selection interval, and obtaining a list (files, invoices, etc.) of the study population ● Ensures proportional representation of the population for some characteristic by de facto stratification (stratification variables: age, grade level, etc.)	● the sampling frame must be well mixed or purposefully arranged for stratification ● High cost and travel across entire geographic spread of the study population, if on-site visit is required ● Inefficient in terms of standard error per unit sampled as stratified sampling
Stratified	Listing with stratifying variables	● Classifies population into subpopulations or strata, based on supplementary information, followed by selection of separate samples from each of the subpopulations or strata	● Reduces standard errors ● Improves precision of estimates and ensures proportional representation of stratifying groups	● Expensive for obtaining the entire population information ● Use of weights in the calculation of standard errors in disproportional stratification ● With restriction: at least one selection sampled from each stratum
Cluster (multistage)	Listing of clusters (cluster) or primary sampling units (multistage)	● Each of the study population is assigned to a group or a cluster flowing by selection of clusters at random and all the population of selected clusters are included in the sample ● Clustering may be done at more than one stage.	● Useful when: a listing of clusters is available, but a list of the population is not available; the data collection involves site visits to reduce travel and training expense ● Does not require member listing ● Concentrates travel time for face to face interview ● Improves efficiency by using multistage sampling	● Economies of cluster sampling results in increase of standard errors due to the decrease in independent selections of the sample ● Loses information due to the formula used to estimate the sampling error ● Affects precision of the sample estimates through using numbers of clusters (more clusters better precision) ● Requires sampling expertise to avoid inadvertent bias when conducting multistage sampling ● Requires a complex process to estimate the sampling variability for multistage samples

Method to increase the response rate

According to Fellows and Liu (2008), a questionnaire tends to have a low response rate being an expected 25%-35% of useable responses from postal questionnaires. Typically, a 30% response rate is also acceptable (Sekaran, 2002). Therefore, methods applied to increase the response rate were implemented during questionnaire administration to assist in maximising the response rate. This ensured the largest possible return of completed questionnaires to enable meaningful data analysis (Fowler, 2002; Saunders *et al.*, 2007).

The adopted methods for increasing the response rate are discussed below, which follow the guidelines provided by Frazer and Lawley (2000), Fowler (2002), and Fellows and Liu (2008).

- **Layout design**: a variety of questions should be designed and limited within four pages to be printed on A3 paper using both sides and then folded as a leaflet (see Appendix 2.1.2). As such, the time respondents spend on the questionnaire will be minimised and it will be easy to read.
- **Cover-letter**: the economic driver will be that of landfill tax, which will be increased to £80 per tonne in 2014/2015. The legislation driver is the new government construction strategy 2011 and fully collaborative 3D BIM for all UK public projects of more than £5 million from 2016 onwards. These drivers should be stated on the cover-letter as incentives for respondents to participate in the research. A promise should be made in the cover-letter that a summary report of findings will be sent to those who tick the box as being willing to receive the report in the questionnaire. It can also explain the research objectives, questionnaire duration, contact details and a confidentiality statement (i.e. relating to data) and anonymity (i.e. referring to organisations and persons) which will make the respondent comfortable in answering the questions (see Appendix 2.1.1).
- **A self-addressed and stamped envelope**, which encourages respondents to send the completed questionnaire back to the researcher, was attached to each questionnaire.
- **A pilot study** has been conducted to enhance the clarity and comprehensiveness of the questionnaire.
- **Targeted participants**: efforts have been made to identify each respondent name rather than sending the questionnaire directly to organisations.
- **Administration period**: four follow-up rounds at the beginning of the third, fourth,

fifth, and sixth weeks of the administration period should be carried out during the administration process (telephone calls and emails).

Questionnaire administration

The questionnaires were sent out by post, followed by four follow-up reminders. The survey period accounted for seven weeks starting from Monday 11th July 2011 through to Friday 26th August 2011. All questionnaires were posted on the same day. Telephone and email follow-ups were processed for all non-respondents on weekly intervals during the seven-week period. By the end of the questionnaire period, 50 completed questionnaires were received by postal mail and email. As shown in Table 3.7, only 12 of the questionnaires were received after two weeks from the initial mailing. The second, third and fourth follow-up rounds increased the total completed questionnaires up to 39. Respondents tended to respond to questionnaires during the last week of the questionnaire period or immediately after being engaged by follow-up phone calls or emails. They could decline participation in the survey after the first follow-up round.

Table 3.7 Questionnaire administration

Survey duration (Week)	Number of questionnaires			Follow-up (via telephone and email)
	by Mail	by E-mail	Rejection	
1	4	0	1	
2	8	0	0	
3	3	3	7	1st
4	3	0	0	2nd
5	5	5	0	3rd
6	4	4	0	4th
7	7	4	1	
Sub-total	34	16	9	
Total	50		9	

The first two rounds of follow-ups revealed that a number of targeted respondents were out of the office for their summer holiday; also some respondents did not receive the questionnaire. Hence, to achieve a satisfactory response rate the response time was extended by three weeks for completion of the questionnaire. The third and fourth follow-up rounds were conducted to engage those returning from holiday and who agreed to complete the questionnaire during the follow-up rounds. This accounted for a total of 18 questionnaires being received by the end of week six. By the end of the questionnaire period (week seven), a total of 50 completed questionnaires (response rate of 50%) had been received. This included 34 questionnaires by post and 16 by e-mail. Nine companies rejected the questionnaire claiming that BIM had not been used for any of their projects.

3.5.2.2 Interviews

Interviews are that of data collection techniques whereby a researcher interacts with one or more individuals at each interview with a certain purpose in mind (Kumar, 1999; Gillham, 2000). This interaction is a purposeful conversation to attain instant feedback for the explanation of complex situations (Bogdan and Biklen, 1982; Kumar, 1999). The interview is the most appropriate method in which to investigate a situation. This can include things such as the meaning of a particular phenomena, the perception of processes within a social unit, a historical account in the development of a phenomenon, an exploration prior to a quantitative study. It can provide qualitative data for further clarification and illustration, the meaning of findings or validation of measures gathered from the quantitative study (King, 1994). Three types of interview most popular to researchers are (Walliman, 2006; Fellows and Liu, 2008):

- structured interview: standard questions are read out by the interviewer according to an interview schedule. Answers may be closed-format;
- unstructured interview: a flexible format is usually based on a question guide but the format remains the choice of the interviewer who can allow the interview to ‘ramble’ in order to get insight into the attitudes of the interviewee. No closed-format questions are used; and
- semi-structured interview: one that contains structured and unstructured sections with standardised and open-format questions.

There is another type of group interview namely the focus group, which concentrates in-depth on a particular theme or topic with an element of interaction (Walliman 2006). Walliman (2006) suggested that the group is often made up of people who have specific experience of knowledge regarding the research subject, or those who have a particular interest in it (e.g. consumers or customers). The focus group can be used to (Morgan and Krueger, 1998; Bryman, 2008):

- generate hypotheses based on the informants’ insight;
- gain the participants’ interpretation of results from earlier studies;
- develop an understanding as to why people think the way they do;
- bring forward ideas and opinions not foreseen by the interviewer;

- challenge interviewees between other members of the group regarding their replies; and
- to find interaction within group dynamics which are close to the real-life process of sense-making and acquiring understanding.

Furthermore, Axinn and Pearce (2006) argued that the potential benefits of the focus group is that informants may feel greater confidence within a group setting, which may encourage them to offer comments and discuss matters they would not normally do in a one-on-one interview. On the other hand, focus groups have their problems: difficulty in organising the focus group due to complications in getting a group of people together for a discussion session (Walliman 2006); collaborative settings may present problems for data collection (Axinn and Pearce 2006); how to document the data in a way that allows the identification of individual speakers and the difference between statements of several parallel speakers (Flick 2002).

Interviews can also be carried out through one-on-one face to face, or telephone and computer based methods. The benefits and drawbacks of these methods are summarised in Table 3.8. The one-on-one face-to-face interview is the most suitable interview method to attain in-depth opinions from interviewees (Bugher, 1980), when:

- interviewees are asked their opinions within a properly structured context;
- the questions are appropriately worded;
- the interviewees understand the purpose of the interviews; and
- their responses are respectively guaranteed anonymity.

Once the quantitative study (questionnaire) has been conducted, qualitative data is required to clarify and illustrate the meanings of the findings of quantitative data (King, 1994; Hannabuss, 1996). Thus, the interview method was adopted for data collection in the second phase of the research. This was carried out through face-to-face semi-structured interviews with selected questionnaire respondents. Semi-structured interviews are typically applied to capture the meanings of relationships between variables which are revealed through a descriptive study (Saunders *et al.*, 2007). The data collected from semi-structured interviews was intended to investigate the current use of BIM and construction waste minimisation and establish the image with relation to the impact of using BIM for waste reduction during design. The follow-up interviews were designed to explore the current use of waste minimisation in building design; investigate the current use of BIM for sustainable building design; and to assess the use of BIM for construction waste minimisation.

Table 3.8 Benefits and drawbacks in conducting different interview methods (source: Sekaran, 2002; Novick, 2008)

Methods	Benefits	Drawbacks
Face to face	• Helps to creates environment of rapport and respect • Assists to clarify questions and doubts, and probes new questions • Allows use of visual aids to clarify issues • Facilitates to capture non-verbal cues	• Consumes more time such as travelling • Can be costly when interviews cover a wide range of geographic regions • Needs to be conducted by well trained interviewer • Can have bias by execution of interviewer
Telephone	• Saves travel cost • Assists to reach geographically dispersed respondents • Requires no room space for interview • Allows unobtrusive note taking • Guarantees anonymity • Allows respondents to feel relaxed • Enables the disclosure of sensitive information	• lacks visual or non-verbal cues • can be terminated unilaterally without warning or explanation • Short interview duration compared to face to face interviews
Computer based	• Saves travel cost • Requires no room space for interview • Easy to conduct • Can reach globally or wide geographical area	• Requires knowledge of computer • Requires computer related facilities for respondents to access

Findings from the literature review and questionnaire indicated that:

- Construction waste causes in each building desin stage
- BIM has been used to enhance sustainable building design (e.g. energy efficiency, carbon reduction and building material specification).
- BIM has not being frequently used for waste minimisation, yet it has great potential to assist architects to design out waste.
- Design stages were thought to have a signification effect on BIM potential to minimise CW. BIM could be used efficiently to help with addressing waste causes, such as ineffective coordination and communication, design changes, design and detailing complexity and design and construction detail errors.

Therefore, follow-up interviews (face-to-face and semi-structured) were designed and aimed at investigating the issues above in detail, seeking a way in which to develop a BIM-aided waste minimisation framework.

Interview template design and development

The interview template contained five sections: (1) background information (three questions); (2) current construction waste minimisation in building design (six questions); (3) current use of BIM in building design (five questions); (4) Current use of BIM in sustainable building design (three questions); (5) BIM to address construction waste minimisation (seven questions); and (6) further thoughts. All questions were open-ended. The questions in section three and most questions in section four were directly related to the findings of the questionnaire (i.e. current use of BIM for design-related activities, current use of BIM for building design and sustainable design, and the use of BIM to address waste causes throughout building design stages). The final version of a follow-up interview template (see Appendix 2.2) was designed within three pages, which was based on three revisions and a pilot study.

Interview sampling

The questionnaire respondents were asked whether they were willing to participate in a follow-up interview. Consequently, 23 respondents showed an interest in doing so. The selection of interview participants was based on three factors: the interest from the respondent to be involved in an interview; their experience in waste minimisation and the use of BIM for sustainable building design issues (energy efficiency, carbon reduction and material specification) in design, and travelling cost to the location of the respondents' organisation, which resulted in 11 (out of 23) respondents. Additionally, other respondents (i.e. those who ticked 'no' to a follow-up interview) were contacted as they fitted the selection criteria laid down. They were asked if they would like to re-reconsider their participation in the interviews, but unfortunately none of them were willing to take part.

Interview process

A pilot interview was carried out with construction management researchers at the School of Civil and Building Engineering at Loughborough University to enhance the clarity of questions, assess the time required for each section, test the audio recording devices, and act as a practice session prior to actual interviews.

Two documents were designed for follow-up interview dissemination, those being an interview schedule and interview questions (see Appendix 2.2). These documents were sent out to interviewees one week prior to the scheduled interview date. This allowed them to prepare for the interview questions.

In order to facilitate the investigation and the discussion of specific topics to the questions, probed questions could be asked during the interviews (Hannabuss, 1996). The probed questions contained emerging issues extracted from the literature review, results of the questionnaire and responses during the interviews. An audio recorder was used to record all interviews with the permission of the interviewees, which assisted further data analysis to ensure accuracy and objectivity when recording responses (Fellows and Liu, 2008). All interviews (see Table 3.9) were conducted over approximately four weeks during November 2011.

Table 3.9 Interview detail

Interview participants	Interview location	Interview duration
I1	Bristol	1 hour and 15 minutes
I2	London	1 hour and 16 minutes
I3	Gloucester	1 hour and 12 minutes
I4	London	1 hour and 15 minutes
I5	London	1 hour and 10 minutes
I6	Cheshire	1 hour and 11 minutes
I7	London	1 hour and 13 minutes
I8	Bristol	1 hour and 13 minutes
I9	London	1 hour and 14 minutes
I10	London	1 hour and 10 minutes
I11	London	1 hour and 14 minutes

3.5.3 Data analysis

The data analysis process is described as the interplay between the researcher and the data, whereby the analysis is focused on the understanding and interpretation of data collected in a systematic, logical way to reach a reliable conclusion (Knight and Ruddock, 2008). The quantitative data analysis (i.e. statistical analysis) and qualitative data analysis (i.e. content comparative analysis) were respectively accepted for the data analysis of the questionnaire and interview.

3.5.3.1 Questionnaire survey data analysis

The 'questions' data (other than open-ended questions) of the questionnaire survey was analysed through quantitative techniques. Quantitative data analysis works through numbers and utilises the mathematical operation to investigate data properties (Walliman, 2006). The main objective of the questionnaire was to capture a general view on the aspects of construction waste minimisation and BIM. As such, statistical techniques are useful tools to enable the researcher to disseminate the data and to discover and quantify relationships between different variables (Saunders *et al.*, 2007). Hence, the descriptive proportion of responses within each category became the main data reporting method for both the questionnaire survey and the BaW Framework validation questionnaire. The selection technique used for data analysis is based on the source and type of collected data and its scale of measurement such as nominal, ordinal, interval and ratio (Gaito, 1980). In other words, classifying the data scale of measurement for each question is essential to the quantitative data analysis. The questionnaire survey data was classified into different scales of measurement as shown in Table 3.10.

This shows that where data having categorical questions (e.g. questionnaire question 1.1, 1.2 and 2.1II) were considered as nominal data and experiences including rating scales (e.g. questionnaire question 3.2, 3.3 and 4) were regarded as ratio data. The data scales of measurement could then be analysed through quantitative data analysis software packages.

Table 3.10 Data scale of measurement from questions of the questionnaire survey

Data scale of measurement	**Question ID from questionnaire**
Nominal	1.1, 1.2, 2.1II, 3.1II & III, 7.1, 7.2, and 7.3
Ratio	2.1I, 2.2, 3.1I, 3.2, 3.3, 4, and 5.1

Data analysis software

Through the use of software, quantitative data can be easily manipulated and displayed with greater efficiency by the mechanisation of tedious tasks, such as searching and copying text segments (Kelle and Laurie, 1995). This makes the process of analysis more comprehensive and replicable to increase the reliability and validity of data analysis (Robson, 2002). Moreover, the use of software can make data analysis more rigorous and transparent through a systematic process, which enables the researcher to codify exactly what will be analysed and how (Conrad and Reinarz, 1984). Furthermore, the analytic function of software such as textual analysis allows the researcher to conduct more creative tasks by playing with the data and thoroughly exploring relationships between different categories (Lee and Fielding, 1995). Statistical Package for the Social Sciences (SPSS) is one of the most widely used and user-friendly software packages for statistical data analysis. Therefore, SPSS version 19 has been adopted for the presentation and calculation of quantitative data analysis for the research. One type of statistical analysis was performed through the SPSS, namely, descriptive statistics.

Descriptive statistics describes or summarises data including the counts (numbers or frequency), proportions (percentages), measures of central tendency (the mean, mode and median) and measures of variation (range and standard deviation) (Tan, 2002; Fink, 2006). Descriptive statistics were conducted for this research to analyse data by numbers or frequency, percentages and the mean to present views of respondents on each related question. It was used for questionnaire (see Table 4.3).

On the other hand, the data from open-ended questions of the questionnaire survey was analysed through qualitative technique that is discussed in the following section.

3.5.3.2 Interviews data analysis

Qualitative data collected through interviews and the questionnaires were analysed using content analysis. Content analysis is the most used qualitative data analysis technique and can be implemented to explore large amounts of textual information (Weber, 1990; Mayring, 2000). It can ascertain trends and patterns of words that are used, their frequency, their relationship and structure and discourses of communication (Weber, 1990; Mayring, 2000; Grbich, 2007). The analysis covers a range of processes and procedures, which presents the transition from collected data into forms of explanation, understanding or interpretation of the views of participants and situations under investigation (Bryne, 2001). The analysis process typically involves identifying, coding, and categorising patterns found within the data (Bryne, 2001). The complete qualitative data analysis process goes from unitising data to categorising data (Lincoln and Guba, 1985), whereby:

1) The unitising process ensures narrative data is divided into the smallest pieces of meaningful information units under each interview question.
2) The categorisation process:
   - brings together the same content related provisional categories and those units of information from the unitising process;
   - devises rules that relate to each category properties;
   - renders each category set internally for consistency making it entirely and mutually exclusive.

All the interviews were recorded through the SONY IC audio recorder device (ICD-PX312) to facilitate the analysis of qualitative data. Firstly the recordings were transcribed to capture the full extent of verbal data. Each transcript of data was read several times in order to tidy and organise the transcription content. Secondly, key points of transcript information were obtained, coded and categorised into key themes to help identify similar and different options. The analysis was conducted manually because the amount of data appeared manageable without the use of qualitative data analysis software. It was also related to the investigated issues, which were distinct to each other as the main interview themes were based on key questionnaire findings. Microsoft Excel 2010 was used for data storing and manipulating purposes when unitising and categorising the processes. Detailed data analysis of interviews including identified themes and sub-themes are discussed and presented in Chapter 5.

3.5.4 BaW Framework development and validation

Figure 3.3 shows the methodological approach for BIM-aided waste minimisation (BaW) Framework development and validation illustrating key stages and methods used to develop and validate the Framework.

3.5.4.1 BaW Framework design and development

The key findings from the questionnaires and interviews clearly informed the structure and design of the BaW Framework. A ‘framework’ is designed and developed to:

- act as a benchmarking process providing a frame of reference (Male *et al*., 1998);
- embody an abstract design for solutions to a family of related problems (Johnson and Foote, 1988);
- provide a method to organise and build interactive object systems and subsystems, which defines the structure and flow of individual objects (Wirfs-Brock *et al.*, 1990); and
- makes recommendations as to what should be done (Hogwood and Gunn, 1985).

The literature review findings, questionnaire and interviews, were used as the data source in developing the BaW Framework, as shown in Figure 3.3. The rationale for the BaW Framework design and its structure were established based upon a BIM process to address waste causes during building design stages, and the current BIM-aided energy efficiency process, which is widely practiced by the selected interviewees.

The structure of the BaW Framework consists of three aspects: framework levels, framework process actions and coding system. The BaW Framework comprises two levels, namely, High-level (strategic) Framework, and Low-level (detailed) Framework with two related evaluation process components. The High-level BaW Framework aims toward a strategic BIM-aided construction waste minimisation implementation process throughout all building design stages from RIBA Plan of Work stages Appraisal to Production Information. The full RIBA Plan of Work stages (RIBA, 2008) are listed in Figure 3.4.

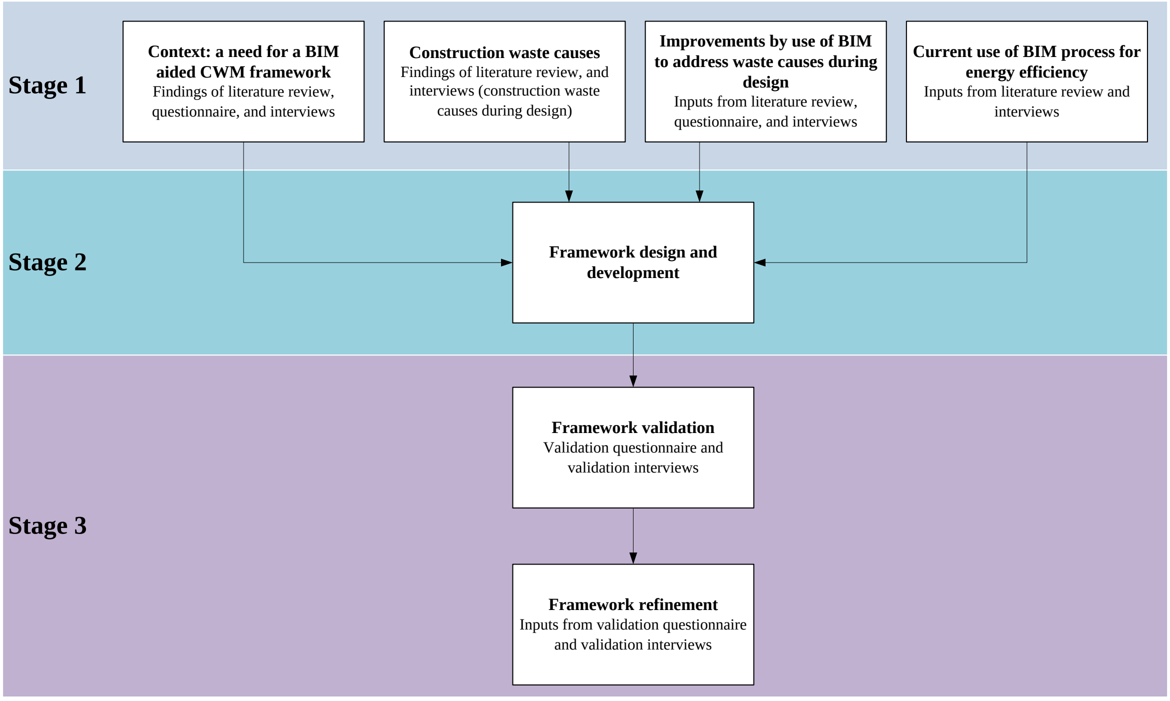


Figure 3.3 Methodological approaches for BIM-aided waste minimisation (BaW) Framework development and validation

The Low-level BaW Framework aims toward a detailed BIM-aided waste minimisation implementation process during Concept to Design Development stages. Two Low-level framework components aim toward a specific BIM-aided waste minimisation evaluation process in each Concept and Design Development stages. The BaW Framework process actions denote key BIM assisted improvements to address waste minimisation during design. The BaW Framework is guided through a coding system linking two Framework levels and their components as well as the content within each Framework and component. Detailed explanation of the BaW Framework design and development is described in section 7.2.

3.5.4.2 BaW Framework validation

Validation is a scientific inquiry whereby a validity judgement acts as an inductive summary of all available information with issues of meaning and interpretation central to the processes (Messick, 1989). There are three types of commonly used methods for validation: (1) content validity that ensures a specific knowledge of functioning represented by the items; (2) criterion-related validity is when scores from an appropriately correlated measure is hypothesised with other constructs or is useful in predicting future scores representing hypothetically related constructs; and (3) construct validity, which overlaps the other two types (Cronbach and Meehl, 1955; Crocker and Algina, 1986). However, construct validity is recognised as the centre or overarching method of validation procedures. This is because it encompasses all types of measurement-related validity evidence, not only measurement-related validity but also all other valid evidence such as design-related evidence, which assesses the appropriateness of logical derived inferences (Cronbach and Meehl 1955, Messick 1995).

RIBA Work Stages			Description of key tasks
A	**Appraisal**		Identification of client's needs and objectives, business case and possible constraints on development. Preparation of feasibility studies and assessment of options to enable the client to decide whether to proceed.
B	**Design Brief**		Development of initial statement of requirements into the Design Brief by or on behalf of the client confirming key requirements and constraints. Identification of procurement method, procedures, organisational structure and range of consultants and others to be engaged for the project.
C	**Concept**		Implementation of Design Brief and preparation of additional data. Preparation of Concept Design including outline proposals for structural and building services systems, outline specifications and preliminary cost plan. Review of procurement route.
D	**Design Development**		Development of concept design to include structural and building services systems, updated outline specifications and cost plan. Completion of Project Brief. *Application for detailed planning permission.*
E	**Technical Design**		Preparation of technical design(s) and specifications, sufficient to co-ordinate components and elements of the project and *information for statutory standards and construction safety.*
F	**Production Information**	**F1**	Preparation of production information in sufficient detail to enable a tender or tenders to be obtained. *Application for statutory approvals.*
		F2	*Preparation of further information for construction required under the building contract.*
G	**Tender Documentation**		*Preparation and/or collation of tender documentation in sufficient detail to enable a tender or tenders to be obtained for the project.*
H	**Tender Action**		*Identification and evaluation of potential contractors and/or specialists for the project.* *Obtaining and appraising tenders; submission of recommendations to the client.*
J	**Mobilisation**		Letting the building contract, appointing the contractor. Issuing of information to the contractor. Arranging site hand over to the contractor.
K	**Construction to Practical Completion**		Administration of the building contract to Practical Completion. Provision to the contractor of further Information as and when reasonably required. Review of information provided by contractors and specialists.
L	**Post Practical Completion**	**L1**	Administration of the building contract after Practical Completion and making final inspections.
		L2	Assisting building user during initial occupation period.
		L3	Review of project performance in use.

Figure 3.4 RIBA Outline Plan of Work 2007 (source: RIBA, 2008)

Validation is also a collective view of the real world which a framework or model has presented from respondents involved in a research (Lincoln and Guba, 1985; Pidd, 2009). It aims to ensure the reliability of research findings, and to enhance the understanding and explanation by strengthening confidence in the research findings (Cronbach, 1984; Patton, 2003). Feedback from research respondents is important in confirming the findings by verification which reflects the perspective of respondents; informing the problematic sections if published (e.g. could be personal or political reasons); and developing new ideas and interpretations (Glesene, 1999). The feedback provides an opportunity for researchers to learn a great deal about the accuracy, completeness and fairness of the final research outcome presented (Patton, 2003).

Hence, the validation methodology in this research aimed to refine and validate BaW Framework in terms of clarity, flow and content, and to discuss the implementation strategy by considering appropriate involvement of people and procedures for validation:

- The involvement of people (1) the researcher (i.e. the Framework development by identifying and synthesising key themes and analysing the responses of validated respondents), (2) research community (i.e. Framework refinement discussions with researchers at the School of Civil and Building Engineering, Loughborough University); and (3) research respondents (i.e. participating architects for the Framework validation pre-interview questionnaire and interviews).
- Aspects of procedures: appropriateness of the Framework content and the logically derived inferences of the Framework structure and flow.

The validation procedure consisted of two main stages: the BaW Framework refinement pilot study (i.e. the Framework pre-validation refinement discussions with construction management researchers at the School of Civil and Building Engineering, Loughborough University), and the BaW Framework validation questionnaire and validation interviews with participating respondents.

BaW Framework validation questionnaire

The validation questionnaire was used to refine clarity of structure and flow and the appropriateness of the BaW Framework content. As shown in Appendix 2.3, the two-page questionnaire comprised five sections: High-level BaW Framework validation (structure, content and flow), Low-level BaW Framework validation (structure, content and flow), evaluation-process validation (structure, content and flow), implementation strategy, and further comments.

BaW Framework validation interview template

The validation interviews aimed to further refine and examine the proposed BaW Framework in terms of issues emerging from the validation questionnaire. As shown in Appendix 2.3.3, interview questions included six sections as the following:

1) Background information - (interviewees' experiences and designation).
2) High-level BaW Framework component validation - (based on the validation questionnaire).
3) Low-level BaW Framework component validation - (based on the validation questionnaire).
4) Validation of the Evaluation-process components - (based on the validation questionnaire).
5) To investigate the implementation strategy for the BaW Framework.
6) To gather further thoughts regarding other issues/suggestions related to the improvement of the proposed BaW Framework.

BaW Framework validation pilot study

The Framework validation pilot study aimed to refine the draft pre-validation BaW Framework in terms of English, structure, clarity of content and flow, and to obtain further suggestions for improvements. Five construction management researchers working at the School of Civil and Building Engineering, Loughborough University, were involved in the discussions regarding the validation process of the pilot study. The BaW Framework was further refined based on comments received, such as formatting and typographical errors.

BaW Framework validation sampling

As shown in Table 3.11, six interviewees from the data-collection stage agreed to participate in the validation stage of the study, of which five were involved in the interview and one responded to the questionnaire only.

Conducting the BaW Framework validation

Four documents were disseminated by e-mail to the six Framework validation participants one week prior to the validation interviews: a covering letter (aim and framework overview) (refer to Appendix 2.3.1), a validation questionnaire (respondents were asked to complete this before the scheduled interview) (refer to Appendix 2.3.2), an interview template for the Framework validation (refer to Appendix 2.3.3) and the proposed BaW Framework (refer to Appendix 2.3.2.1, 2.3.2.2, 2.3.2.3, and 2.3.2.4).

Each completed validation questionnaire was collected prior to the commencement of the follow-up interview. All interviews were conducted during a two week period in October 2012.

Table 3.11 Respondent sample distribution

Respondents (the UK top 100 architects)	Questionnaire survey	Interviews	Framework Validation: Questionnaire & Interviews
1	√	x	x
2	√	I1 √	V1 √
3	√	x	x
4	√	x	x
5	√	I2 √	x
6	√	x	x
7	√	x	x
8	√	x	x
9	√	x	x
10	√	I3 √	V2 √
11	√	x	x
12	√	x	x
13	√	x	x
14	√	x	x
15	√	x	x
16	√	x	x
17	√	I4 √	x
18	√	x	x
19	√	x	x
20	√	x	x
21	√	x	x
22	√	x	x
23	√	x	x
24	√	x	x
25	√	I5 √	x
26	√	x	x
27	√	x	x
28	√	x	x
29	√	I6 √	x
30	√	x	x
31	√	I7 √	V3 √
32	√	x	x
33	√	x	x
34	√	I8 √	V4 √
35	√	x	x
36	√	x	x
37	√	x	x
38	√	I9 √	x
39	√	x	x
40	√	x	x
41	√	x	x
42	√	I10 √	x
43	√	x	x
44	√	x	x
45	√	x	x
46	√	x	x
47	√	x	x
49	√	I11 √	V5 √
50	√	x	V6 √

BaW Framework validation data analysis

The BaW Framework validation process included validation questionnaire and validation interview. Hence, the BaW Framework validation employed the same data analysis methods with the questionnaire and the interview, such as descriptive statistics and content analysis, for the data analysis. As shown in Table 3.12, the BaW Framework validation questionnaire data was classified into two scales of measurement.

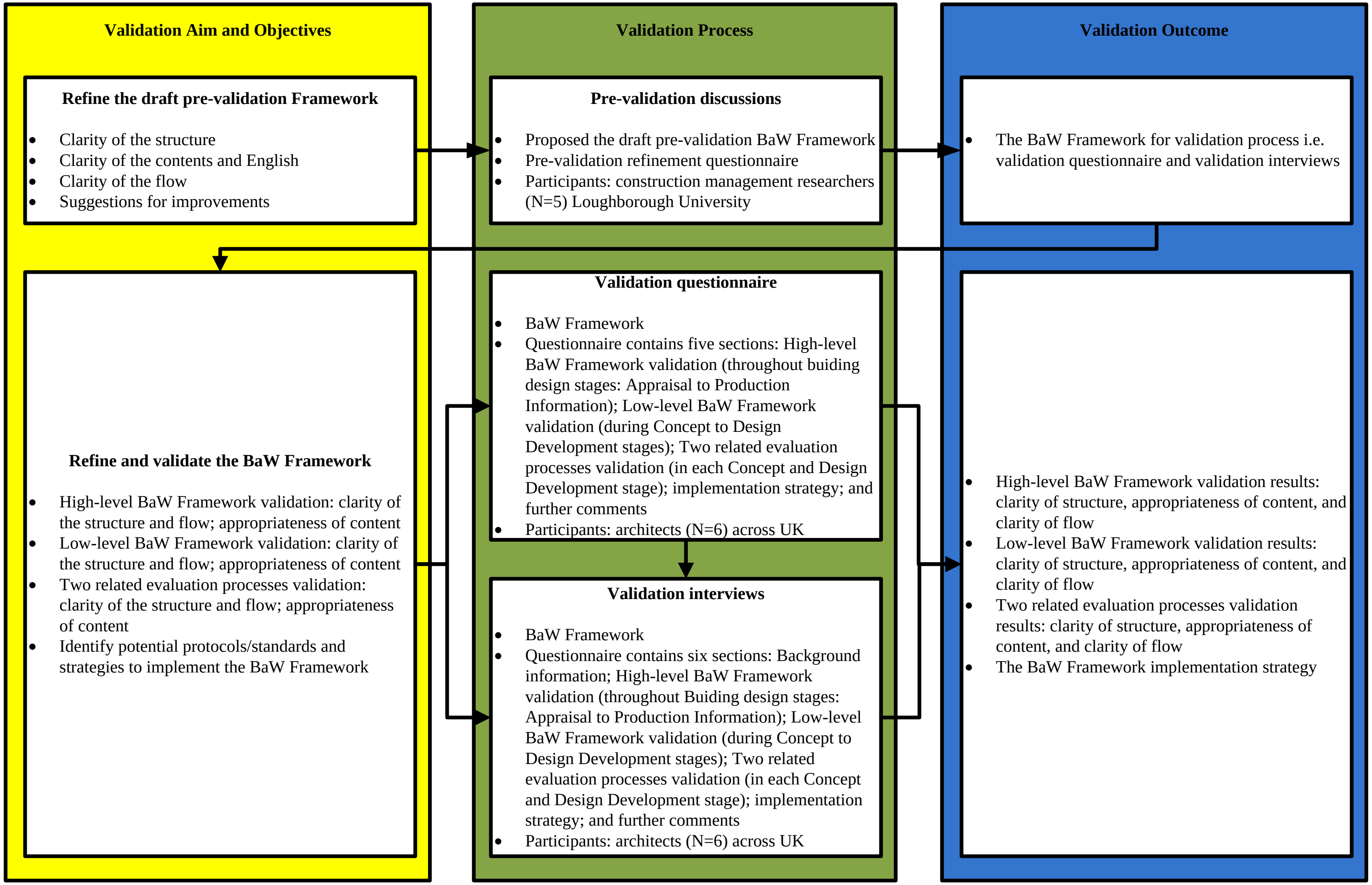
The Framework was finalised based on the suggested refinements that emerged from the validation results. The adopted procedure and outcome of the Framework validation are illustrated in Figure 3.5.

Table 3.12 Data scale of measurement from questions of the BaW Framework validation questionnaire

Data scale of measurement	Question ID from the BaW Framework validation
Nominal	4.1
Ratio	1.1, 1.2, 1.3, 2.1, 2.2, 2.3, 3A.1, 3A.2, 3A.3, 3B.1, 3B.2, and 3B.3

3.6. Summary

This chapter describes the philosophical position of the research as a mixed positivist and constructivist philosophy. Thus, the mixed research strategy (triangulation), which handles both quantitative and qualitative strategies, was adopted for the research. Hence, a two-stage sequential mixed method study was identified as the appropriate data collection method to obtain both quantitative and qualitative data. This data was obtained through a postal questionnaire survey and face-to-face semi-structured interviews. Findings from literature review, questionnaire and follow-up interviews, were used as the basis for the design and development of the BaW Framework. A questionnaire and face-to-face semi-structured follow-up interviews were employed for the BaW Framework validation. The questionnaire results will be presented in the next chapter.



Validation Aim and Objectives

Refine the draft pre-validation Framework

- Clarity of the structure
- Clarity of the contents and English
- Clarity of the flow
- Suggestions for improvements

Refine and validate the BaW Framework

- High-level BaW Framework validation: clarity of the structure and flow; appropriateness of content
- Low-level BaW Framework validation: clarity of the structure and flow; appropriateness of content
- Two related evaluation processes validation: clarity of the structure and flow; appropriateness of content
- Identify potential protocols/standards and strategies to implement the BaW Framework

Validation Process

Pre-validation discussions

- Proposed the draft pre-validation BaW Framework
- Pre-validation refinement questionnaire
- Participants: construction management researchers (N=5) Loughborough University

Validation questionnaire

- BaW Framework
- Questionnaire contains five sections: High-level BaW Framework validation (throughout buiding design stages: Appraisal to Production Information); Low-level BaW Framework validation (during Concept to Design Development stages); Two related evaluation processes validation (in each Concept and Design Development stage); implementation strategy; and further comments
- Participants: architects (N=6) across UK

Validation interviews

- BaW Framework
- Questionnaire contains six sections: Background information; High-level BaW Framework validation (throughout Buiding design stages: Appraisal to Production Information); Low-level BaW Framework validation (during Concept to Design Development stages); Two related evaluation processes validation (in each Concept and Design Development stage); implementation strategy; and further comments
- Participants: architects (N=6) across UK

Validation Outcome

- The BaW Framework for validation process i.e. validation questionnaire and validation interviews

- High-level BaW Framework validation results: clarity of structure, appropriateness of content, and clarity of flow
- Low-level BaW Framework validation results: clarity of structure, appropriateness of content, and clarity of flow
- Two related evaluation processes validation results: clarity of structure, appropriateness of content, and clarity of flow
- The BaW Framework implementation strategy

Figure 3.5 Roadmap of the BaW Framework validation procedure

CHAPTER FOUR

Questionnaire Results

4.1. Introduction

This chapter presents the results of the postal questionnaire survey (Appendix 2.1). The aim of the questionnaire was to explore the potential use of BIM to address waste minimisation during design.

The first section presents the background information to companies and individuals that responded to the questionnaire. Subsequent sections present the results of the current use of BIM in building design, BIM as a potential tool to reduce construction waste, barriers and incentives in the use of BIM in building design, and qualitative comments on the use of BIM to reduce waste during design. The last section explains the questionnaire validity and reliability.

Based on the use of BIM to enhance Sustainable Building Design (SBD) practices that include energy efficiency, carbon reduction, building material specification, water management, and waste minimisation, respondents were divided into two groups for analysis. Group A (28 responding architects) had used BIM for SBD practices, whilst Group B (22 responding architects) had not. The results of categorical and rating questions are described as quantitative statistical summaries, whist the results of open-ended questions are presented as qualitative narratives and quotations.

4.2. Background information

4.2.1 Current work areas of participating companies

Participants were asked to provide information on their respective work areas in terms of operating sectors, nature of work and building types.

As shown in Figure 4.1, most participating companies operate effectively within both public and private sectors.

Participating architectural practices were heavily involved in new build, refurbishment, repair and renovation and commercial works, and undertook residential building projects. Approximately half of respondents reported that their company carried out industrial building projects. Furthermore, around a fifth of respondents specified two particular types of projects they were involved in, namely, education and health care. Figure 4.1 reveals that the respondents who used BIM for sustainable building design (Group A), were more likely to operate in the public sector than those who have not (Group B).

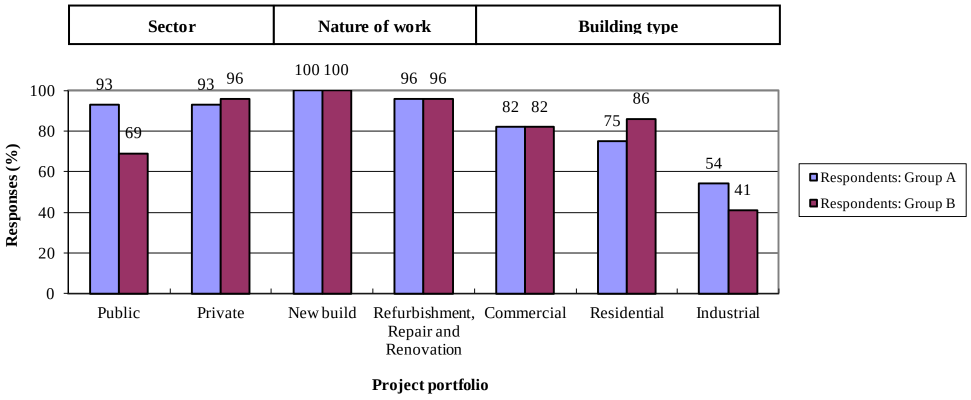


Figure 4.1 Areas of activity by participating companies

4.2.2 Current sustainability policies

Respondents were asked to divulge if their respective companies had a sustainability policy, waste management policy, Social Corporate Responsibility or ISO 14001 accreditation in place.

Table 4.1 indicates that nearly all participating companies had a sustainable policy in place. Moreover, the majority of respondents indicated that their company had, or was in the process of establishing a waste management policy, a Social Corporate Responsibility policy, and ISO 14001 accreditation. Group A respondents seem to have the above policies in place than those of Group B.

Table 4.1 Current company policies

Policies	Responses (%)		
	Yes	**In progress**	**No**
Sustainable Policy			
Group A	100	0	0
Group B	96	0	4
Waste Management Policy			
Group A	82	7	11
Group B	73	4	23
Social Corporate Responsibility			
Group A	78	11	11
Group B	59	9	32
ISO 14001 Accreditation			
Group A	68	18	14
Group B	54	14	32

4.3. BIM in building design

4.3.1 The use of BIM in design projects

On a scale from 1 (never used) to 4 (used in all projects), respondents were asked to rate the usage extent of BIM packages in their design projects and to specify the associated project costs.

It is apparent from Figure 4.2, that the five widely known BIM packages (i.e. Autodesk Revit, Graphisoft ArchiCAD, Nemetschek Vectorworks, Bentley Architecture, and Tekla Structures) were not frequently used in all design projects. The results showed that Group A and Group B had a close low mean value to the use of each BIM package within their design projects.

However, more than two-thirds of respondents reported that Autodesk Revit had been used in their building design projects, in fact over a quarter in most or all projects.

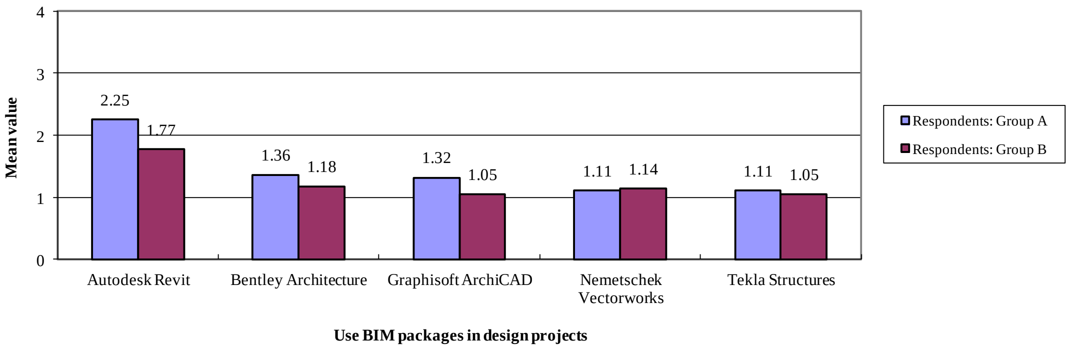


Figure 4.2 The use of BIM packages in design projects

Table 4.2 illustrates the costs associated with the use of BIM packages, indicating that, by and large, these were used principally for projects with a value above £10 million. In addition, it seems that Autodesk Revit was the most preferred package.

On a scale from 1 (never used) to 4 (used in all projects), respondents were also asked to rate the extent to which BIM was used for specific design stages and processes such as design, analysis/simulation, decision making/knowledge database and project performance improvement.

Figure 4.3 suggests that BIM was not being used in most or all design projects to assist activities during the design process, such as CAD outputs, clash detection, modern methods of construction, detailing and building services design. However, Group A used BIM to assist their activities far more frequently in most or all design projects than Group B, as indicated in Figure 4.3.

Table 4.2 The use of BIM packages associated with cost in design projects

BIM packages	The use of BIM packages associated with cost in design projects (Responses %)			
	up to £4.99 million	£5 - 9.99 million	£10 - 49.99 million	£50 million above
Autodesk Revit				
Group A	36	36	57	50
Group B	9	32	27	18
Bentley Architecture				
Group A	14	18	18	25
Group B	4	14	18	4
Graphisoft ArchiCAD				
Group A	14	14	18	18
Group B	4	0	0	0
Nemetschek Vectorworks				
Group A	11	14	7	7
Group B	0	0	0	4
Tekla Structures				
Group A	11	11	11	14
Group B	0	0	4	0

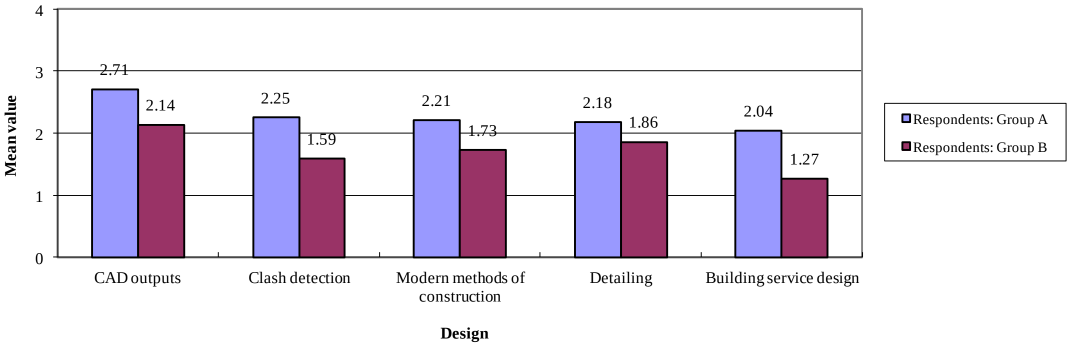


Figure 4.3 The use of BIM for design

As shown in Figure 4.4, it is clear that activities such as lighting analysis, cost estimation, lifecycle assessment, sourcing and analysis/simulation processes, have not been frequently facilitated through the use of BIM in most or all their design projects. BIM even had been rarely used in most or all design projects to facilitate these activities by Group B. However, BIM was used more frequently in most or all design projects to assist visualisation and simulation than the other four activities. Figure 4.4 shows that Group A had used BIM to aid the listed five activities for analysis/simulation processes more frequently in most or all their design projects than Group B.

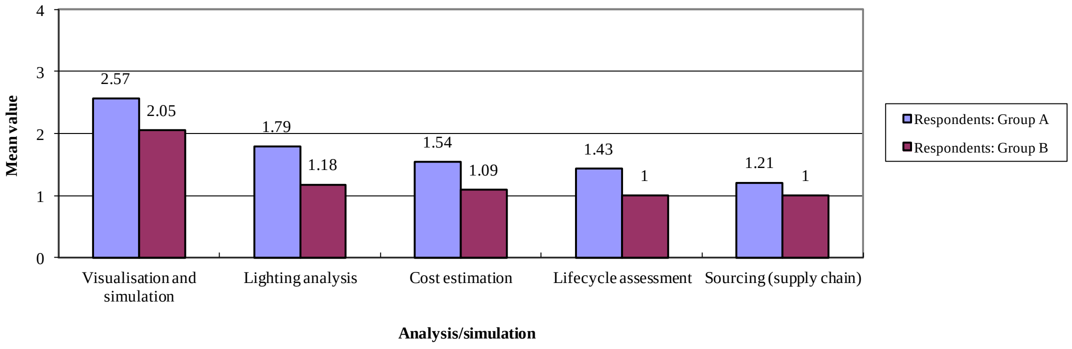


Figure 4.4 The use of BIM for analysis/simulation

Figure 4.5 indicates that BIM was not frequently used in most or all their design projects to improve communication and coordination, obey codes and regulations, and comply with facility management to improve decision making/knowledge. BIM was more frequently used in most or all their projects to improve communication and coordination than other two activities. Compare to Group B, Group A used BIM to facilitate the listed three activities more frequently in most or all their design projects.

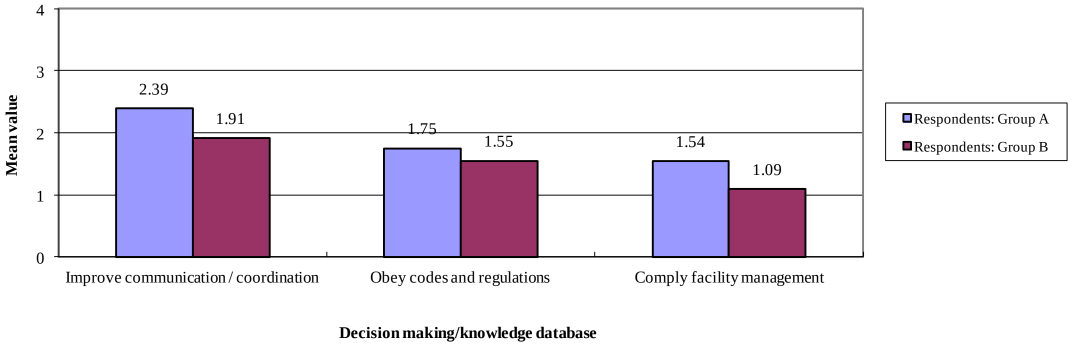


Figure 4.5 The use of BIM for decision making

BIM was not frequently used in most or all their projects to improve project performance through assisting at briefing, design, on-site performance, or refurbishment stage, as illustrated in Figure 4.6. However, Figure 4.6 also shows that BIM was more frequently used in design projects by Group A than Group B for improving project performance throughout briefing, design, on-site construction and refurbishment, where design was the stage that BIM was most used to help with in most or all projects.

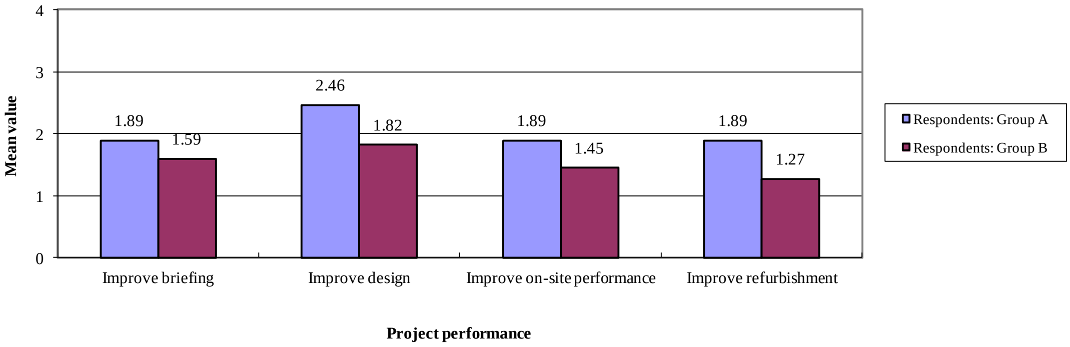


Figure 4.6 The use of BIM for project performance improvement

4.3.2 Current sustainable building design practices

On a scale from 1 (never used) to 4 (used in all projects), respondents were asked to rate the extent to which they used sustainable building design (SBD) practices in their current/recent projects.

Figure 4.7 indicates that SBD practices such as energy efficiency, carbon reduction and building material specification, had been frequently implemented in most or all their current design projects. On the other hand, water management and waste minimisation had not been frequently used in most or all their current design projects. Interestingly, Group B had used the above all the five SBD practices more frequently within their current design projects compared to Group A.

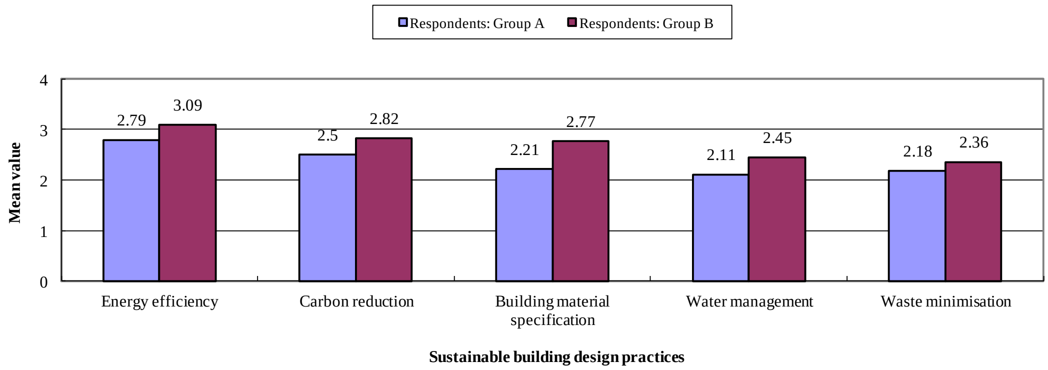


Figure 4.7 The use of sustainable practices in current design projects

4.3.3 The use of BIM for sustainable building design

Respondents were asked to specify whether BIM was used for SBD practices in their current/recent design projects.

It is apparent from Figure 4.8, that the use of BIM for SBD practices is not common practice. Almost half of respondents (Group B: 22 responding architects) had not implemented BIM to facilitate any form of SBD practices in their current/recent building design projects. Indeed, nearly all of Group A regularly used BIM as a vehicle for energy efficiency. Around three fifths used it for carbon reduction and building material specification, nearly half for waste minimisation and more than a third for water management.

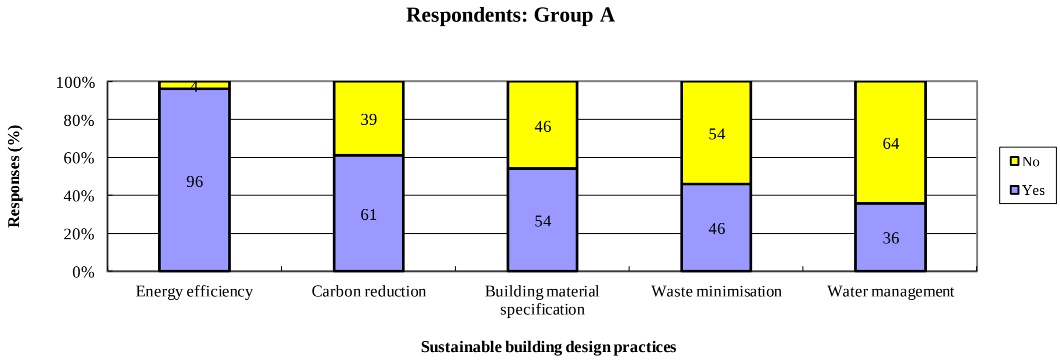


Figure 4.8 The use of BIM for sustainable building design

4.3.4 The potential use of BIM to enhance sustainable building design

Respondents were asked to specify whether BIM had the potential to enhance SBD practices.

More than two-thirds of respondents believed that BIM had the potential to assist all SBD practices. As illustrated in Table 4.3, all Group A respondents and most of Group B believed that energy efficiency, carbon reduction and waste minimisation could be enhanced by the potential use of BIM. The overwhelming majority of Group A and the majority of Group B thought that BIM had the potential to facilitate building material specification and water management.

4.3.5 Barriers to the use of BIM in building design

Respondents were asked to rate the barriers to the use of BIM in building design on a scale from 1 (not a barrier) to 4 (major barrier).

Figure 4.9 reveals that Group A and Group B shared the same view that the lack of standards and protocols for interoperability, lack of framework / road map, resistance to change, and not being used by other project partners, such as contractors and quantity surveyor, are significant barriers. The different project sizes are seen as an insignificant barrier to the use of BIM in building design.

Table 4.3 The potential use of BIM to enhance sustainable building design

BIM potential for sustainable building design practices	Responses (%)	
	Yes	No
Energy efficiency		
Group A	100	0
Group B	86	14
Carbon reduction		
Group A	100	0
Group B	82	18
Waste minimisation		
Group A	100	0
Group B	86	14
Building material specification		
Group A	93	7
Group B	73	27
Water management		
Group A	86	14
Group B	68	32

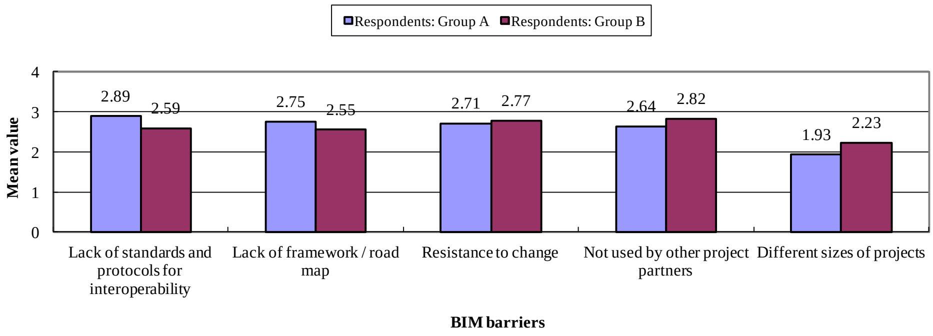


Figure 4.9 Barriers toward BIM in building design

Subsequently, respondents were asked to provide additional qualitative information on specific barriers facing architects to the use of BIM as a potential tool to reduce construction waste during building design. There were 27 qualitative comments from respondents which were summarised into two key additional barriers:

- Technology barriers: slow uptake of BIM by family libraries for building products.
- Knowledge barriers: lack of experience in the use of BIM, and lack of a holistic and integrated approach to use BIM for construction waste minimisation during design.

4.3.6 Incentives to the use of BIM in building design

On a scale from 1 (not an incentive) to 4 (major incentive), respondents were asked to rate the incentives of using BIM in building design.

As shown in Figure 4.10, Group A and Group B concurred that incentives such as client driven, increasing staff production, new Government Construction Strategy (May 2011) and uptake at project level for cost efficiency and increase in delivery speed, are significant incentives in the use of BIM in building design. The interest of project managers appeared as an insignificant incentive.

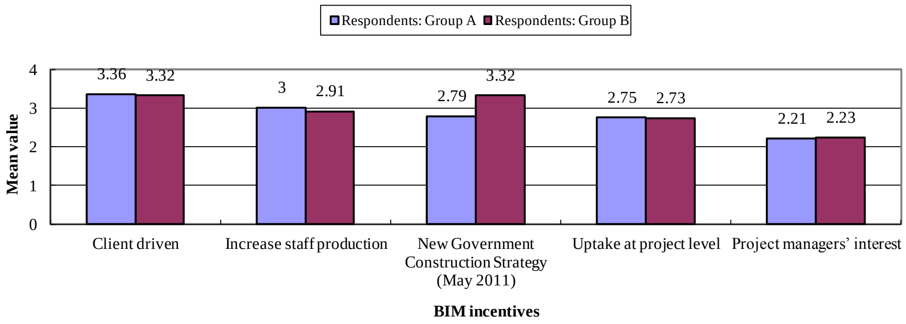


Figure 4.10 BIM incentives in building design

Subsequently, respondents were also asked to provide additional qualitative information on specific incentives for architects to use BIM as a potential tool to reduce CW during building design.

Three key incentives summarised from 13 qualitative comments resulted in the following:

- Advanced automation tool for design decision making by improved collaborative working and design coordination, better visualisation in initial design studies, defined material analysis from early project stage to reduce waste possibilities, and automated schedules and material takeoff.
- Economic and environmental benefits if better design through cost saving and greater rating of environmental assessment methods, such as BREEAM.
- Marketing advantage via early adoption of using BIM to reduce design waste.

4.4. BIM as a potential tool to minimise construction waste in building design

4.4.1 BIM for construction waste minimisation across the RIBA Plan of Work stages

Respondents were asked to rate on a scale from 1 (no effect) to 4 (major effect), the potential effect of applying BIM to construction waste minimisation throughout each of the RIBA Plan of Work stages (ie. Appraisal, Design Brief, Concept, Design Development, Technical Design, Production Information, Tender Documentation, Tender Action).

As shown in Figure 4.11, the use of BIM was thought to have a different potential effect on CWM during design throughout all stages from Appraisal to Tender Action. There was a consensus between Group A and Group B in that that the use of BIM as a vehicle to minimise waste had a potentially significant effect across design stages (i.e. Concept, Design Development, Technical Design and Production Information stages).

On the other hand, briefing stages (i.e. Appraisal and Design Brief) were believed by both groups to be insignificant in construction waste reduction through the use of BIM. There were conflicting views between Group A and Group B on the potential use of BIM to minimise construction waste in terms of design at Procurement stages (i.e. Tender documentation and Tender action), which were deemed to have a potentially significant effect by Group A, whilst considered insignificant by Group B.

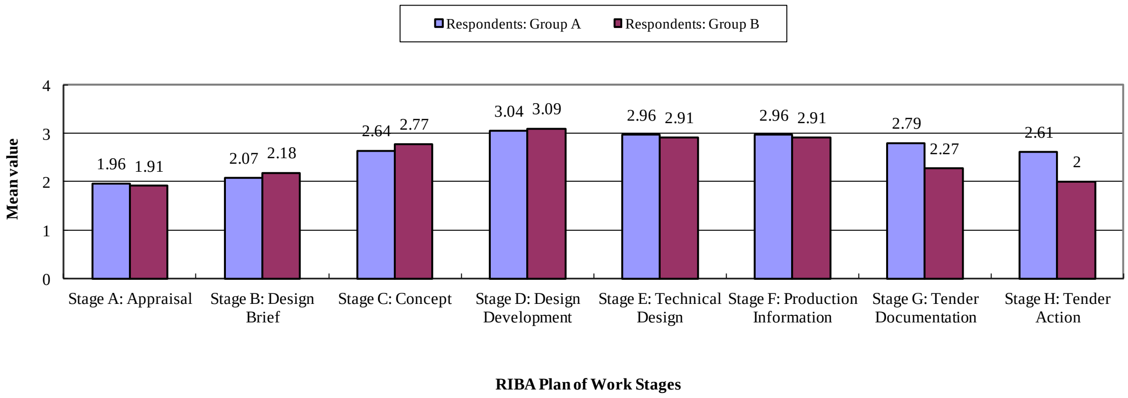


Figure 4.11 The potential effect of BIM on construction waste reduction across RIBA Plan of Work stages from Appraisal to Tender Action

4.4.2 BIM to address construction waste causes during building design

On a scale from 1 (no effect) to 4 (major effect), respondents were asked to rate the potential effect of using BIM to address construction waste causes during building design.

Figure 4.12 shows that regardless of respondents' experience in using BIM for SBD, participating architects reported BIM as having a significant effect in addressing the following construction waste causes through design: ineffective coordination and communication at all three levels (i.e. company level, design team level and project level), design changes, design and detailing complexity and design and construction detail errors. Half of the participants indicated that BIM could potentially have a major impact in addressing ineffective coordination and communication among designers. On the other hand, respondents rated BIM as having insignificant impact on specification flaws.

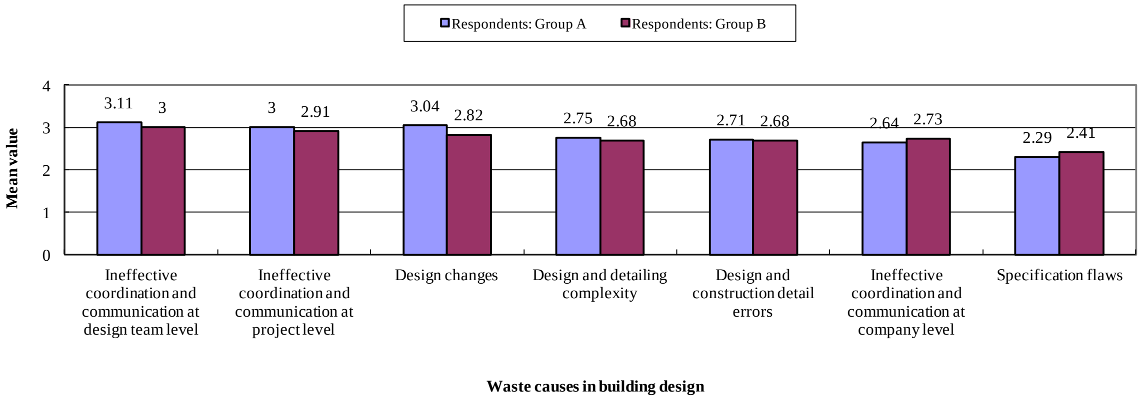


Figure 4.12 The potential effect of BIM in addressing construction waste causes during building design

4.4.3 Further comments on the use of BIM for construction waste minimisation

Respondents were asked to provide additional qualitative comments on the use of BIM to reduce construction waste during building design.

There were 13 qualitative comments whereby participating architects acknowledged that BIM has a huge potential to help minimise construction waste during design. Respondents went on to suggest that BIM potentially require development for software package extension; supported by a better standard of connection between 3D-model and analysis modules for interoperability; driven from the top-down and commitment from the whole team for implementation; implemented in early design; and associated with waste minimisation strategies by stakeholders, i.e. the design team, quantity surveyor, contractor and client.

There was also a concern over the outcome of using BIM to reduce waste during design, which was raised by participating architect 3 who argued that *"waste is largely due to on-site management and practices, as such BIM will not affect this in design"*.

The above results suggested that although BIM is deemed as a vehicle to assist minimising construction waste through design, the implementation of BIM in achieving it requires more work to refine it such as future development of a BIM software package focusing on construction waste and interoperability, efficient management strategy and methods, in addition to cultural changes.

4.5. Questionnaire data reliability and validity

Cluster sampling (see section 3.5.2.1) was used to ensure reliability of the questionnaire data source. All respondenting architects had provided their background information such as name, designation and email account. Moreover, the variety of representative architecture companies provided strong evidence in the reliability of the data source in terms of areas by operating sectors, project types and building types (see section 4.2.1), which ensures that the sample is a good representation of the population under study. As such, this representative sample will provide valid results.

There were other evidential parameters showing that the questionnaire had acceptable reliability and validity of data sources such as the following: almost 40% of respondents (19) answered the majority of open-ended questions; approximately half of respondents (23) consented to being involved in follow-up interviews; and 80% of respondents (40) were interested in receiving a summary report of the questionnaire findings.

4.6. Summary

This chapter presented the questionnaire findings that sought to explore issues relevant to the relationship between BIM and construction waste minimisation.

The questionnaire results indicated that BIM was not frequently used in building design in general and for construction waste minimisation in particular. However, there was an agreement that BIM had great potential to facilitate waste minimisation. Moreover, the design stages were thought to have a significant or a major effect on the potential of BIM to minimise waste. Furthermore, questionnaire results emphasised that BIM was believed to have a significant or major effect on addressing construction waste causes such as ineffective coordination and communication, design changes, design and detailing complexity, and design and construction detail errors.

The questionnaire results also revealed that the lack of standards and protocols was a significant or major barrier to the use of BIM in building design.

Furthermore, results reported that knowledge barriers, such as lack of experience in using BIM to aid construction waste minimisation was a serious impediment in the use of BIM as a potential tool to aid waste minimisation.

There was a need to conduct further research to explicitly build on the questionnaire findings by investigating detailed insights into the relationship between BIM and construction waste minimisation. Therefore, the next chapter presents the results of semi-structured follow-up interviews to gather qualitative data. The emerging research themes are presented using narratives and quotations (see section 3.5).

CHAPTER FIVE

Interview Results

5.1. Introduction

This chapter presents the results of semi-structured exploratory interviews that were designed to examine the relationship between construction waste causes and the use of BIM, and investigate the BIM potential to assist architects for waste reduction during design. Eleven interviews were conducted with interviewees selected from the questionnaire participants (see Table 3.11) who had hands-on experience in the use of BIM for sustainable building design. These interviews were based upon the results that emanated from the literature review and questionnaire findings. Narratives and quotations were used for the emerged themes from the research (see section 3.5.3.2).

As shown in Appendix 2.2, the background information regarding construction waste minimisation (CWM) in current projects is presented, followed by current CWM in building design including the views of interviewees on causes of construction waste in each RIBA Plan of Work Stages, current CWM practices used in their projects, and barriers to implementing CWM in building design are discussed. Subsequently, the current use of BIM in building design are reported, which comprises sustainable building design and barriers to adopting BIM in building design. The use of BIM for construction waste minimisation is presented in the last section, which contains BIM for addressing waste causes (e.g. ineffective coordination and communication, and design changes) and BIM potential for construction waste minimisation throughout each RIBA Plan of Work Stages.

5.2. Background information

5.2.1 Importance of construction waste minimisation

Interviewees were asked about the importance of CWM in their current projects.

Nearly all of them (10 out of 11) indicated that CWM is very important or important in their current projects.

Two thirds of the interviewees attributed the importance of CWM to the aim to achieve successful environmental assessment methods (e.g. BREEAM), which is being driven by contractors. Interviewee I7 emphasised that contactors call for better CWM performance during the design stage, because *"architects can control waste if contractors inform them of waste causes"*. However, interviewee I1 argued that CWM is not that important, as "*waste minimisation is not driven by the architect but by the client"*.

5.2.2 Construction waste production

Interviewees were asked to indicate which type of projects tends to produce significant construction waste.

Nearly half of the interviewees (five out of 11) indicated that renovation and refurbishment projects produce significant waste due to planning and controlling difficulties, poor re-use and recycle rates of materials and changes to design. In addition, around one third of the interviewees nominated complex projects as having considerable waste generation owing to ineffective coordination, communication and collaboration.

5.2.3 Approach to reduce construction waste

Interviewees were questioned about the most suitable approach to reduce construction waste generation during the design process.

Half of the interviewees (six out of 11) indicated that BIM have the potential to improve communication and coordination, and as such it would be the most suitable approach to reduce waste during building design. For instance, interviewee I3 stated that "*all project team members are working with the same drawings to address clash detection and design changes*". Interviewee I9 further suggested that *"the use of BIM should not be considered as a piece of software but as a process as it is all about good work flow, good communication, re-sharing and re-using data affectively, and understanding the needs of the recipient*". Interviewee I2 added that "*through BIM, the architect can realise early on how much waste the project will produce, and try from there to minimise it"*.

In addition, one third of the interviewees (four out of 11) suggested that modularisation and offsite fabrication is the most suitable approach to assist construction waste reduction in design. Furthermore, almost a third of interviewees emphasised that involvement of the contractor at very early design stages would be a significant step to reduce waste, because "the *contractor provides key advice on aspects of design related construction waste"* (I7).

5.3. Current construction waste minimisation practices

5.3.1 Construction waste causes

Interviewees were asked to state the causes of construction waste during the project lifecycle stages such as Briefing, Concept and Design Development, Technical Design and Production Information, and Procurement stages (RIBA Plan of Work Stages: Appraisal to Production Information). These are summarized in Table 5.1 and discussed in the following sections.

Table 5.1 Construction waste causes (views of interviewees)

Project Stages	Construction Waste Causes	Agreement level
Briefing	Lack of waste feasibility studies	10 out of 11
	Failure to identify needs of client	10 out of 11
	Ineffective communication	Seven out of 11
	Lack of a clear goal of waste minimisation	Six out of 11
	Lack of early involvement by contractor	Four out of 11
	Lack non-allocation of waste responsibility	Four out of 11
Concept and Design Development	Not fully evaluated design leads to design changes during construction period (design decision)	10 out of 11
	Ineffective coordination and communication	Seven out of 11
	Difficulties in resolving design issues of architectural, structural and service design complexity	Six out of 11
	Unclear outline specification of material purpose	Six out of 11
	Lack of attention paid to dimensional coordination	Four out of 11
	Limited design standardisation	Three out of 11
	Lack of buildability consideration	One out of 11
	Unfrozen design brief	One out of 11
	Lack of prefabrication design	One out of 11
	Lack of considering design for deconstruction and flexibility	One out of 11
Technical Design and Production Information	Ineffective coordination and communication	11 out of 11
	Design and construction detail errors / lack of information on drawing / lack of coordination of detail design	11 out of 11
	Unclear specification of material	11 out of 11
	Not fully evaluated design leads to design changes during construction period (design decision)	10 out of 11
	Unclear specification of products and components	Six out of 11
	Specification of material quantity (over specification)	Two out of 11
	Inexperience in method and sequence of construction	Two out of 11
	Lack of knowledge about standard sizes available in market	One out of 11
	Unfamiliarity with alternative products	One out of 11
Procurement	Errors and insufficient detail in contract documents /tender documents	11 out of 11
	Ineffective coordination and communication	Nine out of 11

5.3.1.1 Construction waste causes in Briefing stages

The overwhelming majority of interviewees (10 out of 11) agreed that a lack of waste feasibility studies and failure to identify the needs of the client are critical causes in terms of initial decision making, as interviewee I3 commented "*the consequential waste in later stages is the result of Briefing stages*". Approximately two thirds of the interviewees mentioned that these causes are also indirectly linked to ineffective communication. In addition, approximately half of interviewees reported that the lack of a clear goal of waste minimisation and lack of non-allocation of waste responsibility leads to the generation of construction waste. Furthermore, a third of the interviewees suggested that there was a need for early involvement of the contractor to assist the architect and client in reducing waste. However, interviewee I8 pointed out that the architect can do little in terms of designing out waste, because "*the opportunities in getting the schedule correct and making sure things are designed efficiently at briefing stages are quite limited to architects*".

5.3.1.2 Construction waste causes in Concept and Design Development stages

Nearly all interviewees concured that design decisions that had not been fully evaluated could cause design changes during construction, which have the most influence on the amount of construction waste generation during construction stages. For instance, interviewee I1 noted that *"at Concept stage, to pick a curved building will cause a large amount of construction waste on site if the architect doesn't try to deal with design decisions on whether or not it can be optimised to reduce waste"*. Another interviewee (I7) argued that a design brief that has not been frozen could lead to waste generation, because "*if the client doesn't sign off the design brief, it results in making design changes eventually*".

Moreover, most interviewees indicated that some aspects related to collaborative design working can result in waste generation. These aspects are ineffective coordination and communication, difficulties in resolving design issues of architectural, structural and service design complexity and unclear outline specification of material purpose.

Furthermore, about one third of the interviewees mentioned that the technical issues of design, such as lack of attention paid to dimensional coordination, limited design standardisation, lack of build ability consideration, lack of pre-fabrication design, and lack of considering design for de-construction and flexibility, have a direct impact on construction waste generation. Again, one third of the interviewees suggested that getting advice on the above issues from a contractor could lead to a better waste reduction performance, "*because they have build experience, so architects will know what will produce on-site waste and have the opportunity to reduce it*" (I10).

5.3.1.3 Construction waste causes in Technical Design and Production Information stages

All interviewees indicated that ineffective coordination and communication in the design team causes on-site waste through problems in detailing, such as design and construction detail errors, lack of information on the drawing and lack of coordination of the detailed design, because "*if design issues are coordinated and communicated well with structure and service engineers in Technical Design and Production Information stages, architects don't need to do things twice when constructing on-site, and that's likely to be the most efficient way to reduce construction waste*" (I8). About a third of the interviewees (three out of 11) added that efficient coordination and communication with contractors also has an impact on on-site waste generation.

Material specification related issues were identified by all interviewees as significant waste causes. These include unclear specification of materials, products and components; over specification; lack of knowledge regarding standard sizes available in the market and unfamiliarity with alternative products. Interviewee I5 clearly stated that "*full design level specification activities at the end of Technical Design and Production Information stages, can help reduce construction waste significantly later on*". Interviewee I7 argued that Technical Design and Production Information should not be fully restricted in terms of selecting materials, products and components, but "*be more flexible and allow contractors to implement their waste reduction practices*".

A fifth of the interviewees affirmed that because of inexperience in the methods and sequence of construction, the design could potentially lead to the production of waste rather than minimising it during construction. For instance, interviewee I2 stated that "*architects need to design how building elements come together to fit the use of methods and sequence for construction, so they may be able to find the way to drive out a lot of waste*".

5.3.1.4 Construction waste causes in Procurement stages

All interviewees indicated that errors and insufficient detail in contract documents and/or tender documents is the key to construction waste causes because "*tender documentation in sufficient detail reflects the design needs clearly, which avoids design changes*" (I3). The vast majority of interviewees (nine out of 11) claimed that errors and insufficient details are partly caused by ineffective coordination of tender information. Additionally, around half of interviewees commented that ineffective communication with the contractor could further cause on-site waste. For example, interviewee I7 noted that "*if architects only issue a set of drawings of the building without giving any further explanation or presentation to all contractors about how the building is supposed to be built, the contractors more likely will not consider this assumed construction process in the tender, which can cause waste*".

5.3.2 Current construction waste minimisation practices in design projects

Interviewees were asked to comment on current CWM practices within their own design projects.

Approximately half of interviewees reported that effective communication and coordination with the contractor has been used to avoid construction waste production. As such, one interviewee (I7) pointed out that: "*through effective communication and coordination with contractors, specialist contractors and suppliers, architects can come up with more efficient design proposals by considering how things get built, which suits the contractors' construction performance to ensure resulting in as-designed construction".* Interviewee I9 added that BIM have been used as a communication and coordination platform with their contractor throughout the tender process to minimise waste. Another interviewee (I2) claimed that CWM is implemented as a subsequent process to a well established design and delivery process, based on effective communication and coordination for optimising the use of material and energy.

Approximately half of interviewees indicated that waste has been reduced through the implementation of widely adopted low-waste design techniques for CWM, such as modular design / grid design and offsite manufacture / pre-fabrication.

Around one third of the interviewees mentioned that a waste review for sustainable design has been conducted for CWM. The waste review was described as a type of specification review process as to "*whether design will generate waste; what the best materials are to be used in terms of waste reduction; selecting the best products in terms of waste performance; and whether that requires off-cuts*" (I10). Interviewee I11 suggested that this review not only benefits CWM for on-going projects and the project members involved, but also for future projects and other people by educating them through their gained CWM experiences.

Furthermore, CWM practices and guidelines from WRAP such as designing out waste (WRAP, 2008) were being used by nearly one third of the interviewees.

5.3.3 Barriers to construction waste minimisation

Interviewees were asked to report on the barriers of implementing CWM strategies within building design.

Results suggested that those barriers are mainly related to building design culture influenced by communication and coordination, and cost. One third of the interviewees highlighted that the culture-related nature of the building design process affects the implementation of CWM. This comes from the traditional design process whereby various professionals are involved in a project at different stages with diverse time periods, as interviewee I3 explained: "*structural and services engineers join in at later stages with a shorter duration compared to architects who tend to be involved in projects from the early stages. This causes less awareness on waste minimisation strategies by these engineers".*

A fifth of the interviewees emphasised that the lack of awareness regarding construction waste causes in the design thinking by architects is influenced by the culture of building design, whereby "*architects don't naturally think about construction waste causes during design stages*" (I8).

Additionally, ineffective design communication and coordination was thought to have an impact on the culture barriers by one fifth of the interviewees. Interviewee I11 further commented that the role of the contractor during on-site construction can influence the culture barriers, because "*there is a lot of on-site waste that is controlled by the contractors, therefore architects can do nothing about it*".

Furthermore, the culture related barriers are heavily affected by cost. One third of the interviewees indicated that cost related issues, such as the implementation of CWM during design and the built cost rather than lifetime cost (as is the focus of client and contractor), are seen as barriers to adopting CWM, because the implementation requires commercial benefits to drive it. Interviewee I1 argued that *"although architects employ waste minimisation strategies in their projects, they sometimes only get paid 0.95% of the total project fee to complete the design. Therefore it is unlikely that waste minimisation will be considered as a top priority unless it is paid for".*

Interestingly, most of the interviewees called for related information on construction waste causes during design, *"because architects are unaware of construction waste causes, so documentation or the approach to identify causes of waste diagnosis would be very helpful"* (I7).

5.4. Current use of BIM in building design

The interviewees were asked to describe the use of BIM for the main design related activities which were identified by the questionnaire respondents (see section 4.3.1). These included detailing, clash detection, visualisation and simulation and improved communication and collaboration in building design, of which results are shown in Figure 5.1. The sections below summarise the interviewees' responses on the four main activities for BIM use during building design.

5.4.1 BIM use for detailing

All interviewees made it clear that they use BIM for detailing through 3D parametric modelling, having a certain Level of Detail (LOD) associated coordination process. The majority of interviewees (seven out of 11) described this process as a '3D plus 2D information' process. This allows the 3D building model set to coordinate between 3D-model elements and 2D-specification enhanced information elements with details. An example was given by interviewee I1 who claimed that "*all the detailing is a front line in BIM, in which designers have to create 2D-information detailing because they cannot detail everything in 3D*". A third of the interviewees reported that the shared 3D model should be kept as light as possible for general coordination. Interviewee I8 further exemplified the importance of the balance between the amount of detailed information and the shared 3D model by stating "*it has to be efficient for use without taking too much time to load, and seriously slowing down and crashing the entire model*". Interviewee I9 encapsulated the topic by indicating that the 3D coordination model should be used to create re-purposed models, such as rendering, analysis, quantification and clash detection, as part of the detailing process within BIM. This was provided its overall mass geometry was correct, space was reserved for structure and services, interconnections and relationships were made clear and the net data was linked correctly. Approximately one third of the interviewees reported that the detailing process is required prior to conducting the formal clash detection.

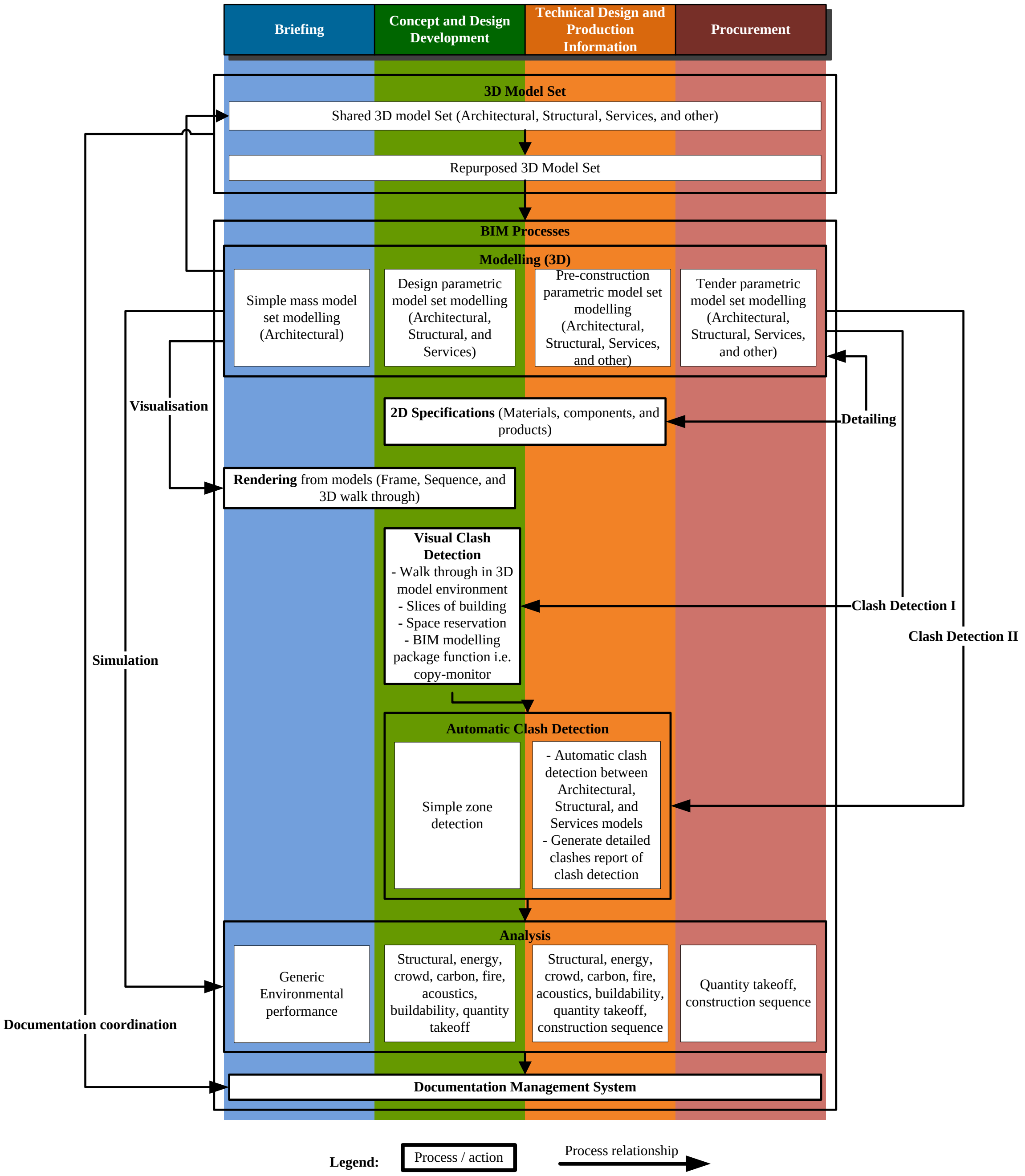


Figure 5.1 The use of BIM in building design (views of interviewees)

There was an agreement among interviewees that 3D modelling should be in line with LOD throughout building design stages as:

- Briefing stages: simple mass model set modelling (architectural).
- Concept and Design Development stages: design parametric model set modelling (architectural, structural, and services).
- Technical Design and Production Information stages: pre-construction parametric model set modelling (architectural, structural, services, and other).

- Procurement stages: tender parametric model set modelling (architectural, structural, services, and other).

The questionnaire results showed that 26% of respondents suggested that detailing activity is conducted through BIM in most or all of their current projects (see section 4.3.1). Therefore, the interviewees were probed regarding their views on the use of detailing through BIM in their current building design projects.

All interviewees affirmed that detailing is very important to building design projects through the use of BIM in terms of 3D parametric modelling, model information coordination and communication. A simple example was given by interviewee I7 who argued that "*modification through BIM for detailing allows a synergy between changes to a parametric component and an automatic BIM model update, which enables architects to consider more solutions accordingly".*

All interviewees added that the use of BIM for detailing has a positive impact on construction waste generation. These include:

- better understanding by the client of design through a detailed building model resulting in fewer on-site design changes.
- getting LOD right leading to less on-site waste.
- more detail, better clash detection, and fewer on-site clashes, and
- better detailing coordination and specification leading to less re-work.

Interviewee I7 gave further classification by revealing that a shared 3D model having certain LOD has the most potential to minimise construction waste, because "*all information generated from one model source makes less errors and less construction waste in terms of efficient coordination*".

5.4.2 BIM use for clash detection

All interviewees indicated that BIM is used for clash detection to improve the coordination of information between models from different disciplines. Interviewees' responses indicated that there are two types of clash detection (i.e. visual and automatic) that have been applied through BIM. The clash detection process is illustrated in Figure 5.1. It is described as:

1) Visual clash detection by users.
2) Detailed architectural, structural, and services models.
3) Automatic clash detection between architectural model and structural model, and architectural model and services model through software.

4) Generating a detailed clash report.

One third of the interviewees reported that BIM is used to detect clashes visually during Concept and Design Development Stages, where the visual clash detection is conducted by a walk-through virtual 3D model enabled environment, viewing slices of the building, space reservation and a copy-monitor within the BIM architectural design packages, such as Revit, ArchiCAD, Bentley, and Vectorworks.

Two thirds of the interviewees indicated that automatic clash detection enhanced by BIM is executed through software, such as Navisworks, at Technical Design and Production Information stages, which is the more precise clash detection than after visual clash detection. Around a third of the interviewees suggested that more accurate and detailed models are required before performing automatic clash detection, because "*clash detection on the software front is detecting the one piece of geometry touching another piece of geometry, so the best way to use that feature is to construct an accurate digital model of the project in detail*" (I2).

One third of interviewees further affirmed that the automatic clash detection improves coordination and communication for collaborative working through 3D BIM model enhanced design review meetings. This was clarified by interviewee I9: "*clash detection is a reporting tool and part of a design review event to ensure everybody is engaged and to fully understand the design developing and changing made by other team members*".

Subsequently, interviewees were probed for their views on the use of BIM for clash detection activity, which had a 26% response rate from the questionnaire (see section 4.3.1).

The overwhelming majority of interviewees (nine out of 11) emphasised that clash detection is a very important activity in their building design projects in terms of design coordination and communication. However, interviewee I1 had stated that clash detection is not important, because "*the contractor will eventually fix clash problem during on-site construction*".

Interviewee I7 argued that automatic clash detection should not be promoted too much in terms of affecting the working attitude of project members by claiming that "*it is important for checking coordination as part of a design process, but it encourages project members to be inefficient in design, which means if project members do the job properly, there should be no clashes in the first place*".

All interviewees concurrently took the view that clash detection activity through BIM could benefit CWM. These benefits provide a better coordinated design, fewer clashes, less re-work and re-design, and less on-site waste.

5.4.3 BIM use for visualisation and simulation

All interviewees concurred that the process of parametric 3D modelling is essential to enable visualisation and simulation. As interviewee I2 put it: "*through parametric 3D modelling, architects start from the conceptual 3D model to a high level of detail parametric model, and this process allows them to do further visualisation and simulation*". Approximately one third of the interviewees went further to argue that the parametric 3D model should be re-purposed and split into various LOD models coordinated with one original model to provide models having different purposes, such as visualisation and simulation. An example was given by interviewee I5 who explained that "*it is simply to give the correct 3D model information for a certain purpose, for instance, if project members want visualisation they only need the 3D model for rendering. If they need thermal simulation and analysis they should use the different 3D model information, such as U-value or R-value*".

Moreover, all interviewees recognised that visualisation in BIM is a tool for presentation through rendering-based 3D model working environment. The latter facilitates 3D walking through, frame capture and sequence rendering (animation) for visualisation.

However, interviewee I9 argued that the 3D BIM model is not always suitable for a high-quality photorealistic rendering process and instead a re-purposed model is needed because "*it doesn't have the level of detail you want in certain areas*". Around two thirds of the interviewees held the view that visualisation is used frequently in very early design stages to enhance communication with the client, which "*helps clients visualise their buildings*" (I7).

Furthermore, all interviewees contended that BIM-enhanced simulation is conducted through the parametric 3D modelling process for the purpose of building design analysis. As illustrated in Figure 5.1, they further portrayed that in relation to the environmental performance analysis, which is the major concern during Briefing and Design stages, such as energy and carbon, whilst material takeoff is conducted throughout Design and Procurement stages.

Therefore, visualisation and simulation through BIM were implemented by the participating architectural practices for a different purpose at different building design stages as presented in Figure 5.1.

The questionnaire results showed that 46% of respondents agreed that visualisation and simulation are the most preferred BIM enhanced design related activity in most or all their current projects (see section 4.3.1). Hence, interviewees were probed regarding their views on the use of visualisation and simulation through BIM in their current building design projects.

All interviewees stressed that visualisation and simulation are used for design communication and coordination with project stakeholders, such as the client and design team members. This was reinforced by interviewee I7 who affirmed that "*visualisation and simulation facilitate more integrated design and faster design, and quicker design decisions at very early stages*". They shared the view that BIM enhanced visualisation and simulation associated design decision making has a positive impact on construction waste reduction, resulting in:

- early client's understanding of the design to avoid subsequent on-site design changes.
- better understanding by contractors of the building and visualised and simulated construction process leading to less on-site waste, and
- enhanced communication and collaboration of design between the design team to eliminate uncoordinated design resulting in fewer on-site clashes.

5.4.4 BIM use to improve coordination and communication

Nearly three quarters of the interviewees concurred that BIM improves coordination and communication through working in 3D model environment. This was because project members can discuss and argue the overlay information issues in a 3D collaborative environment to mark up areas and send the information backward and forward to each other. Almost half of interviewees suggested that 3D model environment should be shared between disciplines as a common 3D model, so that all sets of information could be generated to enhance coordination and communication across those disciplines. Interviewee I3 went further to clarify that the shared 3D model should act as "*Russian dolls*". Therefore, it should be settled with different LODs in terms of each model having a different purpose throughout different design stages, also to install a BIM database server to improve coordination and communication.

In addition, one third of the interviewees held the view that the BIM virtual environment with certain standards would efficiently improve coordination and communication, because "*the interoperability problem will be reduced*" (I5). As such, participants endorsed an earlier set up of the BIM virtual environment platform to coordinate and communicate once the design project started. Interviewee I1 further argued that the same knowledge level in the use of BIM by project members in both technique and management is essential to achieving effective coordination and communication through BIM.

Furthermore, half of interviewees indicated that improved coordination and communication through BIM could work naturally. This is in line with findings from previous interview sections that confirmed the use of BIM to improve visualisation and simulation, detailing and the clash detection process. These were further explained by interviewee I2 who stated that "*visualising and simulating a building in detail and conduct clash detection will force project members to better coordinate and communicate to optimise design*".

Therefore, the use of BIM for improving coordination and communication can be portrayed as shown in Figure 5.2.

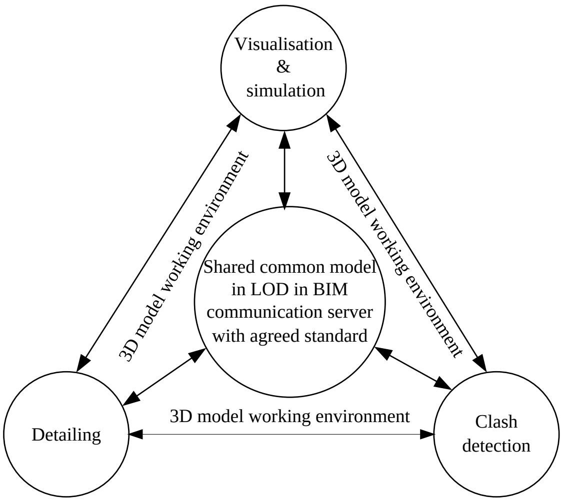


Figure 5.2 BIM use to improve coordination and communication (views of interviewees)

The questionnaire findings showed that improved coordination and communication through the use of BIM received a response rate of 34% (see section 4.3.1). Thus, the interviewees were probed about their views on the extent to which BIM have improved coordination and communication in their current building design projects.

All interviewees agreed that improving coordination and communication through BIM is important in their current building design projects. Interviewee I7 established that BIM is a process and platform to improve coordination and communication among project members throughout project stages by providing rich information for better understanding and sharing of what information is useful and how it can be used, which is the key to success of the project.

Finally, all interviewees agreed that the use of BIM to improve coordination and communication could have a positive impact on construction waste reduction by producing effective and efficient multi-disciplinary design.

5.4.5 Current use of BIM in sustainable building design

The questionnaire results showed that more than half of respondents agreed that carbon reduction, building material specification, and energy efficiency are implemented in all or most of their projects, being facilitated through the use of BIM (see section 4.3.3). Therefore, interviewees were asked as to what extent carbon reduction, building material specification and energy efficiency were being implemented through BIM in their projects. They were probed regarding the detailed processes on the use of BIM for each of the above sustainable building design practices. This included describing the processes and actions in line with each building design stage from Appraisal to Production Information and responsibilities for their actions. Their responses are illustrated in Figure 5.3. These responses were generated based upon the suggested key issues and their relationships, which are discussed in the following sections.

5.4.5.1 BIM use for carbon reduction

There was a common view between interviewees (10 out of 11) that BIM facilitates the carbon analysis process in building design by assigning the 3D model to the material specification information, as interviewee I6 portrayed: "*BIM allows material information input into the models, which informs assessment and calculation throughout the modelling*". The view is illustrated in Figure 5.4. The BIM-assisted carbon analysis process is facilitated by the development of a 3D BIM model which is generated from a simple mass model to a fully detailed model to achieve various carbon reduction targets during each of the building design stages. For instance, this could entail gaining the general idea regarding carbon reduction at Briefing stages. They also agreed that this process is usually conducted after energy efficiency at each design stage and associates with building material specification (see Figure 5.3). They further expressed that carbon reduction is linked to energy efficiency and was influenced by building material specification in terms of embodied carbon. One third of interviewees strongly emphasised that carbon reduction should not only be analysed through BIM for construction, but also for the long term use of the building throughout its lifecycle.

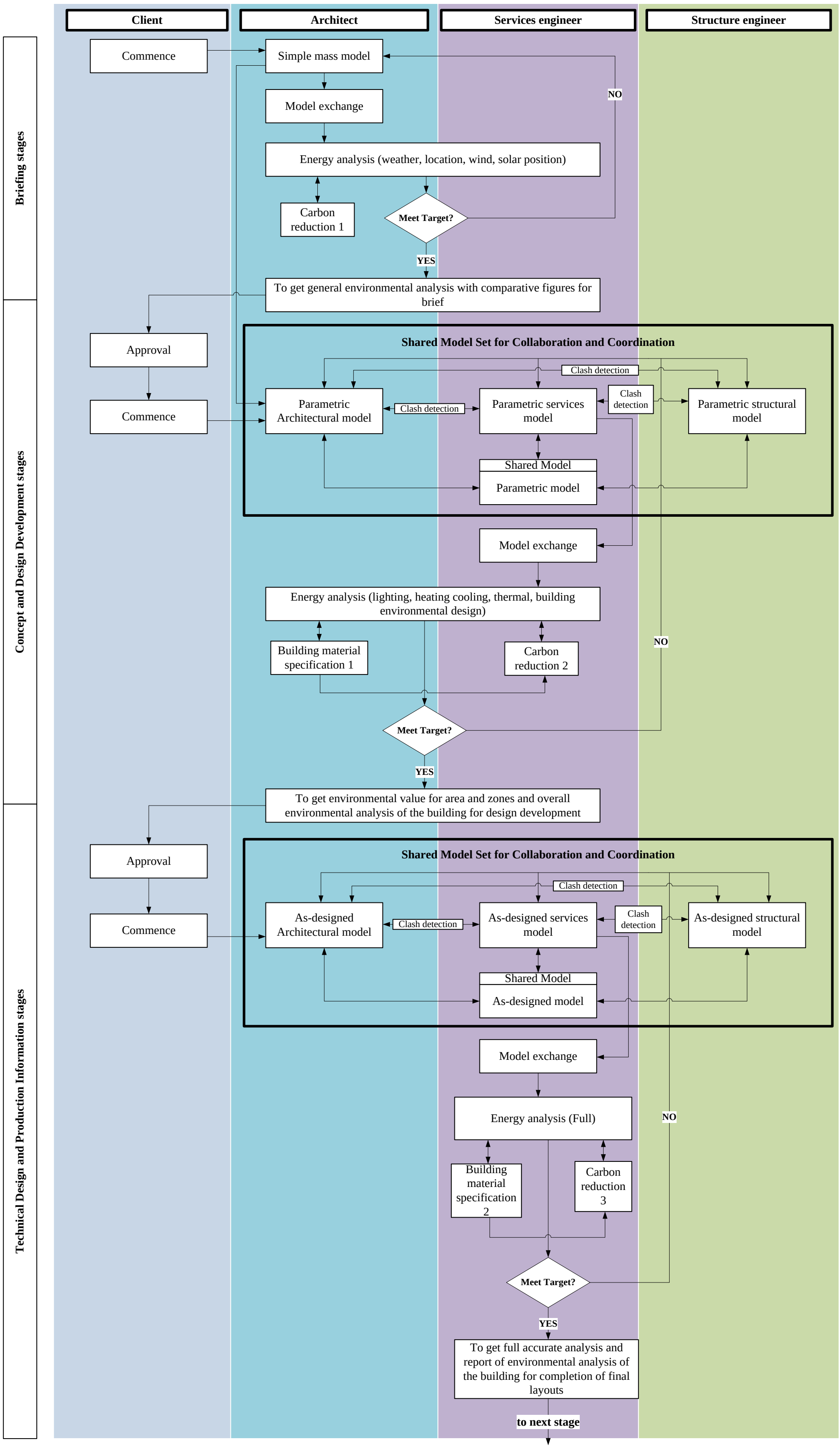


Figure 5.3 BIM use for energy efficiency, carbon reduction and material specification (views of interviewees)

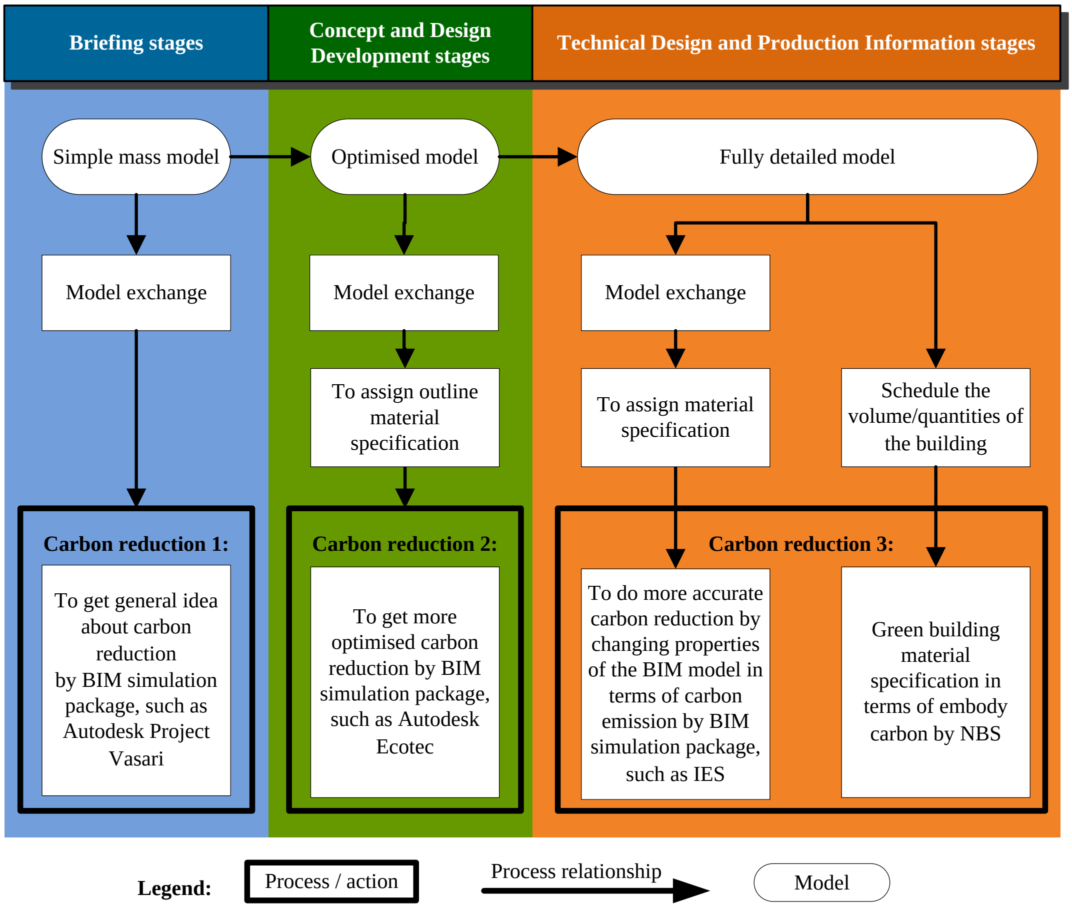


Figure 5.4 BIM use for carbon reduction (views of interviewees)

5.4.5.2 BIM use for building material specification

There was a general agreement between interviewees in that BIM-assisted building material specification is used to facilitate energy efficiency and the carbon reduction process within BIM. Their views are illustrated in Figure 5.3 and Figure 5.4. For example, building material specification 2 through BIM was conducted for carbon reduction 3 and full energy analysis in Technical Design and Production Information stages (see Figure 5.3). This is whereby the material specification is assigned to the fully detailed BIM model to enable more accurate carbon reduction (see Figure 5.4). The vast majority of interviewees (nine out of 11) stated that they associate National Building Specification (NBS) documentation with the 3D BIM model for building material specification as a '3D plus 2D' information process, to achieve a better performance of energy efficiency and carbon reduction. More importantly, BIM-enhanced quantity takeoff of building volume was used to enable this specification process, as reported by two thirds of the interviewees. Interviewee I2 argued that the result of the specification process is a trade off between carbon reduction and energy efficiency in terms of cost of materials, components and products, which is driven by the contractor or client.

In order to effectively and efficiently use BIM for building material specification, there was a call from around a third of the interviewees for manufacturers and suppliers to develop their database library of 3D building material for BIM to use directly (pure 3D process), rather than through external NBS documentation (2D process). Interviewee I4 confirmed that "*by having 3D materials in database, you can look at the whole model and should be able to assess sustainability performance of materials and products across the whole building lifecycle stages*". Nevertheless, interviewee I9 commented that his company is developing that type of 3D building material library for its own benefits and claimed "*the library generates standard material types that are available directly within the BIM applications*".

5.4.5.3 BIM use for energy efficiency

The views of interviewees on current energy efficiency through BIM during building design is summarised in Figure 5.3. All interviewees indicated that energy efficiency is implemented through energy simulation via a coordinated 3D model environment in BIM. This indicated the shared model set for collaboration and coordination during building design stages from Concept to Production Information, as shown in Figure 5.3.

Half of the interviewees emphasised that BIM enhanced energy simulation is conducted through different LOD models at different design stages for different energy efficiency purposes, as illustrated in Figure 5.3. This implied a simple mass model at Briefing stages, parametric models at Concept and Design Development stages, and as-designed models at Technical Design and Production Information stages. Around one fifth of interviewees further stressed that clash detection should be conducted prior to the detailed energy simulation during the Technical Design and Production Information stages for model coordination. Half of the interviewees held the view that architects should lead energy simulation at Briefing stages and service engineers should take the lead throughout Design stages (i.e. Concept, Design Development, Technical Design and Production Information stages) according to their expertise. Interviewee I7 suggested that the service engineer should be involved at the early design stage to provide suggestions for better design concepts in terms of energy efficiency.

Briefing stages

Half the interviewees mentioned that energy simulation through BIM at Briefing stage is crucial to energy efficiency in terms of decision making during building design, because "*architects can change the building by five degrees and re-run the analysis within several* *minutes to see the differences in energy performance during feasibility studies*" (I1). As such, the architect can lead the BIM-assisted energy efficiency process during Briefing stages to obtain the target of energy efficiency for the brief, which is indicated in Figure 5.3. Based upon the comments of interviewees, the detailed BIM assisted simulation process for energy efficiency at Briefing stage, as shown in Figure 5.3, is summarised as:

1) Create a simple mass model with geometry, orientation and facade in a certain location.
2) Exchange model: export model using standard format, such as gbXML; then import model (gbXML format) into energy simulation BIM package, such as Autodesk Project Vasari.
3) Generate general environmental analysis with comparative figures.

Concept and Design Development stages

There was a consensus between interviewees that energy efficiency simulation through BIM at Concept and Design Development stages enables architects and service engineers to work on a variety of design options to optimise the design in terms of better energy performance. This is indicated in Figure 5.3, where the services engineer leads the BIM-assisted energy efficiency process. An example was given by interviewee I9 who claimed that "*architects can optimise building design such as geometry, orientation, the use of material, and even the colour of the paint, which will affect the energy use of the building*". Listed below are the views of respondents on the BIM-assisted energy efficiency simulation process at Concept and Design Development stages, as shown in Figure 5.3.

1) Optimise model with certain detail.
2) Exchange model: export model using standard format, such as gbXML; then import model (gbXML format) into energy simulation BIM package, such as Autodesk Ecotect.
3) Generate overall analysis of the building.

Technical Design and Production Information stages

Interviewees agreed that through accurate analysis at Technical Design and Production Information stages, BIM-aided energy efficiency simulation facilitates further development of the design in detail with its specifications. For instance, interview I8 reported "*heating and cooling calculations based on the actual design can feedback into the design to optimise shading or reduce windows in a certain location*". The agreement is demonstrated in Figure 5.3, where the processes of BIM-aided building material specification and carbon reduction contribute to the full energy efficiency analysis. As confirmed by interviewees, the simulation process for energy efficiency Technical Design and Production Information stages through BIM, as shown in Figure 5.3, are described below:

1) Update full detailed model with specifications.
2) Exchange model: export model using standard format such as gbXML; then import model (gbXML format) into energy simulation BIM package such as IES or TAS.
3) Generate full accurate analysis and report of building.

5.4.6 Barriers to the use of BIM in building design

Interoperability, resistance to change and not used by project partners, were nominated as the top three significant or major barriers in the use of BIM in building design by questionnaire respondents (see section 4.3.5). Hence, interviewees were asked for their views on addressing the identified top three barriers to the use of BIM in building design.

All interviewees contended that the three barriers are interrelated by technology, communication, and understanding of BIM. As such, interviewee I9 gave an explanation to address these barriers as having an early stage conversation about types of technology to be used in the project; having very open communication between all project partners; and understanding the purpose of using BIM for the project. Third of the interviewees suggested a set of methods to address these barriers, which are summarised in Figure 5.5. This analysis was generated based upon suggested key elements and their relationships.

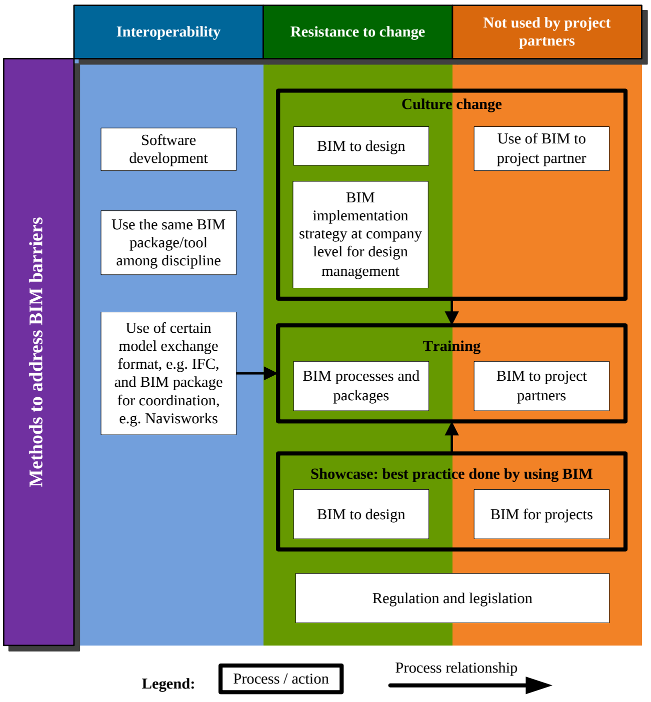


Figure 5.5 Methods to address barriers in the use of BIM in building design (views of interviewees)

There was a common view among interviewees that the interoperability problem is related to communication and translation between different software packages. Half the interviewees indicated that this problem could be solved by further development of the compatibility of BIM software packages, whereby the information could be easily shared, or the use of the same software package by project members, which would "*enhance communication and modelling between software packages to improve information sharing*" (I5). In addition, three fifths of the interviewees suggested the use of a certain standard model format, i.e. IFC, which can assist in addressing model exchange problems of interoperability, as shown in Figure 5.5. This can also benefit the BIM-related training to overcome resistance to change and the lack of use of BIM by project partners. As reported by interviewee I6, although IFC is the most commonly used as a model interchange format for sharing information across all parties, it tends to lose information such as semantic parametric information (e.g. constraints related to 3D model elements). Furthermore, interviewee I10 suggested that BIM software packages used for model coordination and clash detection, such as Navisworks, could be an alternative way in which to improve interoperability by "*allowing the users to merge all models from different disciplines*". However, around one third of the interviewees argued that interoperability should not be a barrier, because "*the project member can always work out a way to navigate out of it"* (I7).

Based upon the views of interviewees, the barriers of resistance to change and not being widely used by project partners can be penetrated. This can be achieved through the implementation of culture change, training, showcase of best practice and regulation and legislation, which is summarised in Figure 5.5.

Three fifths of the interviewees took the view that the resistance barrier could be addressed through training in the knowledge of how to use BIM software packages and processes. They also indicated that through the provision of training project partners, it would eventually promote the use of BIM at project level, which is indicated in Figure 5.5. For example, interviewee I9 stated "*educating the project partners will lead to full collaborative engagement in terms of understanding what all the benefits are to having a BIM process*". Moreover, around half of interviewees highlighted that culture issues act as an important role in resistance. A simple example was given by interviewee I11 arguing that *"generally, architects do not like the software controls design options*". However, interviewee I7 claimed that the culture change to BIM-assisted design should be prior to the training in overcoming the resistance barrier by affirming that *"if people don't believe in BIM, you cannot train them"*. Thus, the culture change within BIM-assisted design should be the change of design management at organisational level rather than the change in use of a piece of BIM software package at technical design level. This was made clearer by interviewee I8 who stressed that "*more high level individuals to encourage designers to do that from top-down structure will really change design management by taking them through the way BIM works as painless as possible*".

Furthermore, one third of the interviewees suggested that regulation is a driver for both architects and project partners in the use of BIM for building design. Interestingly, a fifth of the interviewees believed that project partners could be driven to implement BIM for better communication and coordination by issuing and sharing design digitally, because "*BIM will lead to multi-disciplinary design and practices making it more effective and efficient"* (I8). However, interviewee I1 argued that though it may not be used by project partners, this should not be a barrier to the use of BIM for building design by architects, because "*actually, architects can benefit from using BIM to assist design*".

5.5. BIM use for construction waste minimisation

5.5.1 BIM for addressing ineffective construction waste minimisation coordination and communication

The majority of interviewees concurred with the questionnaire findings (see section 4.4.2) in that BIM can potentially have a significant or major effect on addressing construction waste cause: ineffective coordination and communication at three levels: design team level (74%), project level (72%) and company level (56%). The improvement of communication and collaboration of design related activities through BIM was explored in section 5.4.4. Therefore, the interviewees were asked to provide their views on how BIM could address ineffective coordination and communication at those levels to minimise waste.

There was a consensus among interviewees that ineffective coordination and communication could be addressed for CWM by using BIM through technical and documentation management methods at the three levels as presented in Figure 5.6. This analysis was generated based upon suggested key elements and their relationships.

Technical method:

All interviewees made it clear that coordination and communication could be more effective through sharing the coordinated 3D model known as the common model, between disciplines at design team level (architect, structural engineer and services engineer), project level (design team and project partners) and organisational level (architects). Their views are summarised in Figure 5.6. This informs the shared common 3D model and coordinated information associated with both BIM-assisted technical and management methods, such as clash detection, documentation management, design and project reviews. Half the interviewees agreed that a coordinated 3D model should be a simple model in terms of sharing information between disciplines, and interviewee I9 suggested that "*not a giant model but several small models to make changes flexible*". Interviewee I3 further suggested that contractors should be involved at early design stages in terms of better constructability consideration in design for constructing the 3D model in the first place. This would contribute to either improving communication of the early understanding of building model components or addressing ineffective coordination of multi-disciplinary design to minimise construction waste, because "*contractors will be the key users of the system*" (I10). In addition, one third of the interviewees contended that clash detection (see section 5.4.2) have been implemented through BIM in their projects to overcome ineffective coordination and communication, as shown in Figure 5.6, which assists to reduce on-site clashes. Interviewee I11 made it simple by claiming "*clash detection will force project partners to communicate with coordination problems resulting in fewer on-site clashes*".

Management method:

The interviewees agreed that the BIM process having the right standard ensures that the disciplines involved at the same level of communication through the use of BIM, which could allow coordination at the same level in multi-disciplinary design to minimise waste. The agreement of the interviewees is illustrated in Figure 5.6. This indicates that the top-down implementation of BIM standardisation processes for design management directly influences the level of the shared common 3D model environment and the documentation management database system. Nearly half of interviewees stressed that the management outlook of top-down structure for the standard BIM process implementation into a project is essential to enable addressing ineffective coordination and communication in terms of waste reduction through multi-disciplinary design in BIM. Additionally, a third of the interviewees (four out of 11) emphasised the importance of the design and project review process which improves multi-disciplinary coordination and communication in order to locate the best opportunity for waste reduction. Furthermore, half the interviewees held the view that the use of a documentation management associated BIM system (database), such as Newforma, Bently Projectwise, Autodesk Buzzsaw, 4Projects, Asite, Navisworks, and Tekla BIMsight, strengthens management methods, as illustrated in Figure 5.6, where the coordination and communication through shared 3D common model and design/project reviews can be enhanced by coordinated design documentation which reduces waste caused by lack of coordination of detail design.

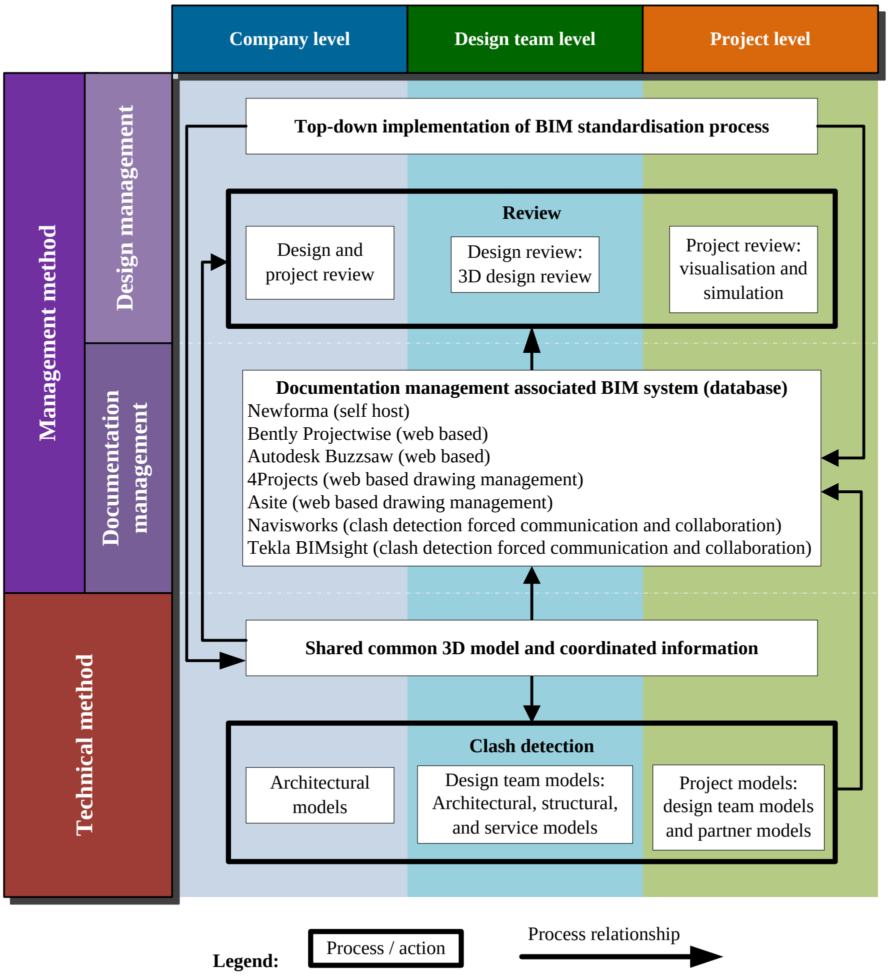


Figure 5.6 BIM to address ineffective coordination and communication (views of interviewees)

5.5.2 BIM for addressing design changes

The questionnaire results showed that 72% of respondents agreed that BIM had the potential to have a significant or major effect on addressing design changes (see section 4.4.2). Thus, the interviewees were asked for their views on how BIM could address design changes.

All interviewees shared the view that design changes made by the client during site operation could be eliminated at design stage by evaluating the design through BIM to ensure it meets the needs of the client. An example was given by interviewee I4 who claimed that the design evaluation should "*eliminate design changes by giving the client a clear view of what the finished scheme will be like through visualisation and walk through*". Three quarters of the interviewees went further by highlighting another benefit associated with the use of BIM to address client-led changes. This would be through 3D parametric modelling, model coordination and simulation within BIM (see section 5.4), because "*designers can quickly establish the changes that would impact upon the project by optimising the design in coordination with others*" (I2). Approximately, one third of the interviewees suggested that the documentation management method (see section 5.5.1), associated with BIM for communication and coordination, could help manage design changes efficiently during construction to reduce consequential construction waste through the design changes during site operations.

5.5.3 BIM potential for construction waste minimisation throughout building design stages

More than half of the questionnaire respondents reported that BIM has the potential to minimise construction waste across all building design related stages (i.e. RIBA Plan of Work stages: Appraisal to Tender Action) (see section 4.4.1). Hence, the interviewees were asked for their views on how BIM could help minimise construction waste during those stages.

The overwhelming majority of interviewees (nine out of 11) strongly argued that the Concept and Design Development Stages offer the greatest opportunities to minimise waste through BIM. The sections below summarise the perspectives of interviewees on the potential use of BIM to minimise construction waste during design.

5.5.3.1 BIM potential for construction waste minimisation during Briefing stages

Two thirds of the interviewees held the view that BIM have the potential to minimise construction waste throughout Briefing stages through visualisation and simulation allowing for better communication (see section 5.4.3) with the client, fitting the high-level sustainability needs of the client including feasibility studies, and to assist decision making for strategic brief development. On the other hand, a fifth of the interviewees argued that the potential to minimise waste through BIM at Briefing stages is limited, because "*the design is loose at this stage*" (I8). However, about half of interviewees commented that the high-level sustainability studies have an impact on CWM in terms of seeking opportunities to minimise construction waste and capturing the sustainability needs of the client, for instance "*it allows the link to the geometry data for performance of the site and can have a significant impact on the design process which could influence waste reduction*" (I9). Nearly one third of the interviewees further suggested that the management setup plan for BIM protocol (see section 5.5.1) is critical to enable high-level sustainability studies through the use of BIM to communicate the findings to clients.

5.5.3.2 BIM potential for construction waste minimisation during Concept and Design Development stages

The overwhelming majority of interviewees (nine out of 11) suggested that the use of BIM could help minimise construction waste throughout the Concept and Design Development stages by assisting early design decisions to prepare and develop concept design for the brief through 3D parametric modelling, shared 3D common model enhanced coordination and communication, clash detection and visualisation and simulation (see section 5.4 and 5.5.1). This was illustrated by interviewee I6 who articulated that "*architects are putting off waste-related decisions further down the line, but they could make the decisions earlier by using BIM*".

One fifth of the interviewees agreed that the brief could be developed efficiently by using BIM for energy efficiency (see section 5.4.5.3) to influence CWM, for example "*BIM assists designers to work out the areas in space, as such, designers can track the design of the areas and perform energy analysis based on 3D BIM models to optimise design which could subsequently influence the development of waste minimisation*" (I10).

Moreover, around one third of the interviewees recognised that outline material specification associated with the coordinated 3D BIM model could minimise waste by coordinating material dimensions. Interviewee I4 recommended that the quantity surveyor should be involved in using BIM for coordination of outline material specification in the production of the outline material cost plan specifying appropriate material quantity to minimise waste.

Furthermore, interviewee I1 affirmed that construction waste could be evaluated and calculated though simulation of the 3D model volume of the building by claiming that "*this is the way designers could very easily work out volumes of structure, timber and concrete and cladding and services design. As such, they can digitise and calculate waste by using the building volume and material sizes*".

5.5.3.3 BIM potential for construction waste minimisation during Technical Design and Production Information stages

All interviewees made it clear that the potential of using BIM to facilitate CWM throughout the Technical Design and Production Information stages entails facilitating technical design decision making and production information by detailed modelling and coordination, efficient specification of material, improved communication and collaboration, and simulation (see section 5.4 and 5.5.1). This was reinforced by interviewee I2 who stated that during Technical Design and Production Information stages "*designers make decisions on the precise detail of how the building material and products can be optimised to minimise waste, and how they can simulate how the design can be prefabricated and constructed with cost and schedule through BIM*". Nearly three quarters of the interviewees emphasised that detailing-enabled simulation and evaluation through BIM for technical design decision making could have a great impact on CWM, because "*The BIM system allows the designer to zone in on the small parts of the building and check its detail, which enables the designer to design in great detail by understanding the relationships between design and construction through BIM simulation*" (I3).

Nearly half interviewees suggested that the detailed model coordination for technical design and production information between designers and the main contractor, sub-contractors and specialist contractors, is the key to CWM in terms of effective coordination and communication. This is because "*designers can perform scenarios on the building in terms of material usage and specification by involving contractors and sub-contractors to optimise the design for waste reduction, and subsequently share the coordinated design information with them to avoid re-creation of the design by themselves resulting in potential waste generation*" (I9). Importantly, a third of the interviewees stressed that clash detection for detailed model coordination eliminates design and construction detail errors, which in turn minimises waste (see section 5.4). Interviewee I10 went further to disclose that BIM 3D parametric modelling could strengthen the design drawing coordination in construction to improve information for CWM by claiming that, "*traditionally, architects work with 2D symbol groups for drawings such as windows and doors, which can be easily explored and modified to 'hide' design problem that cause waste related to clashes of the unconstrained designs*". However, interviewee I7 argued that ownership of the detailed and coordinated model should be allocated to the lead designer rather than the contractor in terms of coordination with the construction model, to minimise waste influenced by design, because "*the as-designed model owned by the lead designer can always affect the construction model during construction*".

Furthermore, half interviewees stressed that material and product specification through BIM could influence construction waste reduction performance. As such, interviewee I5 reported that "*specification links the information to the real product on the market through BIM, which helps predict the waste performance*".

5.5.3.4 BIM potential for construction waste minimisation during Procurement stages

All interviewees agreed that the potential use of BIM for CWM during Procurement stage is through improving coordination and communication (see section 5.4 and 5.5.1). They argued that a shared and coordinated 3D model could improve coordination and communication with contractors, therefore resulting in more sufficiently detailed tender documentation in line with design. However, there was a major concern regarding the release of the shared and coordinated 3D model to contractors, whereby the model ownership could cause construction waste by accidental changes being made to the published model, as such "*wrong building materials or products could be ordered resulting in construction waste*" (I1). Consequently, a solution was proposed through the use of an unchangeable drawing format such as PDF, but with its associated 3D model for tender documentation.

In addition, two thirds of the interviewees stressed that the quantity extracted from the shared and coordinated 3D model through BIM, known quantity takeoff, could benefit contractors when seeking opportunities to minimise construction waste. One fifth of the interviewees gave further insight by revealing that the quantity surveyor should be involved in the use of BIM for coordination of material, components and building products, to better tender decision making in terms of CWM.

Furthermore, a fifth of the interviewees confirmed that visualisation through BIM could enrich the tender documentation in considering waste reduction.

5.5.3.5 Suggested potential approach to reduce construction waste through the use of BIM

The interviewees were asked to give their suggestions on the most suitable BIM approach to reduce construction waste generation during building design.

All interviewees emphasised that the shared 3D model powered by BIM parametric modelling in the 3D virtual environment is essential to BIM enabled CW reduction approaches, in terms of improving communication and coordination.

The vast majority of interviewees (eight out of 11) agreed that BIM enhanced communication, collaboration and coordination is the best approach to reduce waste generation. This is because the building design is shared and coordinated with project members through the BIM 3D model in different LODs throughout building design stages, which naturally reduces opportunities for waste generation. Interestingly, only two out of 11 interviewees suggested that the 3D model content information from the manufacturer could contribute to the BIM approach toward waste reduction in terms of coordination of standard materials, components, product sizes and production information. Interviewee I1 further commented that the standard 3D model content should be data driven through parametric modelling within BIM, automatically highlighting the potential wasted part when the designer progresses the design.

A fifth of the interviewees reported that BIM for modularisation could help minimise waste as construction modularisation had already been used for waste reduction and promoted by organisations, such as WRAP.

Interviewee I3 believed that BIM could be implemented in line with Site Waste Management Plans (SWMPs) during building design stages to seek opportunities to target construction waste during construction.

Interviewee I11 encapsulated the topic by indicating that a well established BIM management in building design to improve communication across disciplines, design optimisation and effective decision making, is the backbone for any approach to reduce construction waste generation.

5.6. Summary

This chapter has presented key results related to current CWM and the use of BIM for design practices, and explored the potential use of BIM to minimise construction waste during design.

Interview findings disclosed that the BIM-related improved communication and coordination approach would be the most appropriate in reducing construction waste. Results also indicated the need to overcome design culture related barriers in implementing CWM. It also called for culture change in terms of designers' attitude to BIM-aided design and implementing BIM for design, and training needs to overcome barriers in the use of BIM in building design.

Findings suggested that shared and coordinated 3D model and documentation management system methods in the use of BIM could help with addressing CW causes such as ineffective coordination and communication. Design changes could be effectively addressed through BIM for design evaluation to fit the needs of the client brief.

BIM-enhanced practices (i.e. clash detection, detailing, visualisation and simulation and improved communication and collaboration) were reported as having impact on CWM. Additionally, results suggested that BIM was deemed to have the potential to reduce construction waste generation throughout all design stages, particularly at Concept and Design Development stages. Furthermore, results gave an account of the underlying reasons and methods behind addressing construction waste causes through BIM. It also showed that BIM is being gradually used in architectural practices to improve sustainable building design, namely energy efficiency, carbon reduction and building material specification, which paves the way for an integrated approach linking the current use of BIM for sustainable building design to address construction waste causes during building design stages.

The next chapter presents discussion of questionnaire and interviews findings to the context of literature.

CHAPTER SIX

Discussion

6.1. Introduction

This chapter discusses the themes emerging from the study results, which relate findings from Chapters 4 and 5 to the context of the literature (Chapters 2).

Research regarding the BIM-aided CWM (BaW) Framework is discussed in the main sections of this chapter, which comprises BIM for CWM improvements associated with construction waste causes, BIM-enhanced design activities, and BIM-enhanced energy efficiency process. The last section of this chapter presents discussion of barriers and incentives to the use of BIM for CWM.

6.2. Potential BIM-aided construction waste minimisation process throughout building design stages

A number of studies were found in existing literature on the correlation between BIM and CWM during building design. Recent studies emphasised that BIM has shown a potential to manage construction waste (Sacks *et al.*, 2010; Ningappa, 2011; Ahankoob *et al.,* 2012; Hewage and Porwal 2012; O'Reilly, 2012; Porwal and Hewage, 2012; Cheng and Ma, 2013; Porwal, 2013; WRAP, 2013a;). These studies employed either qualitative or quantitative research method, such as questionnaire, interviews, and case study, as shown in Table 2.20. Only this research has adopted mixed methods (i.e. questionnaire and interviews) for investigation of relationship between CWM and BIM.

The questionnaire findings (see section 4.4.1) indicated that there was an agreement among the respondents that BIM has a great potential to aid CWM during building design stages.

Furthermore, the past studies did not suggest a BIM related process or methodology for CWM. The BaW Framework provides a integrated method for using BIM to aid CWM across all building design stages.

The questionnaire results indicated that the use of BIM has a potentially ‘significant’ effect on CWM during four design stages: Concept, Design Development, Technical Design, and Production Information) (see section 4.4.1). The interview results further underlined that the Concept and Design Development stages had the greatest potential for the use of BIM for CWM in design (see section 5.5.3). This was in line with O'Reilly’s (2012) research findings on the BIM potential to CWM. This also has been echoed by a number of research studies that recommended that CWM practice should focus on early project stages rather than on-site waste management (Key *et al.*, 2000; Osmani *et al.*, 2008; Osmani, 2013). However, these studies did not explore CWM improvements through BIM across all design stages. These have been examined in this research and summarised in the sections below.

6.2.1 Potential BIM-aided construction waste minimisation process during Briefing stages

Nothing has been found in the literature on the BIM-aided CWM decision making process to drive out construction waste during Briefing stages.

The interview results suggested that the use of BIM can potentially minimise waste in Briefing stages through visualisation and simulation for better communication (see section 5.4.3). This could assist the client's decision making for strategic brief development. The interview results also indicated that setting up a management plan for BIM protocol is critical to enable high-level sustainability studies, including opportunities to minimise construction waste (see section 5.5.1). These have been embedded within the High-level BaW Framework. The development of a BIM protocol/management plan to aid CWM is absent from literature.

There are four BIM aided CWM improvements (see Table 7.1), which have been set in the High-level BaW Framework Briefing stages (RIBA Plan of Work stage A&B) (see Figure 7.4), and which are associated with identified construction waste causes (see Table 7.1), such as lack of waste feasibility studies, lack of clear goal of waste minimisation, lack of waste responsibility, and lack of early involvement of contractor. These waste causes identified from interview results are in line with the following studies:

- lack of waste feasibility studies in the early project stages (Briefing stage) is seen to be one of the most significant waste generators, which is in agreement with Osmani *et al.*, 2008 and Osmani 2013.
- the requirements of a design brief can have an exerted impact on CWM, such as the lack of a clear CWM goal and non-allocation of waste responsibility, which is in line with the study of Osmani (2013).
- lack of early involvement of the contractor who can provide suggestions to the client and design team on buildability and its impact on CWM. This finding is also in line with the studies of Bossink and Brouwers, 1996; Tam *et al.*, 2007; Osmani *et al.*, 2008; Gamage *et al.*, 2009.

6.2.2 Potential BIM-aided construction waste minimisation process during Concept and Design Development stages

There was no developed BIM-aided CWM decision making process in literature that embeds the BIM-enhanced design related activities and BIM-enhanced energy efficiency process to improve CWM performance across Concept and Design Development stages. The BIM-enhanced design related activities, and BIM-enhanced energy efficiency for CWM are discussed in sections 6.2.2.1 and 6.2.2.2 respectively.

6.2.2.1 BIM-enhanced design related activities for construction waste minimisation

The results of the interviews indicated that the process of using BIM could minimise construction waste at Concept and Design Development stages (see section 5.5.3.2). This could be improved by assisting at the early design stages in preparing and developing design concepts through various BIM-assisted design activities (e.g. improved coordination and communication, visualisation and simulation, detailing, and clash detection). These four BIM-enhanced design related activities could be used to help with on-site construction waste reduction during design as noted in Table 6.1. These activities also could be used for addressing the identified ineffective coordination and communication related construction waste causes (see Table 7.1), such as design changes, lack of attention paid to dimensional coordination in design, design complexity and material specification, and unclear specification of material.

Both the literature (see section 2.2.3.1) and findings of interviews (see section 5.3.1.2) emphasised that one of the key construction waste causes throughout the building design stages is ineffective coordination and communication. The causes of material off-cuts associated with lack of attention paid to dimensional coordination in design (Al-Hajj and Hamani, 2011), and re-work for design changes (Love *et al*., 1999) during the construction stage were mainly due to ineffective coordination and communication during design stages. In addition, the interview results (see section 5.3.1) indicated that design decisions not fully evaluated during the design stages, particularly during the Concept, Design Development, and Technical Design stages, are most likely to impact on design changes during construction, which is also influenced by ineffective coordination and communication. The design decisions were also directly related to the failure in identifying the needs of the client. This is consistent with other studies that reported that well captured client's needs during the design process will improve CWM performance (Rounce, 1998; Lee *et al*., 1999; Muhwezi *et al*., 2012). Furthermore, the interview results indicated that ineffective coordination and communication has the impact on design complexity and material specification. This can result in waste generation which is caused by difficulties resolving design coordination issues of architectural, structural and service design complexity, and unclear specification. These findings are in line with the findings of Alwi *et al*. (2002), Polat and Ballard (2004), Poon *et al*. (2004), Kulatunga *et al*. (2006), Osmani *et al*. (2008), and Osmani (2013). These construction waste causes are presented in Table 6.1.

Table 6.1 The potential use of BIM-enhanced design related activities for construction waste minimisation (the research findings)

The use of BIM	The positive impact on construction waste minimisation
Improved coordination and communication through BIM	Effective and efficient multi-disciplinary design leading to less on-site waste
Visualisation and simulation within BIM	Earlier understanding of the design by the client to avoid subsequent on-site design changes
	Better understanding of the building by contractors and a visualised and simulated construction process to lead to less on-site waste
	Enhanced communication and collaboration design between the design team to eliminate uncoordinated design resulting in fewer clashes on-site
BIM for detailing	Better understanding of design by clients through a detailed building model resulting in fewer design changes
	Getting LOD right leading to less on-site waste
	More detail, better result of clash detection and fewer on-site clashes
	Better detailing coordination and specification leading to less re-work
Clash detection through BIM	Better coordinated design resulting in less on-site waste
	Fewer clashes leading to less on-site waste
	Less re-work and re-design resulting in less on-site waste

I. BIM-enhanced coordination and communication for construction waste minimisation

Little has been published in the literature to provide a clear indication as to how BIM can help with addressing the identified construction waste causes during design.

The questionnaire results (see section 4.4.2) suggested that ineffective coordination and communication, along with design changes, have been reported as the main waste causes that BIM could have a ‘significant’ effect in being able to address through design.

The interview results (see section 5.4.4) indicated that the 3D collaborative working environment through a shared 3D parametric model in BIM is a key element to 3D collaborative working for CWM. The results of interviews highlighted the use of clash detection through BIM to improve design coordination and communication. The interview results suggested that BIM-enhanced visualisation and simulation are critical activities within design coordination and communication, which facilitate informed CWM decision making during design. These results corroborate the findings of Greenwood *et al*. (2008), Kim and Grobler (2009), Grilo and Jardim-Goncalves (2010), Shelden (2013), and Davies and Harty (2013), which reported the importance of BIM-facilitated design decision making.

However, the literature failed to specify how coordination and communication exactly take place through BIM in terms of building design activities and the processes. This has been addressed in the research through the BaW Framework through:

- working in the 3D model environment;
- sharing a common model in LOD in the BIM communication server with an agreed standard; and
- conducting visualisation and simulation, detailing, and clash detection.

The interviews results (see section 5.5.2) reported that the application of BIM to aid CWM evaluation through 3D parametric modelling, model coordination, and simulation, can fulfil the needs of the client, resulting in fewer client-led design changes during site operation. In addition, if design changes are unavoidable, the BIM-facilitated documentation management system (see section 5.5.1) could drive the reduction of the consequential construction waste generation caused by design changes during construction.

As illustrated in Figure 5.6, the results of interviews (see section 5.5.1) also suggested that ineffective CWM coordination and communication could be addressed through technical management methods through the use of BIM. This research proposed five elements within the technical and management methods:

- three technical methods (i.e. shared common 3D model and coordination information, and clash detection); and
- two management methods (i.e. top-down implementation of BIM standardisation process/protocol and design and project review).

The interviews results further indicated that BIM-enhanced coordination and communication for CWM can be more effective through BIM-assisted technical methods by performing clash detection and sharing the coordinated 3D model (common model). This should be a simple model if/where possible in terms of sharing information between disciplines. The shared common 3D model with certain LOD also has the most potential to minimise construction waste as all information generated from one model source produces less errors (see section 5.4.1).

The results of interviews highlighted that the shared common 3D model embeds the model and coordination information, which is created in line with the implementation of BIM protocol. This is used for design and project review for effective design to minimise waste, being connected to the BIM-enhanced documentation management system. The latter is associated with all aspects of technical and management methods through the use of BIM. This allows facilitation of the design and project team to provide solutions (e.g. platforms and roadmaps) on the use of BIM to enable delivery of effective coordination and communication at design and project team level respectively for CWM.

II. BIM-enhanced visualisation and simulation for construction waste minimisation

Literature failed to show clear BIM-enhanced visualisation and simulation process to help with CWM.

The process of using BIM to enhance visualisation and simulation for waste reduction has been proposed by the research based on research findings. The interviews (see section 5.4.4) stressed the importance of 3D parametric modelling through BIM within building stages, whereby the process of parametric 3D modelling has been reported as essential to enable visualisation and simulation for waste reduction practices. Equally, the current BIM practices for visualisation and simulation are being routinely used throughout all project stages to aid waste evaluation. However, the results of interviews emphasised the importance of visualisation and simulation for different purposes for each design stage in terms of assisting CWM. For example, the interview results (see section 5.4.3) emphasised that these were used frequently at the Briefing and Concept Design stages to enhance communication with the client. These are in line with recent research findings that recommend that BIM-enhanced visualisation and simulation through the human–computer interface could easily facilitate examination of the building design from different perspective views during the early design stages (Yan *et al.*, 2011). Additionally, the early integration of BIM-enhanced simulation (e.g. energy) can work as a mode of design assessment to support design evaluation and decision making within the design concept (Sanguinetti *et al*., 2012).

III. BIM-enhanced detailing for construction waste minimisation

Literature has not drawn a clear picture of using BIM for detailing during design for CWM.

The research also added value to the literature by providing a clear view of the use of BIM for detailing to reduce construction waste, where 3D parametric modelling having a certain LOD associated coordination process that works as a '3D plus 2D information' process. This enabled the 3D building Model Set to coordinate between the 3D-model and 2D-specification elements with sufficient detail, resulting in less on-site waste, in line with each of the building design stages (see section 5.4.1).

The interview results indicated that participating architects recognised the beneficial facet of using BIM for detailing in building design projects though 3D parametric modelling, model information coordination and communication to reduce waste.

IV. BIM-enhanced clash detection for construction waste minimisation

The literature failed to indentify a clear process of clash detection used in BIM for building design and for CWM.

As shown in Figure 5.1, this research (see section 5.4.2) proposed a clear clash detection process through BIM during design to eliminate clashes in design resulting in less on-site waste, which starts with a visual detection to inspect clashes during the Concept and Design Development Stages, and followed by the automatic detection executed via software during the Technical Design and Production Information stages, whereby detailed models are required prior to the automatic clash detection. The results of the interviews showed that the use of BIM for clash detection (see section 5.4.2), detailing (see section 5.4.1), and visualisation and simulation (see section 5.4.3) to assist design decision making during building design stages, can also have a positive impact on construction waste generation in terms of on-site design changes. The positive impacts concluded by this research are shown in Table 7.1.

The results of interviews (see section 5.4.2) revealed that visual and automatic clash detections have been applied through BIM. This is in agreement with Leite *et al*. (2011) who conducted an analysis on the differences between precision and comprehensiveness of the clashes detected by performing visual (manual) clash detection (e.g. using 2D drawing overlays) and automatic clash detection. The interviews results also indicated that clash detection is being practiced by participating architects for design coordination and communication among different disciplines. This supports Grilo and Jardim-Goncalves' (2010) conclusion that clash detection is not only performs as an essentially efficient activity to coordinate multiple efforts by different team members, but also as an important engagement in achieving successful results whereby participants would be unable to accomplish them alone. This enables multi-disciplinary design coordination to reduce on-site design errors, which cause waste generation.

6.2.2.2 BIM-enhanced energy efficiency for construction waste minimisation

Literature failed to provide a BIM process to aid CWM in Concept and Design Development stages, which is correlated with BIM-enhanced energy efficiency.

The use of BIM for energy efficiency (see section 5.4.5.3) could be associated with CWM during design development, where outline material specification related 3D model coordination could eventually contribute to construction waste reduction. As such, existing energy efficiency process through BIM provides the foundation for the BaW Framework.

However, nothing was found in the literature stating a clear process for understanding of how the use of BIM aid energy efficiency evaluation throughout building design stages. Interview results revealed that meeting energy targets is evaluated through energy analysis in BIM during each building design stage, where:

- shared and coordinated BIM model(s) is/are updated in line with certain LOD of each design stage,
- the BIM model(s) should be exchanged for each energy analysis,
- the energy analysis becomes more comprehensive and accurate when design is developing, and
- carbon reduction and building material specification are involved in the analysis.

The interview results revealed that BIM-enhanced energy efficiency is implemented through energy estimation and evaluation within a coordinated 3D model environment for design decision making (see section 5.4.5.3), which could pave a way for construction waste estimation and evaluation.

The results of the interviews revealed that outline material specification related 3D model coordination via the BIM-enhanced energy efficiency evaluation processes could be achieved through coordinating material dimensions and construction, whereby waste can be evaluated and calculated by simulating a 3D model volume of the building design as illustrated in the BaW Framework sections of virtual waste minimisation evaluation.

Above discussed issues have been included in both High-level and Low-level of the BaW Framework.

6.2.3 Potential BIM-aided construction waste minimisation process during Technical Design and Production Information stages

Literature has not shown a clear picture of the CWM decision making process through BIM that associated with BIM-enhanced design related activities.

The BIM-aided CWM decision making process has the same rationale with the process applied during Concept and Design Development stages, and is associated with identified waste causes in Technical Design and Production Information (see Table 7.1). These waste causes are: design and construction detail errors / lack of information on drawing / lack of coordination of detail design; ineffective coordination and communication; unclear specification of material; not fully evaluated design leads to design changes during construction period (design decision); unclear specification of products and components

The results of the interviews highlighted that the shared and coordinated 3D model in the detailing process plays as a crucial role in enhancing CWM coordination and communication for CWM through clash detection to reduce design and construction errors resulting in improved CWM outputs. The interviews results revealed that the potential use of BIM to aid CWM throughout Technical Design and Production Information stages is to facilitate CWM decision making, in terms of detailing, specification, and scheduling, which supports Porwal and Hewage's (2012) study. This is achieved in the research through a number of design activities within the BIM-enhanced environment, such as detailed modelling and coordination, efficient specification of material, improved coordination and communication, and simulation. Furthermore, the results of the interviews suggested that coordination of detailed 3D parametric model, which is produced from BIM-enhanced material and product specification detailing process, is the key to the decision making that can have a great impact on CWM in terms of LOD for a better understanding of the relationship between design and construction. Above issues have been considered in the High-level BaW Framework.

6.3. Barriers and incentives to the use of BIM for construction waste minimisation

The literature failed to identify specific barriers and incentives of using BIM as a potential platform to minimise construction waste during building design. The questionnaire results showed that barriers facing architects are technology barriers (i.e. slow uptake of family libraries for building products to BIM), and knowledge barriers (i.e. lack of experience in the use of BIM, and lack of a integrated and integrated approach to solve identified construction waste causes) (see section 4.3.5). This research identified the following incentives to the use of BIM for CWM (section 4.3.6):

- an advanced automation tool for CWM design decision making through collaborative working with better design coordination, better visualisation, accurate material usage analysis during design (including automated schedules and material takeoff);
- economic and environmental benefits via better design, and enhanced rating of environmental assessment methods, such as BREEAM; and
- marketing advantages via early adoption of the use of BIM to address construction waste through design.

6.4. Summary

The emerging themes from the research have been discussed within the context of literature with a particular focus on the relationship between BIM and CWM that led to the development of the BaW Framework.

The potential process of using BIM for CWM improvement has been discussed, where BIM-enhanced design related activities (e.g. coordination and communication, visualisation and simulation, detailing, and clash detection,) and BIM-enhanced energy efficiency have contributed to the BIM-aided CWM process during design.

Subsequently, the barriers and incentives have been discussed, which the current building design industry is facing for implementation of BIM for CWM during design. These include the insufficient uptake of BIM technology, and lack of experience of using BIM and knowledge of addressing CW causes. On the other hand, the incentives include BIM-enhanced collaborative working for better CWM design decision making, economic and environmental benefits, and marketing advantages.

The next chapter presents the BaW Framework development and validation.

CHAPTER SEVEN

BaW Framework Development and Validation

7.1. Introduction

This chapter presents an account of the development and validation of the proposed BIM-aided construction waste minimisation (BaW) Framework. The first section presents the design and development of the BaW Framework, which is based on findings from the literature review (Chapter 2), questionnaire (Chapter 4) and interviews (Chapter 5). The second section of this chapter outlines the BaW Framework validation process by presenting the approach and analysing the results. The third section summarises suggested key improvements that emerged from the validation process, and presents key actions taken to improve the BaW Framework. The last section presents an insight into the BaW Framework implementation strategy.

7.2. BaW Framework design and development

As shown in Figure 7.1, the findings form the literature review, questionnaire and interviews were used for the design and development of the BaW Framework.

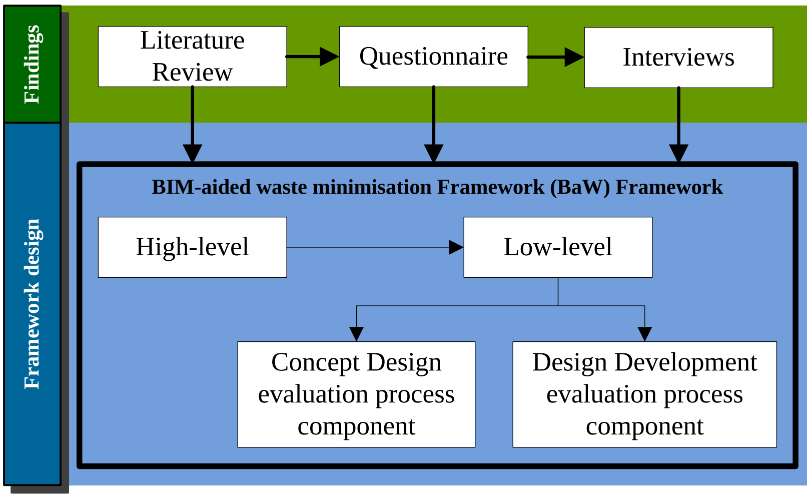


Figure 7.1 Flow chart for the BIM-aided waste minimisation Framework (BaW) Framework design

As shown in Figure 7.2, the rationale of the BaW Framework was to use BIM for addressing CWM through a integrated process of using BIM to aid design-related activities to reduce CW, and assisting decision making of CWM during building design.

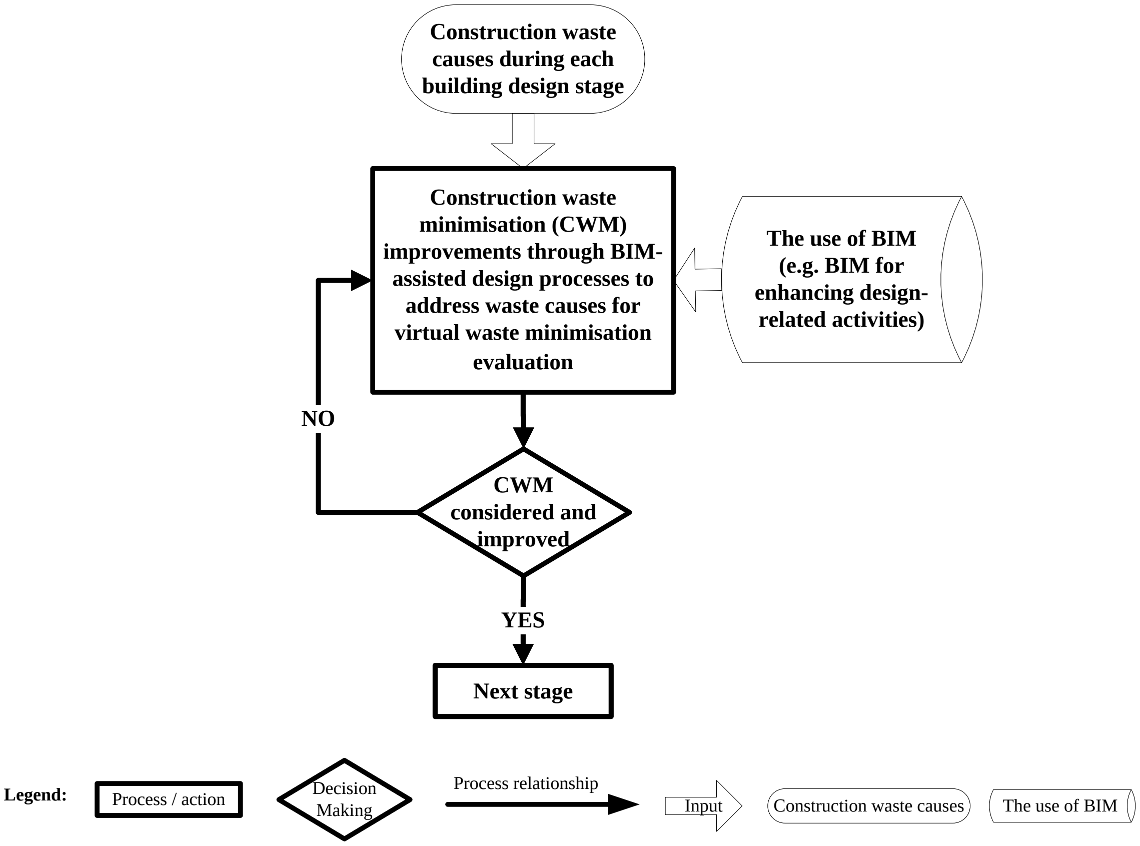


Figure 7.2 Rationale of the BaW Framework

The design and development of the BaW Framework was based on (1) key concepts of a framework design methodology (see section 3.5.4.1), (2) key findings that emerged from the research, including the current use of BIM to aid the energy efficiency process (see section 5.4.5.3). The questionnaire and interviews results informed a BaW Framework to address construction waste causes (Table 7.1) throughout building design stages (i.e. RIBA Plan of Work Stage Appraisal to Production Information), particularly in the Concept and Design Development stages, which were identified from the questionnaire and interview results (see section 4.5.1 and 5.5.3) as the most suitable stages for the use of BIM to aid CWM. The detailed the BaW Framework design and development are discussed in sections below.

Table 7.1 Addressing construction waste causes throughout building design stages in the BIM-aided waste minimisation Framework (BaW) Framework

Stages	**Construction Waste Causes**				**BIM-aided CWM (BaW) Framework contents**
		Literature Review	**Interview**	**Severity**	
Appraisal & Design Brief	Lack of early involvement by contractor	√	4 / 11	Medium	AB-1.1
	Lack of clear goal for waste minimisation	√	6 / 11	Medium	AB-1.2
	Lack of waste responsibility	√	4 / 11	Medium	AB-1.3
	Lack of waste feasibility studies	√	10 / 11	High	AB-1.4
	Ineffective coordination and communication	√	7 / 11	High	AB-1.5
	Failure to identify client needs	√	10 / 11	High	AB-1.6
Concept Design & Design Development	Ineffective coordination and communication	√	7 / 11	High	CD-1, CD-2.2, CD-3.2
	Difficulties with design complexity coordination	√	6 / 11	Medium	CD-2.1, CD-3.1
	Design changes	√	10 / 11	High	CD-2.2, CD-3.2
	Unclear outline specification of material purpose	√	6 / 11	Medium	CD-2.2, CD-3.2
	Lack of attention paid to dimensional coordination	√	4 / 11	Medium	CD-2.2, CD-3.2
	Limited design standardisation	√	3 / 11	Low	NA
	Frozen design brief	√	1 / 11	Low	NA
	Lack of buildability consideration	√	1 / 11	Low	NA
	Lack of prefabrication design	√	1 / 11	Low	NA
	Lack of considering design for deconstruction and flexibility	√	1 / 11	Low	NA
Technical Design & Production Information	Design and construction detail errors / lack of information on drawing / lack of coordination of detail design	√	11 / 11	High	EF-1.1, EF-1.2
	Ineffective coordination and communication	√	11 / 11	High	EF-1.2
	Unclear specification of material	√	11 / 11	High	EF-1.2
	Not fully evaluated design leads to design changes during construction period (design decision)	√	10 / 11	High	EF-1.2
	Unclear specification of products and components	√	6 / 11	Medium	EF-1.2
	Specification of material quantity (over specification)	√	2 / 11	Low	NA
	Inexperience in methods and sequence of construction	√	2 / 11	Low	NA
	Lack of knowledge about standard sizes available in market	√	1 / 11	Low	NA
	Unfamiliarity with alternative products	√	1 / 11	Low	NA

7.2.1 Structure of the BaW Framework

The BaW Framework structure consists of three aspects (see Figure 7.4, 7.5, 7.6, and 7.7):

- Framework levels: the BaW Framework composes two levels, a strategic High-level Framework and a detailed Low-level Framework with two related evaluation process components;
- Framework process actions: process actions representing key improvements to minimise design-related construction waste causes;
- Coding system: the BaW Framework content is guided by a coding system which correlates the High-level to Low-level.

7.2.2 BaW Framework levels

The BaW Framework consists of two levels, as shown in Figure 7.3:

1. High-level (strategy level) which covers Briefing, Concept and Design Development, and Technical Design and Production Information stages;

2. One detailed Low-level (implementation level) of Concept and Design Development with two related evaluation process components.

The relationships between the BaW Framework levels are shown in Figure 7.3.

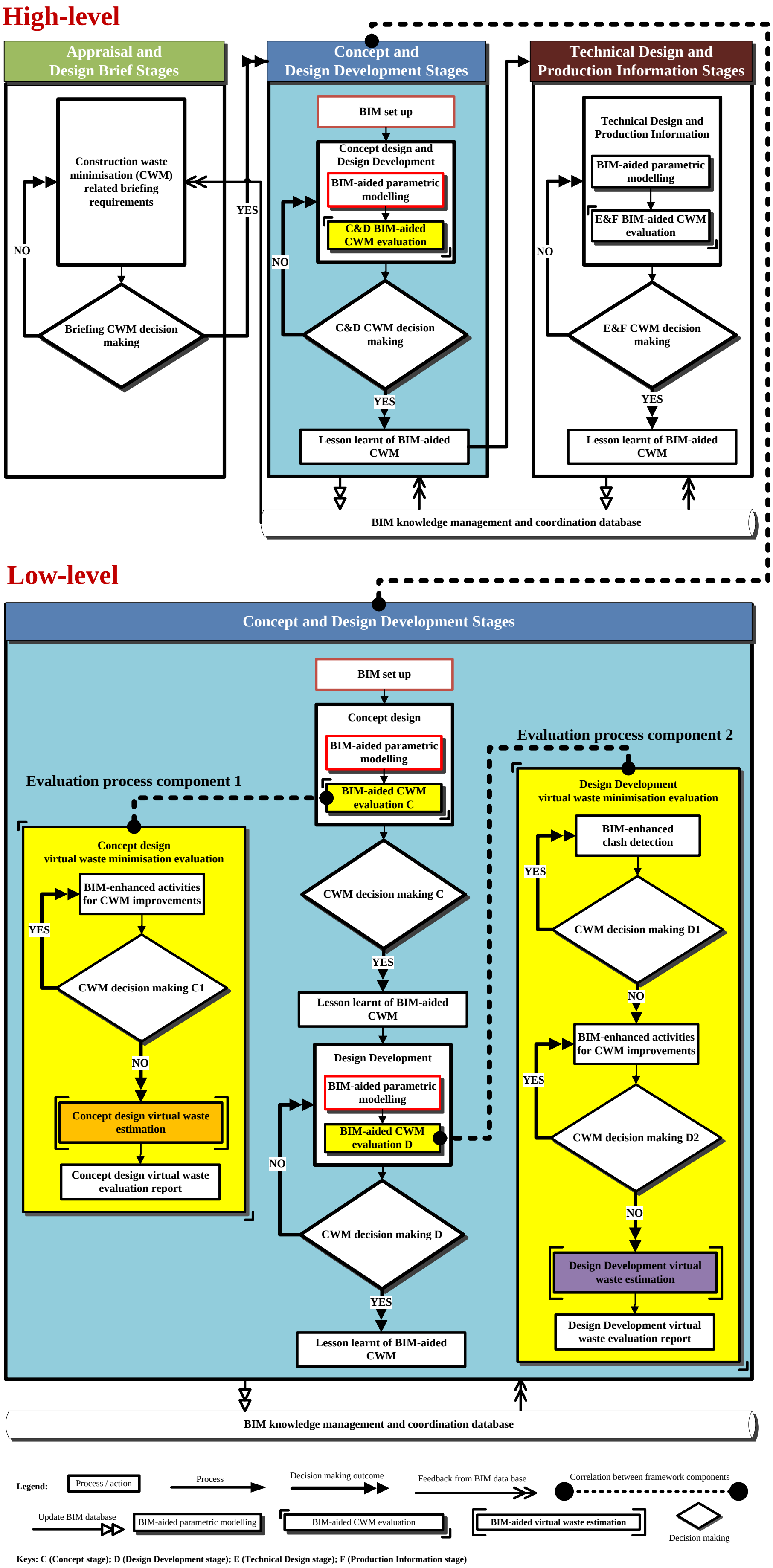


Figure 7.3 BaW Framework levels and structure

7.2.2.1 High-level BaW Framework

As shown in Figure 7.4, the High-level BaW Framework provides the strategic use of BIM to aid CWM for CWM decision making throughout building design stages (i.e. Appraisal, Design Brief, Concept and Design Development, and Technical Design and Production Information stages). The BaW Framework is designed with BIM-enhanced design activities to address design-related construction waste causes during the design process. The design-related waste causes are that of high and medium severity levels. This was identified from literature review findings and interviews as listed in Table 7.1.

Appraisal and Design Brief stages (Briefing stages)

Six specific improvements of waste cause related issues (see Table 7.1) are indicated during Appraisal at Strategic Briefing stages as shown in Figure 7.4, AB-1. This ensures that a CWM strategy and an agreed BIM protocol have been established and fully embedded in the Appraisal at Strategic Briefing stage. The Framework specifies the following actions:

- Involvement of a contractor as a consultant throughout all stages.
- Setting a clear CWM target as ‘the average cubic metre of waste per square metre of floor area’. This is widely adopted in terms of waste benchmarking in the construction industry.
- Establishing CWM responsibilities.
- Conducting CWM feasibility studies.
- Laying a foundation of BIM protocol for collaboration and communication.
- Generation of a simple mass model to capture client sustainability needs for these improvements.

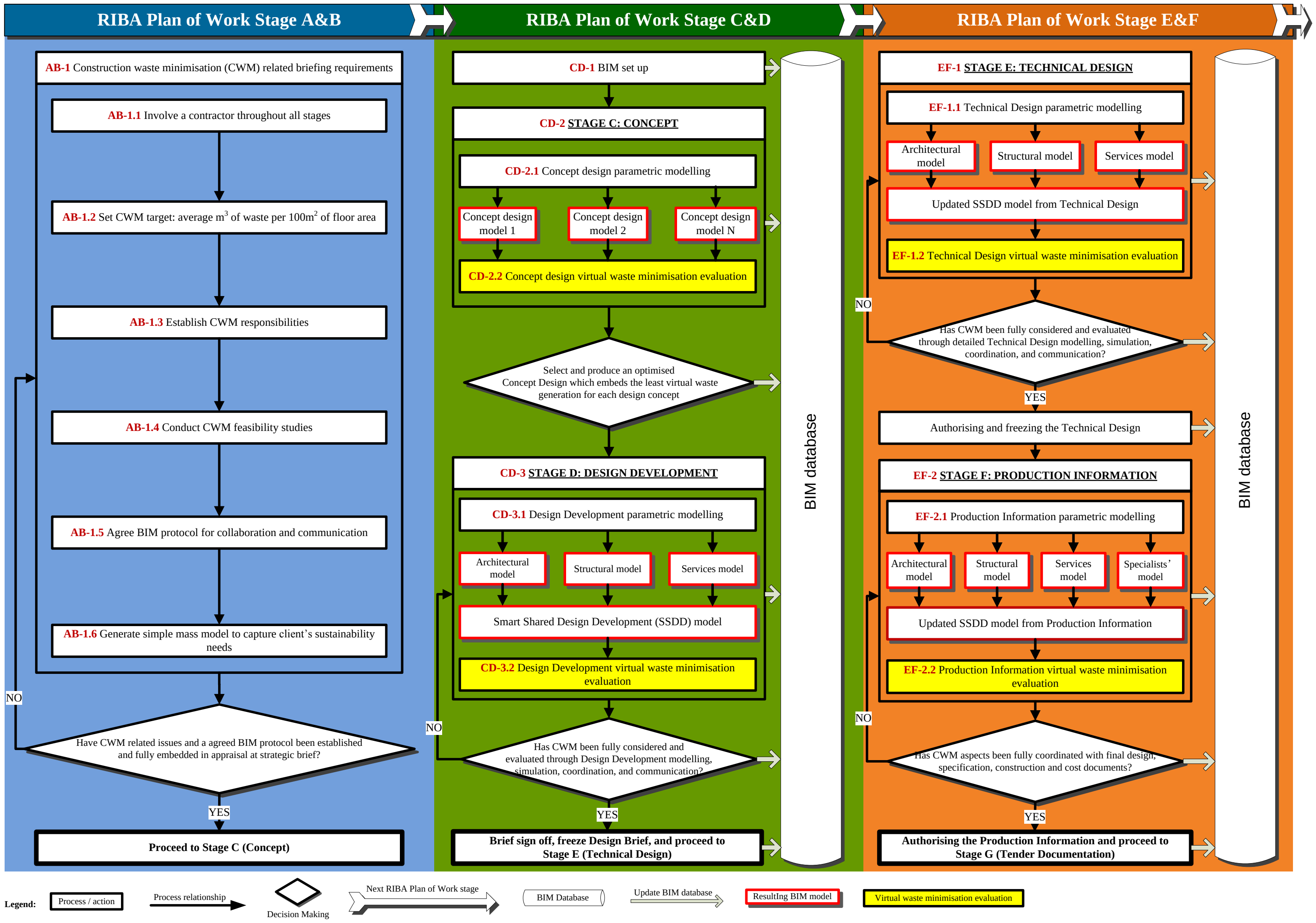


Figure 7.4 High-level BaW Framework

Concept and Design Development stages

As shown in Figure 7.4, prior to commencement of the Concept stage (CD-2), the initial BIM set up (CD-1) has to be established as the basis for effective coordination and communication through the use BIM. The BIM-associated design activities are established to minimise construction waste during the design process. This ensures better decision making for selecting and producing an optimised concept design that embeds the least virtual waste generation for each design concept upon completion of the Concept stage. The process involves Concept design 3D parametric modelling (CD-2.1) to address difficulties in resolving design issues of architectural complexity when creating various concept design models and Concept design virtual waste minimisation evaluation (CD-2.2). Based upon the results of these models they can help tackle design-related waste causes such as unclear outline specification of material purpose, lack of attention to dimensional coordination, and design changes (see section 5.5.3.2) during construction through the unsatisfied design that has not had full evaluation. Related information to the above process is uploaded to the BIM database for continuous knowledge and information management, which is used to enhance communication.

The selected and optimised architectural model, having minimum virtual waste from the Concept stage, is used in Design Development (CD-3) for BIM enhanced design development through coordination and communication with other design team members. This facilitates collaborative decision making, which ensures that CWM has been fully considered and evaluated through modelling, simulation, coordination and communication. The results of the decision making process will help sign off the Brief and freeze the design brief. Design Development 3D parametric modelling (CD-3.1) is used to tackle difficulties to resolve design issues of architectural, structural and service design complexity. It merges multi-disciplinary models from the architectural design, structural design and service design into a well coordinated Smart Shared Design Development (SSDD) model. This is used for Design Development virtual waste minimisation evaluation (CD-3.2) to address design-related construction waste causes.

Aforementioned, the focus of the BaW Framework is upon the Concept and Design Development stages. The structure and content of the Concept and Design Development stages in the High-level Framework are discussed in detail in section 7.2.2.2.

Technical Design and Production Information

Section EF-1 and EF-2 in the High-level BaW Framework presents the process of using BIM to ensure CWM has been fully considered and evaluated during Technical Design and Production Information via modelling, simulation, coordination and communication. The BIM process includes Technical Design and Production Information parametric modelling (EF-1.1 and EF-2.1). The aim of this is to update and coordinate architectural, structural and service models from the Design Development stage, along with models from contactors and sub-contractors for updating the SSDD model of Technical Design and Production information. This in turn facilitates the Technical Design and Production Information virtual waste minimisation evaluation process (EF-1.2 and EF-2.2) to minimise construction waste during design.

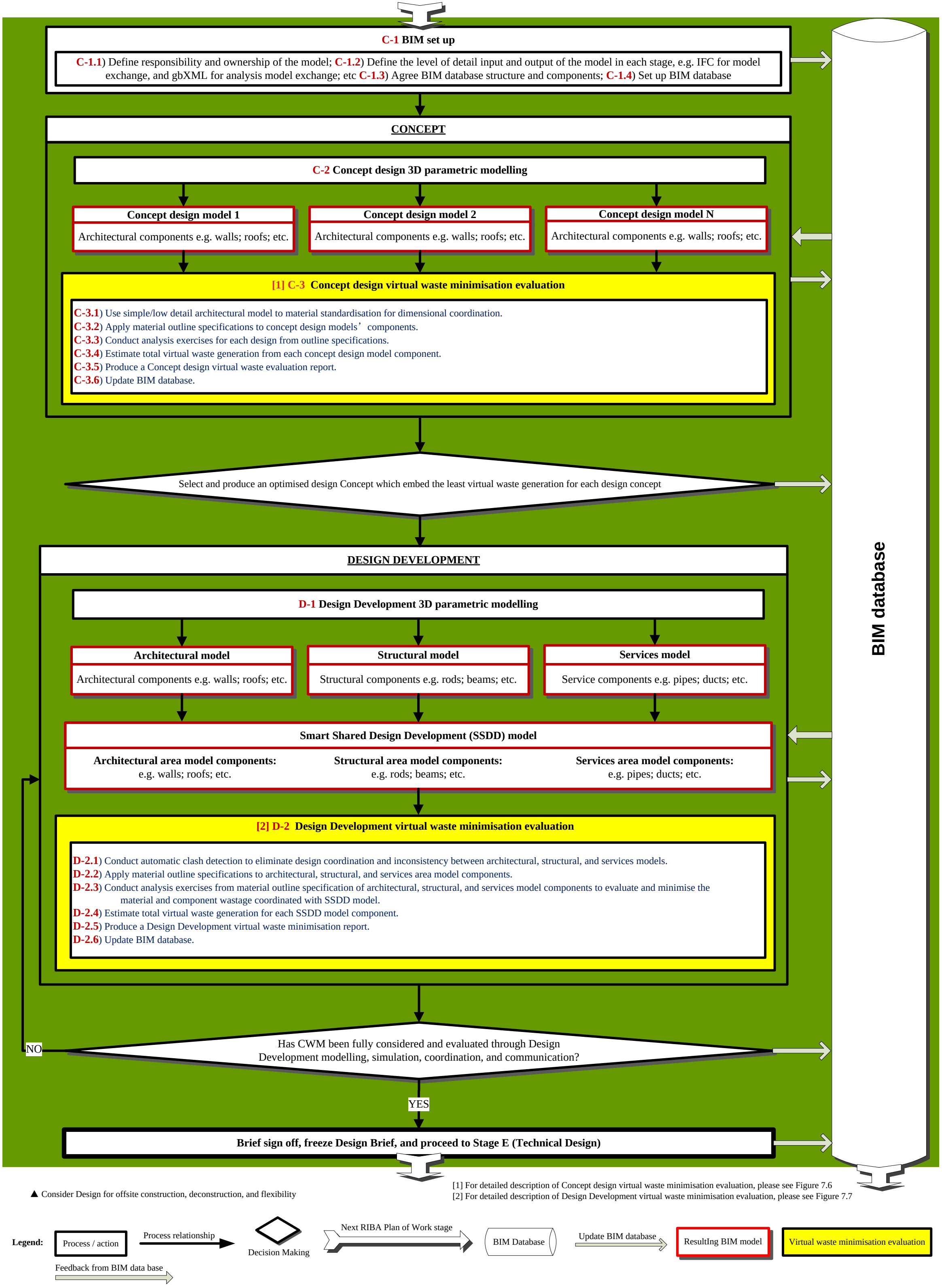
7.2.2.2 Low-level BaW Framework

Each of the coded components within the BaW Low-level Framework contains a detailed process and action of the High-level Framework components, as shown in Figure 7.5.

Concept stage

Coordination and communication can be enhanced by improving interoperability in terms of using BIM, through four activities of the BIM set up, which are presented under CD-1.

Architectural components, such as walls and roofing, are created by implementing 3D parametric modelling techniques (CD-2.1) for each model design concept. Subsequently, each concept design model will be conducted to assess its virtual waste minimisation performance. The BaW Low-level Framework (CD-2.2) specifies six actions related to the evaluation of Concept design virtual waste minimisation, which are discussed in the evaluation process components within section 7.2.2.3.



C-1.1) Define responsibility and ownership of the model; C-1.2) Define the level of detail input and output of the model in each stage, e.g. IFC for model exchange, and gbXML for analysis model exchange; etc C-1.3) Agree BIM database structure and components; C-1.4) Set up BIM database

C-3.1) Use simple/low detail architectural model to material standardisation for dimensional coordination.
C-3.2) Apply material outline specifications to concept design models' components.
C-3.3) Conduct analysis exercises for each design from outline specifications.
C-3.4) Estimate total virtual waste generation from each concept design model component.
C-3.5) Produce a Concept design virtual waste evaluation report.
C-3.6) Update BIM database.

Select and produce an optimised design Concept which embed the least virtual waste generation for each design concept

D-2.1) Conduct automatic clash detection to eliminate design coordination and inconsistency between architectural, structural, and services models.
D-2.2) Apply material outline specifications to architectural, structural, and services area model components.
D-2.3) Conduct analysis exercises from material outline specification of architectural, structural, and services model components to evaluate and minimise the material and component wastage coordinated with SSDD model.
D-2.4) Estimate total virtual waste generation for each SSDD model component.
D-2.5) Produce a Design Development virtual waste minimisation report.
D-2.6) Update BIM database.

Has CWM been fully considered and evaluated through Design Development modelling, simulation, coordination, and communication?

Brief sign off, freeze Design Brief, and proceed to Stage E (Technical Design)

▲ Consider Design for offsite construction, deconstruction, and flexibility

[1] For detailed description of Concept design virtual waste minimisation evaluation, please see Figure 7.6
[2] For detailed description of Design Development virtual waste minimisation evaluation, please see Figure 7.7

Figure 7.5 Low-level BaW Framework

Design Development stage

The structural and services model are based on the architectural model which has been updated from the selected and optimised concept design model. All the model components are constructed through the use of 3D parametric modelling techniques (CD-3.1) which keep changes predictable and coordinated during the design process. The models are assembled as an SSDD model which contains three areas of model components, i.e. architectural, structural and services model component. On the basis of the SSDD model, the BaW Low-level Framework CD-3.2 indicates six actions for the evaluation of virtual waste minimisation during the Design Development stage. These are discussed in the section below.

7.2.2.3 BaW Framework evaluation process components

The specified BIM-aided CWM improvements are presented in Table 7.2 for Concept and Design Development stages' virtual waste minimisation evaluations. These are formulated in the two evaluation process components, as shown in Figure 7.6 and Figure 7.7.

Table 7.2 BIM-associated CWM improvements during Concept and Design Development stages

	Construction waste causes	BIM associated CWM improvements
Concept and Design Development virtual waste minimisation evaluation	Not fully evaluated design leads to design changes during construction period (design decision)	CD-2.2 Concept Design virtual waste minimisation evaluation, CD-3.2 Design Development virtual waste minimisation evaluation
	Ineffective coordination and communication	CD-2.2.5 Produce a Concept Design virtual waste evaluation report, CD-2.2.6 Update BIM database, CD-3.2.1 Conduct automatic clash detection to eliminate design coordination and inconsistency between architectural, structural, and services models, CD-3.2.5) Produce a Design Development virtual waste minimisation report, CD-3.2.6 Update BIM database
	Unclear outline specification of material purpose	CD-2.2.2 Apply material outline specifications to concept design model components, CD-3.2.2 Apply material outline specifications to architectural, structural, and services area model components.
	Lack of attention paid to dimensional coordination	CD-2.2.1 Use simple/low detail architectural model to material standardisation for dimensional coordination.

BIM-enabled qualitative and quantitative analysis significantly enhances the efficiency of architectural, structural and services design simulation for virtual waste minimisation evaluation. It has the ability to reduce multi-design communication, coordination and specification problems to achieve significant CWM improvements.

Concept Design evaluation process components

Architectural components of each concept design model are created through the use of a simple/low-detailed architectural model to material standardisation for dimensional coordination (CD-2.2.1). Based on these architectural components, CD-2.2.2 material outline specifications can be applied to Concept design model components in layers whereby component material thicknesses are identified via five specific steps. This is achieved through applying material outline specifications within each concept design model, followed by two steps of qualitative analysis exercises by means of visualisation (CD-2.2.3) from outline specifications. Such qualitative construction waste analysis exercises are conducted to ensure model components or material outline specifications are reviewed to satisfy minimisation of waste surface areas for the quantitative estimation of total virtual waste generation from each concept design model. Hence, each design concept is substituted into the model for visualisation and quantity take-off to assist the architect working with the total virtual waste analysis as described in CD-2.2.4. Subsequently, a report on Concept design virtual waste evaluation (CD-2.2.5) is produced based on the evaluation results for decision making to select the best Concept design to generate the least virtual waste. Finally, the BIM database is updated for the use of coordination and communication within the project.

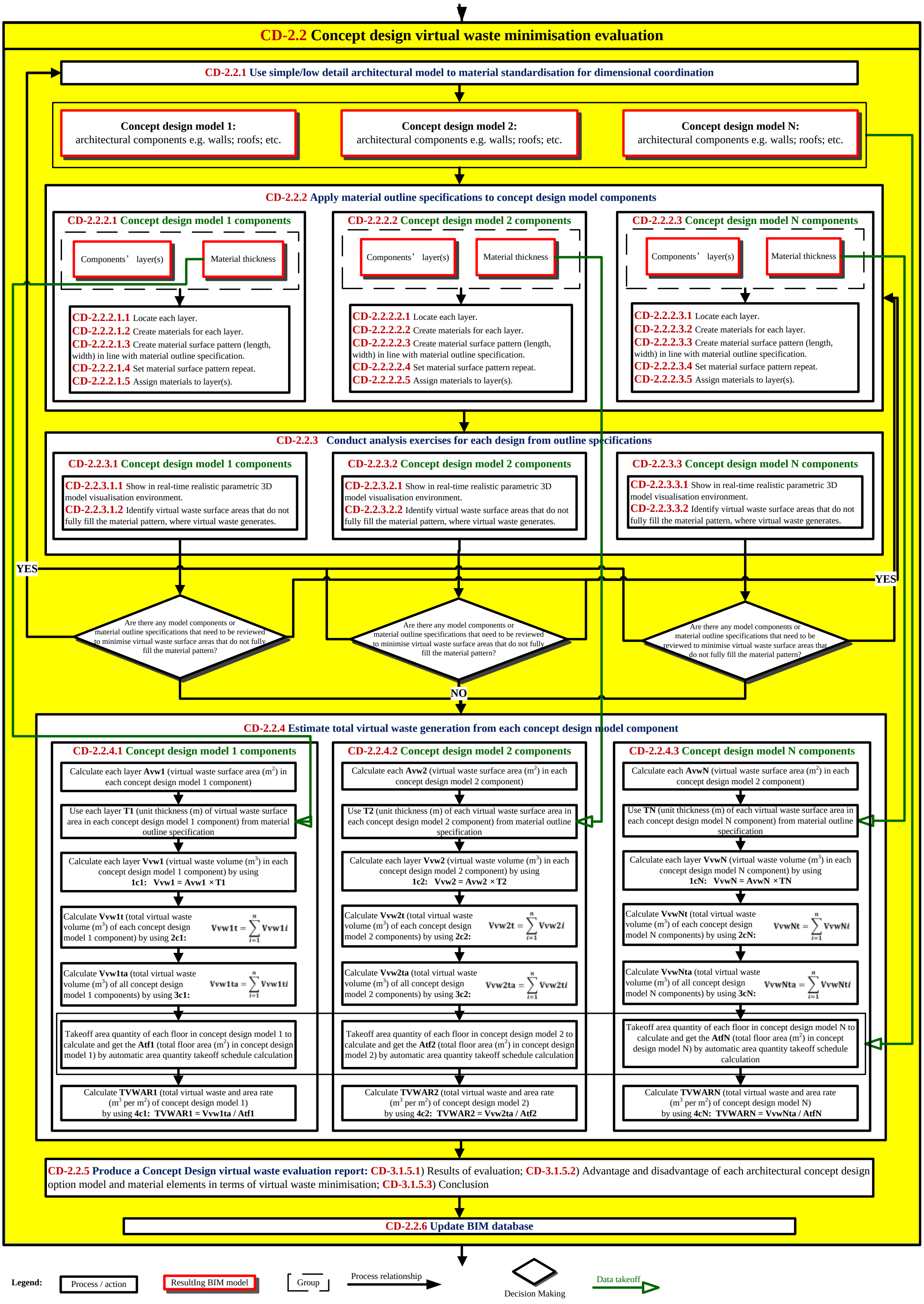
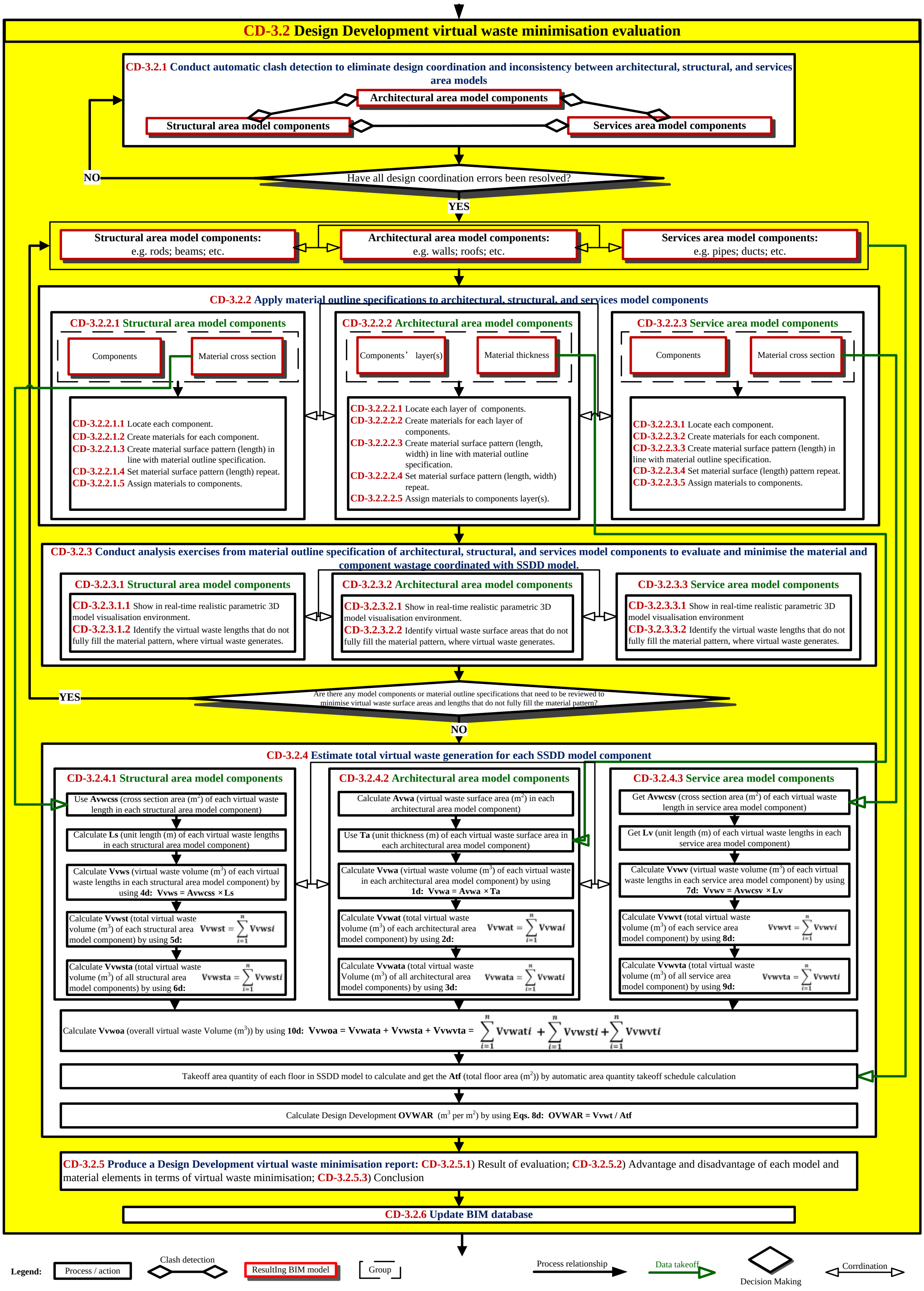


Figure 7.6 Low-level BaW Framework Concept design evaluation process components



CD-3.2 Design Development virtual waste minimisation evaluation

CD-3.2.1 Conduct automatic clash detection to eliminate design coordination and inconsistency between architectural, structural, and services area models

Have all design coordination errors been resolved?

CD-3.2.2 Apply material outline specifications to architectural, structural, and services model components

CD-3.2.2.1 Structural area model components

CD-3.2.2.1.1 Locate each component.
CD-3.2.2.1.2 Create materials for each component.
CD-3.2.2.1.3 Create material surface pattern (length) in line with material outline specification.
CD-3.2.2.1.4 Set material surface pattern (length) repeat.
CD-3.2.2.1.5 Assign materials to components.

CD-3.2.2.2 Architectural area model components

CD-3.2.2.2.1 Locate each layer of components.
CD-3.2.2.2.2 Create materials for each layer of components.
CD-3.2.2.2.3 Create material surface pattern (length, width) in line with material outline specification.
CD-3.2.2.2.4 Set material surface pattern (length, width) repeat.
CD-3.2.2.2.5 Assign materials to components layer(s).

CD-3.2.2.3 Service area model components

CD-3.2.2.3.1 Locate each component.
CD-3.2.2.3.2 Create materials for each component.
CD-3.2.2.3.3 Create material surface pattern (length) in line with material outline specification.
CD-3.2.2.3.4 Set material surface (length) pattern repeat.
CD-3.2.2.3.5 Assign materials to components.

CD-3.2.3 Conduct analysis exercises from material outline specification of architectural, structural, and services model components to evaluate and minimise the material and component wastage coordinated with SSDD model.

CD-3.2.3.1 Structural area model components

CD-3.2.3.1.1 Show in real-time realistic parametric 3D model visualisation environment.
CD-3.2.3.1.2 Identify the virtual waste lengths that do not fully fill the material pattern, where virtual waste generates.

CD-3.2.3.2 Architectural area model components

CD-3.2.3.2.1 Show in real-time realistic parametric 3D model visualisation environment.
CD-3.2.3.2.2 Identify virtual waste surface areas that do not fully fill the material pattern, where virtual waste generates.

CD-3.2.3.3 Service area model components

CD-3.2.3.3.1 Show in real-time realistic parametric 3D model visualisation environment
CD-3.2.3.3.2 Identify the virtual waste lengths that do not fully fill the material pattern, where virtual waste generates.

Are there any model components or material outline specifications that need to be reviewed to minimise virtual waste surface areas and lengths that do not fully fill the material pattern?

CD-3.2.4 Estimate total virtual waste generation for each SSDD model component

CD-3.2.4.1 Structural area model components

Use **Avwcss** (cross section area (m^2) of each virtual waste length in each structural area model component)

Calculate **Ls** (unit length (m) of each virtual waste lengths in each structural area model component)

Calculate **Vvws** (virtual waste volume (m^3) of each virtual waste lengths in each structural area model component) by using **4d:** $\mathbf{Vvws = Avwcss \times Ls}$

Calculate **Vvwst** (total virtual waste volume (m^3) of each structural area model component) by using **5d:** $Vvwst = \sum_{i=1}^{n} Vvwsi$

Calculate **Vvwsta** (total virtual waste volume (m^3) of all structural area model components) by using **6d:** $Vvwsta = \sum_{i=1}^{n} Vvwsti$

CD-3.2.4.2 Architectural area model components

Calculate **Avwa** (virtual waste surface area (m^2) in each architectural area model component)

Use **Ta** (unit thickness (m) of each virtual waste surface area in each architectural area model component)

Calculate **Vvwa** (virtual waste volume (m^3) of each virtual waste in each architectural area model component) by using **1d:** $\mathbf{Vvwa = Avwa \times Ta}$

Calculate **Vvwat** (total virtual waste volume (m^3) of each architectural area model component) by using **2d:** $Vvwat = \sum_{i=1}^{n} Vvwai$

Calculate **Vvwata** (total virtual waste Volume (m^3) of all architectural area model components) by using **3d:** $Vvwata = \sum_{i=1}^{n} Vvwati$

CD-3.2.4.3 Service area model components

Get **Avwcsv** (cross section area (m^2) of each virtual waste length in service area model component)

Get **Lv** (unit length (m) of each virtual waste lengths in each service area model component)

Calculate **Vvwv** (virtual waste volume (m^3) of each virtual waste lengths in each service area model component) by using **7d:** $\mathbf{Vvwv = Avwcsv \times Lv}$

Calculate **Vvwvt** (total virtual waste volume (m^3) of each service area model component) by using **8d:** $Vvwvt = \sum_{i=1}^{n} Vvwvi$

Calculate **Vvwvta** (total virtual waste volume (m^3) of all service area model component) by using **9d:** $Vvwvta = \sum_{i=1}^{n} Vvwvti$

Calculate **Vvwoa** (overall virtual waste Volume (m^3)) by using **10d:** $\mathbf{Vvwoa = Vvwata + Vvwsta + Vvwvta} = \sum_{i=1}^{n} Vvwati + \sum_{i=1}^{n} Vvwsti + \sum_{i=1}^{n} Vvwvti$

Takeoff area quantity of each floor in SSDD model to calculate and get the **Atf** (total floor area (m^2)) by automatic area quantity takeoff schedule calculation

Calculate Design Development **OVWAR** (m^3 per m^2) by using **Eqs. 8d:** $\mathbf{OVWAR = Vvwt / Atf}$

CD-3.2.5 Produce a Design Development virtual waste minimisation report: CD-3.2.5.1) Result of evaluation; CD-3.2.5.2) Advantage and disadvantage of each model and material elements in terms of virtual waste minimisation; CD-3.2.5.3) Conclusion

CD-3.2.6 Update BIM database

Figure 7.7 Low-level BaW Framework Design Development evaluation process components

Design Development evaluation process components

In terms of addressing design coordination errors, the automatic clash detection (CD-3.2.1) should be conducted to inspect design coordination and inconsistency between architectural, structural and service area models. Thus, a fully checked and coordinated architectural, structural, and service model component is established to apply material outline specifications (CD-3.2.2). This will clarify the use of materials through the specified five steps relating to individual model components of architectural, structural and service area models. These five steps are designed to:

- locate each layer of components (CD-3.2.2.2.1);
- create materials for each layer of components (CD-3.2.2.2.2);
- create the material surface pattern (length, width) in line with material outline specification (CD-3.2.2.2.3);
- set the material surface pattern (length, width) repeat (CD-3.2.2.2.4); and
- assign materials to the component layer(s) (CD-3.2.2.2.5).

As shown in CD-3.2.3, the virtual waste analysis is based on the applied outline material specification of the SSDD model and can be performed by visual inspection of material and component wastage in the 3D virtual environment through two identified steps. The two action steps are used for the architectural area model components by showing the realistic parametric 3D model visualisation environment (CD-3.2.3.2.1) in real-time. Thereafter, the virtual waste surface areas that do not fully fill the material pattern where virtual waste generates, can be identified (CD-3.2.3.2.2).

All the SSDD model components with material outline specifications should be examined and complied with estimating total virtual waste generation for each SSDD model component (CD-3.2.4). This will inform the quantitative estimation of total virtual waste generation.

The detailed process of estimating the total virtual waste generation for the SSDD model component is presented in CD-3.2.4 in Figure 7.7. Subsequently, a report on Design Development virtual waste evaluation can be produced based on the results of the estimated total virtual waste generation taken into consideration. Thereafter, the BIM database will be updated for successful project coordination and communication. This facilitates the decision making as to whether the Design Development stage is efficient in terms of the CWM target set in AB-1.2, Figure 7.4. The Design Development processes should be reviewed if the waste minimisation performance fails to meet the CWM target.

7.3. BaW Framework validation

7.3.1 BaW Framework validation process

The aim of the BaW Framework validation was to refine and examine the appropriateness of the BaW Framework and identify its implementation strategy. The BaW Framework validation process contained a validation questionnaire and followed by validation interviews.

As discussed in Chapter 3, section 3.5.4.2, six respondents from the questionnaire and interviews were selected and involved in the BaW Framework validation process (see Table 3.11). As shown in Table 7.3, the vast majority of interviewees (five out of six) had experienced more than 15 years in the field of architectural design. In addition, all interviewees had been involved in sustainable building design for more than seven years and had experience in the use of BIM ranging from five to 12 years.

Table 7.3 BaW Framework validation: profile of respondents

Interviewee ID	Experience as an architect (years)	BIM experience (years)	Sustainable building design experience (years)	Project portfolio
AV1	15	5	10	Private residential housing, education building, commercial office building
AV2	11	7	11	Stadium, arena, sports facility
AV3	26	5	8	Education building,
AV4	16	12	7	Commercial office building, public building
AV5	35	5	20	Education building, health care, public housing
AV6	16	11	13	Retail, education building, industrial building

7.3.2 BaW Framework validation results

Participants of both the validation questionnaire and interviews were requested to comment on each level of the BaW Framework across the following aspects:

- Clarity of structure.
- Appropriateness of content.
- Clarity of flow.

7.3.2.1 Results of BaW Framework validation questionnaire

The respondents were asked to rate their agreement from 1 (strongly disagree) to 4 (strongly agree) on the clarity of each level within the BaW Framework structure and flow and appropriateness of the content. The results are shown in Table 7.4. All respondents agreed or strongly agreed on the clarity of the BaW Framework in terms of structure, content and flow.

Table 7.4 Mean value of clarity and appropriateness of BaW Framework

Aspects	High-level	Low-level	Evaluation process components
Clarity of the structure	3.83	3.83	3.50
Appropriateness of content	3.33	3.33	3.00
Clarity of flow	3.67	3.67	3.17

7.3.2.2 Results of BaW Framework validation interviews

Based on the validation questionnaire answers, the interviewees were asked to give detailed qualitative insights into the BaW Framework in terms of clarity of structure, appropriateness of content, flow of actions, and suggestions.

Clarity of BaW Framework structure

All the interviewees concurred that the High-level BaW Framework had a clear structure based on each building design stage. For example, interviewee V4 stated that "*it is clear what the Framework tries to do. The architect is able to analyse and optimise design at various design stages*". In addition, all interviewees indicated that the Low-level BaW Framework had a clear structure for the design process, helping the user to understand the Framework. Interviewee V5 stressed that "*the Framework has a clear structure that enables the architect to understand and manage BIM-aided CWM design process by checking each step of the BIM-embedded design process*". Furthermore, nearly all interviewees (five out of six) strongly emphasised that the two evaluation process components had a clear structure, providing the user with a thorough understanding of the process, which facilitates the optimisation, analysis and calculation for minimising virtual waste are embedded.

Appropriateness of BaW Framework content

Nearly all interviewees (five out of six) indicated that the High-level BaW Framework presented familiar BIM content. They also stated that the Low-level BaW Framework contained appropriate steps for the CWM process through the use of BIM. They agreed that a diagram with appropriate complexity in sufficient content assists the architect to understand what has to be done to reduce construction waste during design, without any confusion. Interestingly, although two thirds of the interviewees affirmed that two evaluation process components present a BIM user-friendly content that is familiar to architects for evaluating construction waste generation, the complex content of virtual waste evaluation and calculation methods could be a challenge to architects who have less knowledge of advanced mathematics. As such, they suggested that the virtual waste evaluation and calculation parts should be removed and made as appendices to the BaW Framework. They also added that future development of the BIM application for those calculations could overcome the challenge.

Clarity of BaW Framework flow

All interviewees concurred that the flow of the High-level BaW Framework is clearly and logically outlined throughout the building design stages (RIBA Work of Plan Stages Appraisal to Production Information). They also pointed out that the flow of the Low-level BaW Framework is clearly illustrated in terms of the process for BIM-associated CWM. They all agreed that the flow of two evaluation process components are clear for the architect to follow through the proposed steps and actions.

The next section outlines suggestions proposed by interviewees for refining the BaW Framework and presents subsequent actions to refine and finalise the Framework.

7.3.3 Recommendations for improving BaW Framework

The interviewees recommended a number of helpful suggestions to enhance the BaW Framework.

Suggested improvements for the High-level BaW Framework

The improvements suggested by interviewees for the High-level BaW Framework and the actions taken for modifications or/and refinements are presented in Table 7.5 and discussed in the section below. The validated High-level BaW Framework is presented in Figure 6.8.

Table 7.5 Suggested improvements for the High-level BaW Framework and subsequent actions

No.	Interviewee	Issues	Suggested improvements	Actions (modifications/ refinements)
1	V3 and V5	Introduction of facility management. It will be the next layer of reducing waste. It also comes out of the new RIBA Plan of Work 2013	Involve facility management consultant throughout all stages	Inserted a new AB-2 (Figure 7.8): '**Involve facility management consultant throughout all stages**'
2	V5	Possibility of adding waste generation severity ranking, including recyclable and non-recyclable waste as the waste target (Ref AB-1.2 in Figure 7.4)	Add waste generation severity ranking, quantity surveyor could be involved in the process	Inserted a new AB-3 (Figure 7.8): '**Involve quantity surveyor throughout all stages**'
3	V6	It is better if the CWM target should be a percentage of recycled waste (Ref AB-1.2 in Figure 7.4)	Set CWM target as a waste percentage	Re-worded AB-5 (Figure 7.8): '**Set CWM target: average m^3 of waste per m^2 of floor area, considering the percentage of waste reduction to landfill**'
4	V1 and V5	It is not possible to employ a contractor at the start of the Briefing stage (Ref AB-1.1 in Figure 7.4)	Involve a construction advisor at Briefing stage	Re-wordedAB-4 (Figure 7.8): '**Involve a construction advisor**'
5	V5	Virtual waste should be considered at Briefing stage (Ref AB-1.6 in Figure 7.4)	The simplified virtual waste assessment could build on the list of substances required for building from the client such as Considerate Constructors Scheme (CCS) document.	Re-worded AB-9 (Figure 7.8): '**Generate simple mass model to capture client's sustainability needs, where a virtual waste assessment could be considered**'
6	V6	Inappropriateness of 'Brief sign off, freeze Design Brief, and proceed to Stage E (Technical Design)' and 'Authorising the Production Information and proceed to Stage G (Tender Documentation)' (Ref in Figure 7.4)	It should be 'Brief and stage sign off' and 'Authorising and stage sign off'	No modification/refinements, according to the RIBA Plan of Work.

The six suggested improvements to the High-level BaW Framework are as follows:

(1) & (2) Faniran and Caban (1998) indicated that all professionals involved in the building design and construction process (e.g. quantity surveyor and facility management consultants) contribute to CWM during design. Material consumption in

certain construction activities or processes are estimated and measured by the quantity surveyor throughout design stages, whereby the actual amounts of used materials are near or below the exact amounts during construction (Chen *et al*., 2002; Tam and Tam, 2008). Moreover, the newly published 'Designing for material efficiency in building projects BS 8895-1:2013 Part1' (2013) suggests that individuals involved in the decision-making process affect material efficiency and the reduction of construction waste. Furthermore, the latest Government Soft Landings (GSL) Facilities Management (FM) (2013) required that building design should incorporate input and maintenance requirements from the end user into the design of assets through GSL. This should be achieved throughout all building lifecycle stages to meet the environmental performance target such as energy, water, waste and carbon dioxide emissions. Therefore, it is important that the involvement of the facility management consultant and quality surveyor (AB-2 and AB-3 in Figure 7.8) throughout all stages, are stated at the start of the Briefing stage.

(3) In terms of aligning the WRAP (2013) quantification of waste-target setting, 'the percentage of waste reduction to landfill' has been added CWM target setting in AB-5 (Figure 7.8) (Set CWM target: average m^3 of waste per m^2 of floor area, considering the percentage of waste reduction to landfill).

(4) According to the RIBA members' online survey 2012 (RIBA, 2013), the traditional contractual arrangement remains the most prevalent form of procurement, being used by 86% of participating architectural practices within the UK. It reveals that a contractor is unlikely to be employed or involved at the start of a building design project and that most architectural practices are most likely working on the traditional procurement route. Hence, as shown in the re-worded AB-4 (Figure 7.8), architects could gain suggestions for construction waste reduction during design from the involvement of a construction advisor.

(5) The UK Department of Finance and Personnel (DFP) (2013), associated with the Sustainable Construction Group, provides the 'Considerate Constructors' Scheme' for 'The Government Construction Client Group's Sustainability Action Plan'. It requires that client sustainability needs through CWM efforts should be considered to select and use local resources wherever possible, to pay attention to waste management, and should be encouraged to recycle and re-use recycled materials. Additionally, the involvement of building professionals (e.g. quantity surveyor, facility management consultant and construction advisor), enables the knowledge transfer of CWM practices

gathered from previous projects. This facilitates a brief of virtual waste assessment based on the simple mass model of the building and its surrounding environment and to capture client sustainability needs in terms of CWM. Thus, AB-9 (Figure 7.8) can be re-worded as 'Generate a simple mass model to capture sustainability needs of client, whereby a virtual waste assessment can be considered'.

(6) Interviewee V6 argued that 'Brief sign off, freeze Design Brief, and proceed to Stage E (Technical Design)' and 'Authorising the Production Information and proceed to Stage G (Tender Documentation)' in Figure 7.4 were inappropriate in confirming the end of stages because the design had never been frozen. He suggested improvements to include 'Brief and stage sign off' and 'Authorising and stage sign off' instead. However, as underlined in the RIBA Plan of Work: Multi-Disciplinary Services (2008) the Brief and design development should be signed off and frozen at the end of Design Development stage, whilst technical design should be frozen at the end of Technical Design stage. Moreover, as mentioned in section 2.2.3.1, waste could be caused by on-site design changes being partly influenced by not freezing design brief at the end of Design Development stage. Therefore, there no action was undertaken to modify or refine the content.

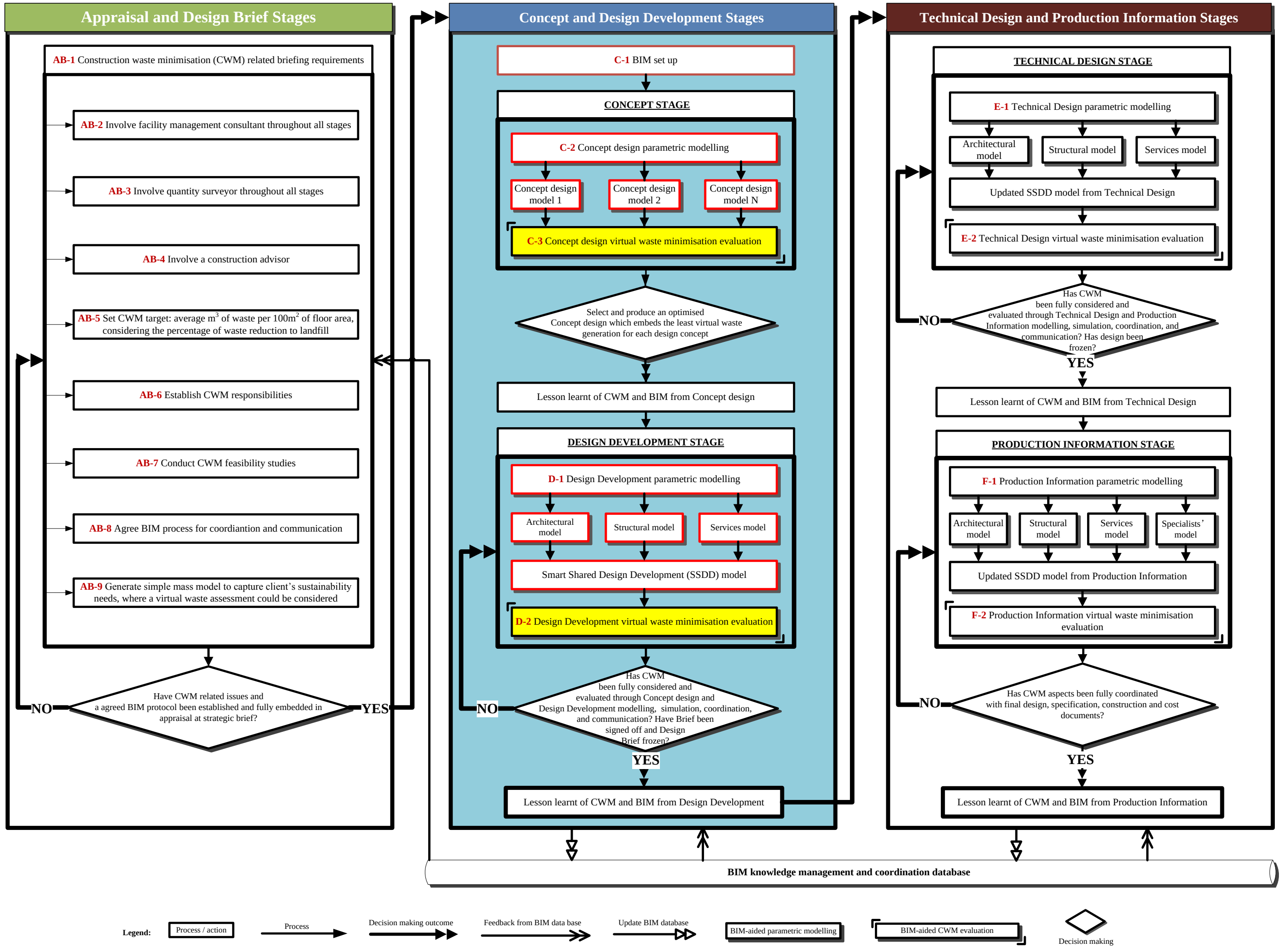


Figure 7.8 Validated High-level BaW Framework

]

Suggested improvements for the Low-level BaW Framework

Suggested improvements by interviewees for the Low-level BaW Framework and actions taken to modify/refine them are presented in Table 7.6. Only one issue was raised by two-thirds of interviewees regarding lessons learned through feedback from the BIM database to each building design stage. The communication flow between project members at company level, design team level and project level, is enhanced and obtained from feedback associated with the BIM database (Arayici *et al.*, 2011). As facilitated by the BIM database, the modelling and simulation process creates a virtual feedback loop whereby design and coordination challenges can be identified before commitment of the field process, in which a final building model is proposed and analysis of CWM optimisation is performed (Porwal and Hewage, 2012). Hence, feedback arrows from the BIM database to each building design stage are inserted into the validated Low-level BaW Framework, as shown in Figure 7.9.

Table 7.6 Suggested improvements for the Low-level BaW Framework and subsequent actions

Interviewee	Issues	Suggested improvements	Actions (modifications/ refinements)
V2, V3, V5 and V6	There should be feedback from BIM database to enable learning from other stages and projects (Ref in Figure 7.5)	Add feedback from BIM database to each stage	New feedback arrows were added to link BIM database to each design (Figure 7.9).

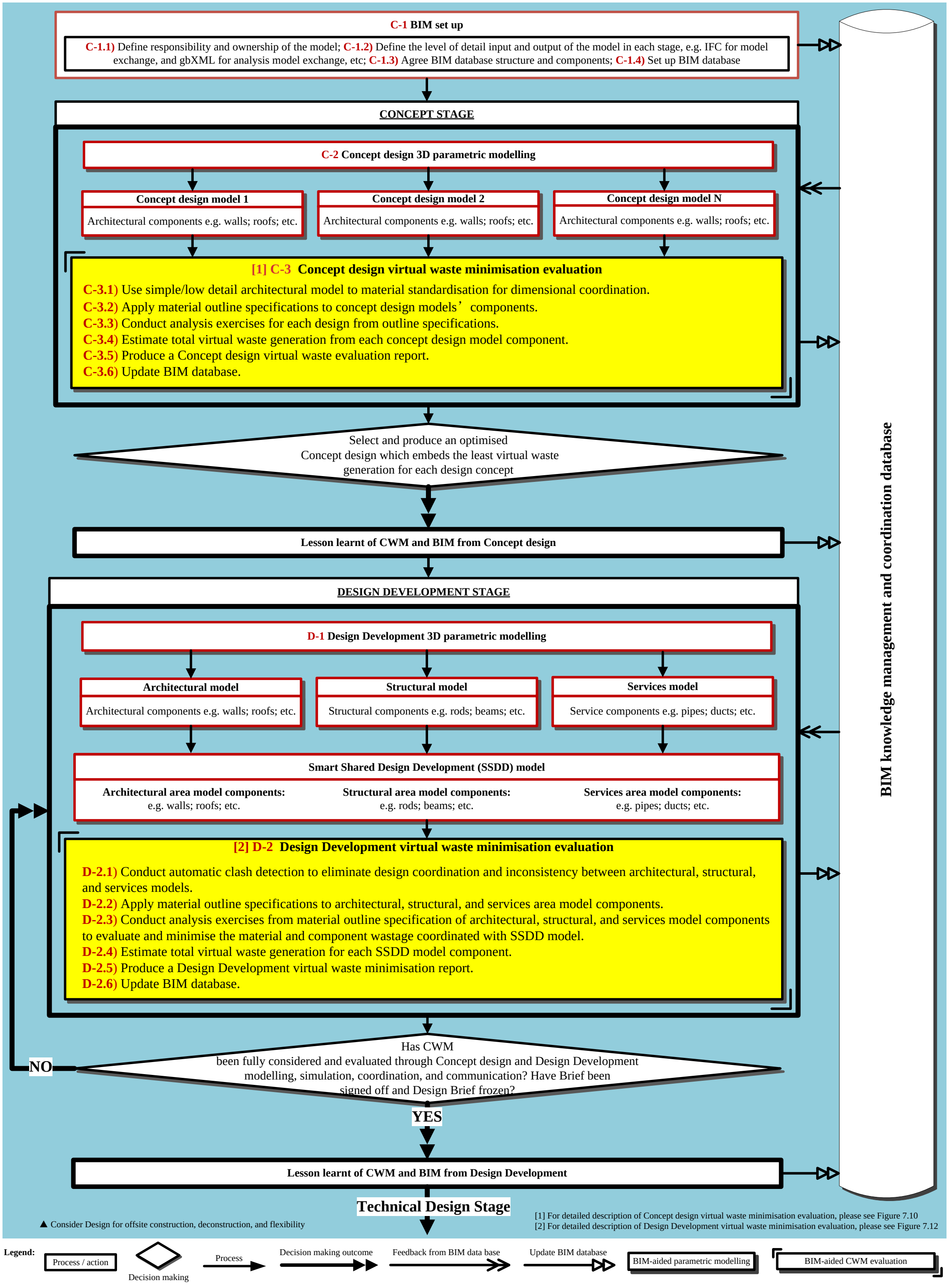


Figure 7.9 Validated Low-level BaW Framework

Suggested improvements to two Low-level BaW Framework evaluation process components

Table 7.7 presents the interviewees' proposed improvements for the two Low-level BaW Framework evaluation process components. Most of the suggested improvements relate to visual presentation issues such as merging duplicate activities and simplifying them. Interestingly, Interviewee V6 argued that the two Low-level BaW Framework evaluation process components contain efficient detailed information for architects to use, and suggested that the two evaluation process components could be attached as appendices to the Low-level Framework. The refined two evaluation process components for the Low-level BaW Framework are presented in Figure 7.10, 7.11, 7.12 and 7.13.

Table 7.7 Suggested improvements for the two Low-level BaW Framework evaluation process components and subsequent actions

Interviewee	Issues	Suggested improvements	Actions (modifications/ refinements)
V3 and V6	Duplication of activities (Ref CD-2.2.2.1, CD-2.2.2.2, and CD-2.2.2.3 in Figure 7.6)	Merge them as one process	● Merge as C-3.2.1 and C-3.3.1 (Figure 7.10) ● Re-worded C-3.2.1 and C-3.3.1 (Figure 7.10): '**Concept design models' components**'
V1, V2, V3, V5 and V6	Architects are usually not keen to prepare formulas and calculations (Ref CD-2.2.4 in Figure 6.6 and Ref CD-3.2.4 in Figure 7.7)	Simplify 'estimate total virtual waste generation from each concept design model component' (CD-2.2.4) and 'Estimate total virtual waste generation for each SSDD model component' (CD-3.2.4) for better presentation of the whole process instead of formula and calculation process	Extract the process of 'C-3.4 Estimate total virtual waste generation from each concept design model component' (Figure 6.10) and 'D-2.4 Estimate total virtual waste generation for each SSDD model component' as appendices for the virtual waste generation calculation (Figure 7.12).
V4	The explanation of formula should not be written using mathematics phraseology (Ref CD-2.2.4 in Figure 6.6 and Ref CD-3.2.4 in Figure 7.7)	Re-define terms for elements in the formula by re-wording them for architects to more easily understand	● * Re-worded C-3.4.1 (Figure 7.10) ● Simplified C-3.4.2 (Figure 7.10) ● Simplified C-3.4.3 (Figure 7.10) ● * Re-worded D-2.4.1 (Figure 7.12) ● * Re-worded D-2.4.2 (Figure 7.12) ● * Re-worded D-2.4.3 (Figure 7.12) ● * Re-worded D-2.4 (Figure 7.12)
V4	The number of formulas such as 4d,5d, and 6d could be misleading if used with BIM terminology 4D, 5D and 6D (Ref CD-3.2.4 in Figure 7.7)	Erase formula numbers: 1d,2d,3d,4d,5d,6d,7d	Removed all formula numbers
V6	Evaluation-level is a detailed Low-level. The Low-level is good enough for use. Therefore, the Evaluation-level will no longer be needed.	Remove Evaluation-level	No modifications/refinements (two evaluation process components of the pre-validation Low-level BAC Framework provide a practical BIM roadmap to minimise waste)

*** Re-worded C-3.4.1:**

- Calculate **virtual waste CA1: (Concept) Area 1 (surface area (m^2) of each virtual waste in each concept design model 1 component)**
- Use **virtual waste (Concept) CT1** (unit thickness (m) of each virtual waste surface area in each concept design model 1 component) from material outline specification (data takeoff from C-3.2.1)
- Calculate **virtual waste CV1: (Concept) Volume 1** (virtual waste volume (m^3) of each virtual waste in each concept design model 1 component) by using **CV1 = CA1 × CT1**
- Calculate **(Concept) VC1** (total virtual waste volume (m^3) of each concept design model 1 component) by using

$$\mathbf{VC1} = \sum_{i=1}^{n} \mathbf{CV1}i$$

- Calculate **(Concept) SVC1: Sum of all concept design model 1 virtual waste volume (m^3)** (all concept design model 1 components) by using

$$\mathbf{SVC1} = \sum_{i=1}^{n} \mathbf{VC1}i$$

- Takeoff area quantity of each floor in concept design model 1 to calculate and get the **(Concept) CAf1** (total floor area (m^2) in concept design model 1) by automatic area quantity takeoff schedule calculation (data takeoff from C-3.1)
- Calculate **(Concept) Area Rate of Virtual Waste (CRvw) (m^3 per m^2)** of concept design model 1 by using **CRvw1 = SVC1 / CAf1**

*** Re-worded D-2.4.1:**

- Use **virtual waste DSA: (Design Development) Structural Area** (cross section area (m^2) of each virtual waste length in each structural area model component) (data takeoff from D-2.2.1)
- Calculate **virtual waste (Design Development) DLs** (unit length (m) of each virtual waste lengths in each structural area model component)
- Calculate **virtual waste DSV: (Design Development) Structural Volume** (virtual waste volume (m^3) of each virtual waste lengths in each structural area model component) By using **DSV= DSA × DLs**
- Calculate **(Design Development) VDS** (total virtual waste volume (m^3) of each structural area model component) by using

$$\mathbf{VDS} = \sum_{i=1}^{n} \mathbf{DSV}i$$

- Calculate **(Design Development) Sum of all structural virtual waste volume (m^3)** (all structural area model components) by using

$$\sum_{i=1}^{n} \mathbf{VDS}i$$

*** Re-worded D-2.4.2:**

- Calculate **virtual waste DAA: (Design Development) Architectural Area** (surface area (m^2) of each virtual waste in each architectural area model component)
- Use **virtual waste (Design Development) DTa** (unit thickness (m) of each virtual waste surface area in each architectural area model component) (data takeoff from D-2.2.2)
- Calculate **virtual waste DAV: (Design Development) Architectural Volume** (virtual waste volume (m^3) of each virtual waste in each architectural area model component) by using **DAV = DAA × DTa**
- Calculate **(Design Development) VDA** (total virtual waste volume (m^3) of each architectural area model component) by using

$$\mathbf{VDA} = \sum_{i=1}^{n} \mathbf{DAV}i$$

- Calculate **(Design Development) Sum of all architectural virtual waste volume (m^3)** (all architectural area model components) by using

$$\sum_{i=1}^{n} \mathbf{VDA}i$$

<u>* Re-worded D-2.4.3:</u>

- Get **virtual waste DBsA: (Design Development) Building Service Area** (cross section area (m^2) of each virtual waste length in service area model component) (data takeoff from D-2.2.3)
- Get **virtual waste (Design Development) DLv** (unit length (m) of each virtual waste lengths in each building service area model component)
- Calculate **virtual waste DBsV: (Design Development) Building Service Volume** (virtual waste volume (m^3) of each virtual waste lengths in each building service area model component) by using **DBsV = DBsA × DLv**

- Calculate **(Design Development) VDBs** (total virtual waste volume (m^3) of each building service area model component) by using

$$\mathbf{VDB}s = \sum_{i=1}^{n} \mathbf{DBsV}i$$

- Calculate **(Design Development) Sum of all building service virtual waste volume (m^3)** (all Building service area model components) by using

$$\sum_{i=1}^{n} \mathbf{VDB}si$$

<u>* Re-worded D-2.4:</u>

- Calculate **(Design Development) Volume of overall virtual waste (m^3) = Sum of all architectural virtual waste volume (m^3) + Sum of all structural virtual waste volume (m^3) + Sum of all building service virtual waste volume (m^3)** i.e.

$$\textbf{DVOVW ((Design Development) Volume of overall virtual waste)}\ (m^3) = \sum_{i=1}^{n} \mathbf{VDA}i + \sum_{i=1}^{n} \mathbf{VDS}i + \sum_{i=1}^{n} \mathbf{VDB}si$$

- Takeoff area quantity of each floor in SSDD model to calculate and get the **(Stage D) DAf (total floor Area (m^2))** by automatic area quantity takeoff schedule calculation (data takeoff from D-2.1)
- Calculate **Design Development Area Rate of Virtual Waste (DRvw) (m^3 per m^2): DVOVW (m^3) / DAf (m^2)**

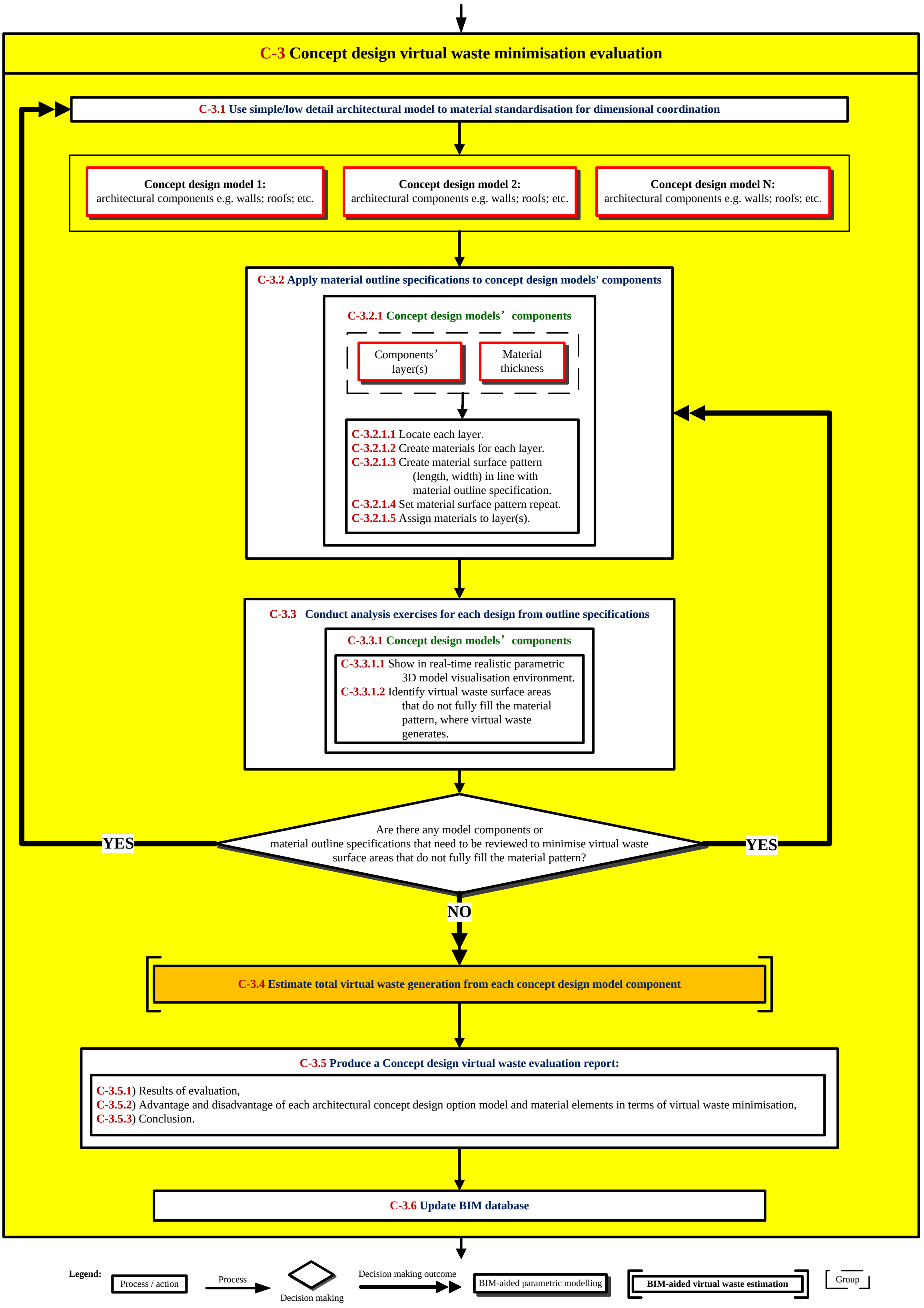


Figure 7.10 Validated Low-level BaW Framework Concept design evaluation process component

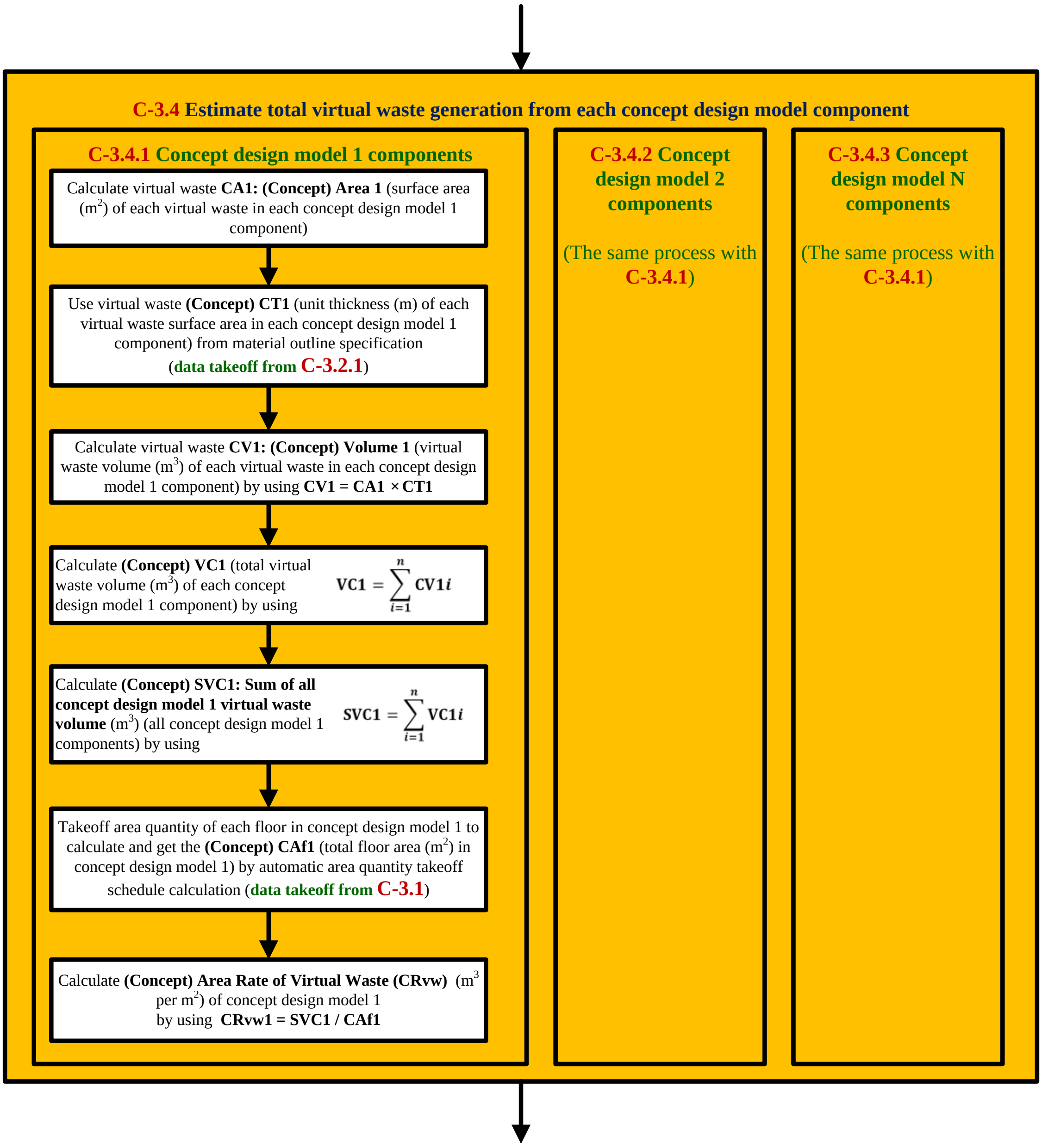


Figure 7.11 Appendix of the validated Low-level BaW Framework Concept design evaluation process component

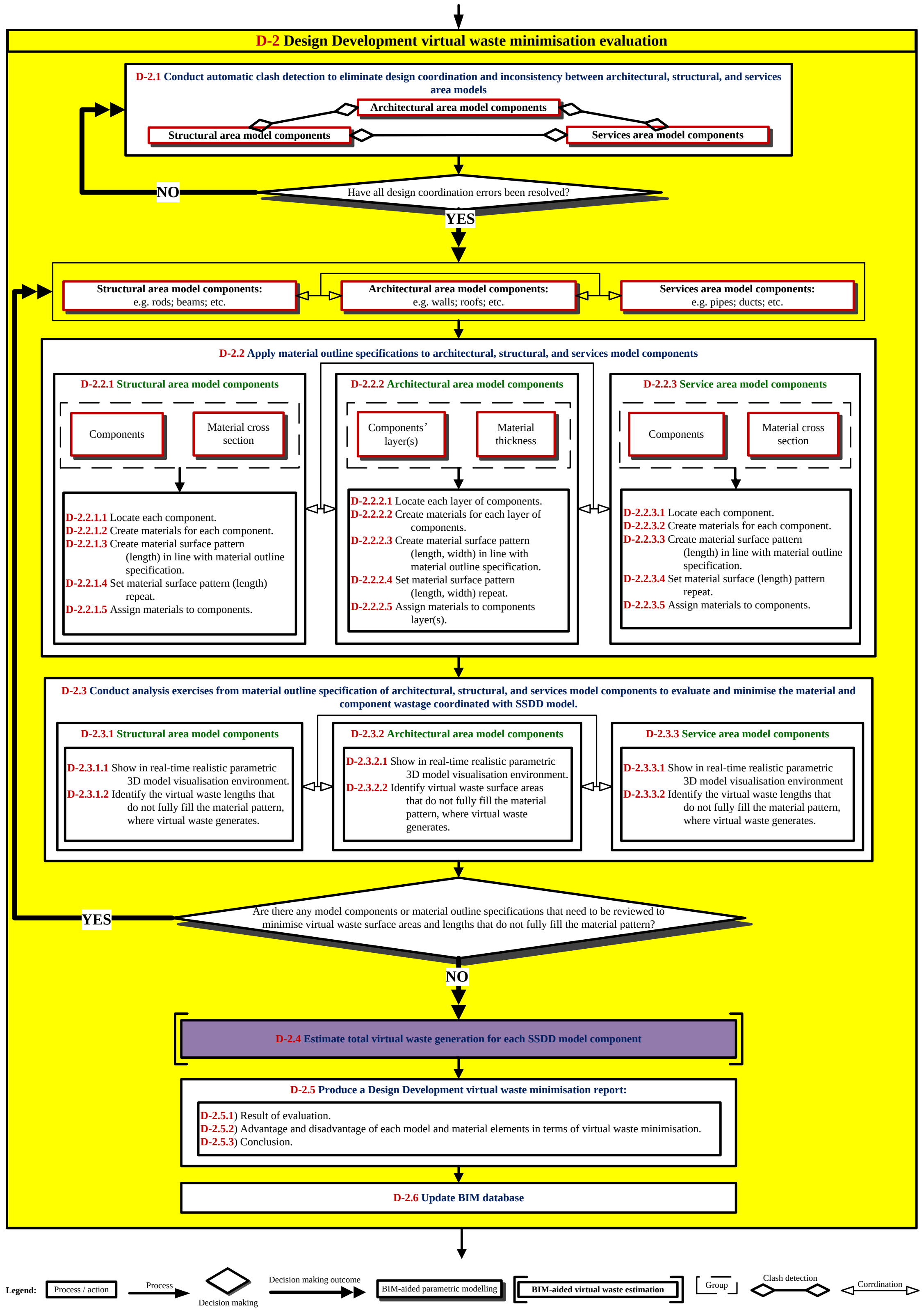


Figure 7.12 Validated Low-level BaW Framework Design Development evaluation process component

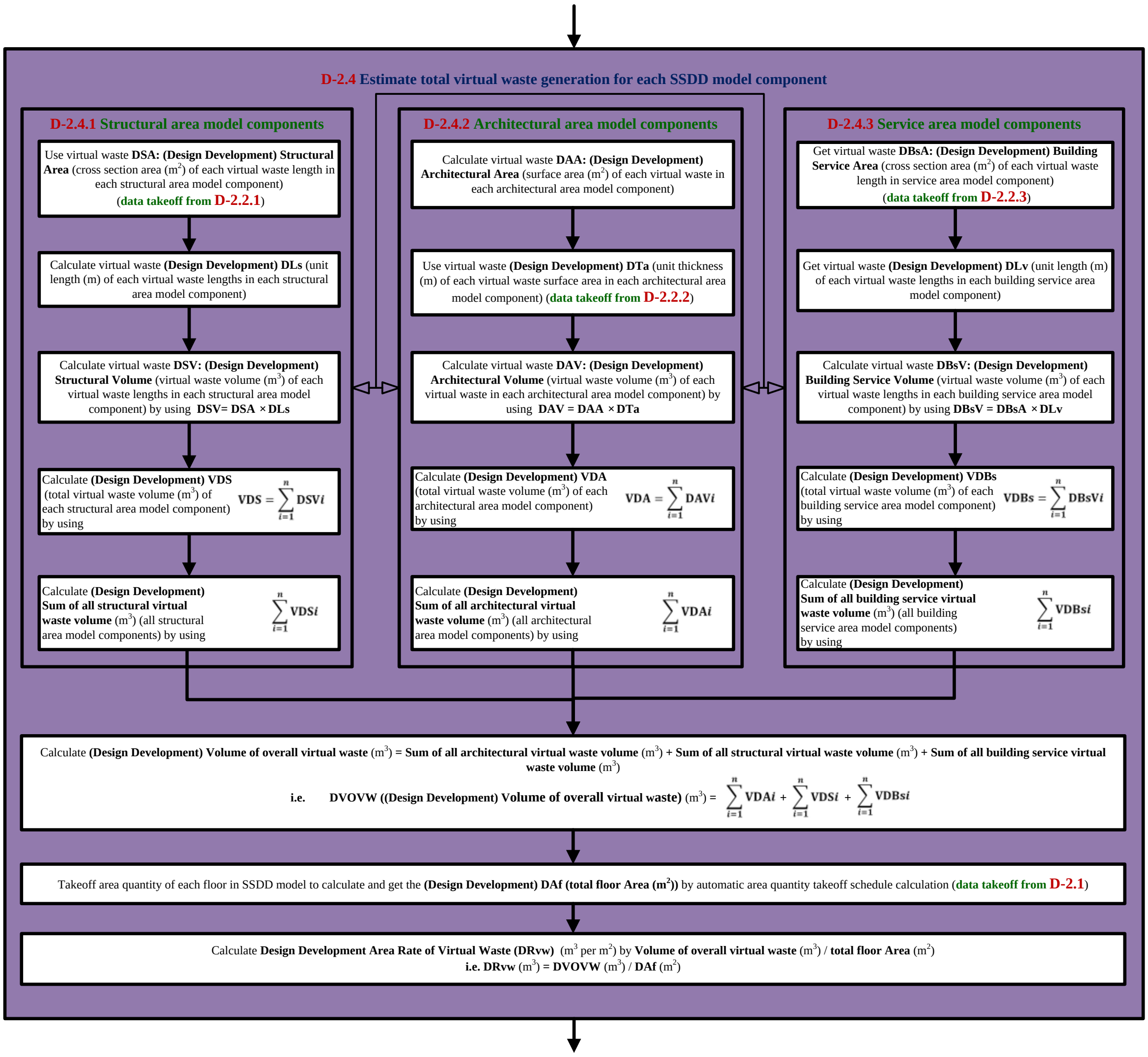


Figure 7.13 Appendix of the validated Low-level BaW Framework Design Development evaluation process component

7.3.4 BaW Framework implementation strategy

A potential strategy for the BaW Framework implementation was investigated during the validation questionnaire and interviews. The following aspects were explored:

- Suitable implementation strategy (i.e. appropriate or relevant protocols and standards).
- Implementation responsibility.
- Procurement and building type suitability.
- Framework post-improvement implementation.
- Potential for Framework implementation in the building design industry.

Potential of the BaW Framework implementation method

Participants of the validation questionnaire were asked to select an appropriate method from a list of existing protocols/standards to implement the BaW Framework within their organisations and to specify any other suitable methods. These protocols/standards were related to daily architectural practice, three (i.e. BIM overlay to the RIBA Outline Plan of Work, AEC (UK) BIM protocol, and CPI (Coordinated Project Information) system) of those were selected from UK's BIM delivery B/555 Roadmap (BSi, 2012) (Design, Construction & Operational Data & Process Management for the Built Environment) and one (Green overlay to the RIBA Outline Plan of Work) for sustainability.

Table 7.8 shows that nearly all participants (five out of six) believed that the BaW Framework could be implemented in line with the RIBA BIM overlay (RIBA, 2012). In addition, other potential ways to implement the BaW Framework were proposed such as BREEAM (BRE, 1990), BS1192:2007 (BSI, 2008), Level 2 BIM (Bew and Richards, 2008), and FM soft landing (BSRIA, 2013).

Table 7.8 Potential protocols and standards for the BaW Framework implementation (validation questionnaire results)

Protocols/standards	Frequency (Number of respondents)
BIM overlay to the RIBA Outline Plan of Work	Five out of six
AEC (UK) BIM protocol	Four out of six
CPI (Coordinated Project Information) system	Four out of six
Green overlay to the RIBA Outline Plan of Work	Three out of six

Based on the validation questionnaire results, interviewees were asked for their reasons behind their suggested implementation options. They responded that architects could use the RIBA BIM overlay as their BIM implementation plan for their design projects. Moreover, three interviewees reported that the RIBA Green overlay (Green overlay to the RIBA Outline Plan of Work) (RIBA, 2011) has been recently integrated within the RIBA BIM overlay. Furthermore, four interviewees indicated that the Framework had been designed accordingly with the CPI (Coordinated Project Information) system, BS1192:2007, and Level 2 BIM.

Interestingly, interviewee V1 stated that the Framework could be implemented with BREEAM to improve construction waste related ratings. This information was put forward to the remaining five interviewees. They collectively agreed on the V1's suggestion and believed that the BaW Framework could enhance BREEAM assessment and credit ratings.

Furthermore, two interviewees emphasised that the government FM soft landing would be the next phase for implementation of the BaW Framework, if it be further extended to the Technical Design stage in detail for developing a set of as-planned 3D model in BIM. The precursor of the as-built 3D model could be handed over to the operation after construction through design, analysis and coordination for CWM, prior to onsite construction.

Responsibility for the BaW Framework implementation

The interviewees were asked as to who would be the most appropriate project stakeholder to take responsibility for the BaW Framework implementation. Five out of six indicated that the responsibility should be allocated to the person who is involved in the project at both management and technical level, such as lead designer. This role was clearly described by interviewee V5 in that the person should not only lead the Framework implementation at strategic level by managing communication and coordination between project stakeholders, but is also required to have specialisation in both construction waste and BIM issues to manage technical issues when delivering a project. Interviewee V4 argued that the role should not be fixed to a specific professional as the responsibility could be shifted from one to another between team members when a project developed into different stages.

Procurement and building type suitability for the BaW Framework implementation

The interviewees were asked if the BaW Framework could be implemented within any specific procurement route or type of building design. Four reported that the BaW Framework could certainly be applied to all procurement systems and building types because of its clearly outlined process for each building design stage. However, interviewee V4 highlighted that the Framework could be applied to any procurement if the responsibility of design changes are clearly written into the employer's requirements for the design and build contract. This is because the contractor has control over the design process and as such the design could be changed by the contractor across all project stages.

Post-improvement BaW Framework implementation

The interviewees were asked as to how the BaW Framework could be improved after its implementation.

Four out of six interviewees suggested the development of a computer programme to facilitate virtual waste estimation content (C-3.4 in Figure 7.11 and D-2.4 in Figure 7.13) within the Framework. All interviewees concurred that third-party computer software plug-ins to current BIM packages could be very helpful. In addition, interviewee V4 suggested that it could be as simple as a Microsoft Excel spreadsheet with well written content. Interviewee V6 went further by proposing a 'Waste-factor (W-factor)' concept for waste evaluation calculation as a percentage of construction waste generation of building materials based on data from previous projects, which could encourage adoption of the validated BaW Framework.

Potential BaW Framework implementation in the building design industry

The interviewees were asked whether the BaW Framework could be adopted by the building design industry.

All interviewees recognised that the BaW Framework has great potential for its adoption in the building design industry. Four interviewees noted the following reasons for such potential:

- Neatly outlined BIM-aided CWM process for each building design stage.
- Useful and clear decision making tool at both strategic High-level and detailed Low-level.
- Being "*an excellent tool to demonstrate and calculate the reduction of construction waste*".

7.4. Discussion

The validated BaW Framework has been designed accordingly with the BS1192: 2007 and Level 2 BIM with interoperable data for integrated collaboration within BIM knowledge management and coordination database environment, where the coordination and communication for CWM has been strengthened. Hence, the BaW Framework has the capability to be implemented across Level 2 and Level 3 BIM, and could be further enhanced by developing the virtual waste evaluation component of the Framework into a computer Programme, such as 'Waste-factor (W-factor)', as shown in Figure 7.14. Further, based on the BaW Framework, the concept of Waste Information Model (WIM) has been added to the current BIMs' family, as shown in Figure 7.14.

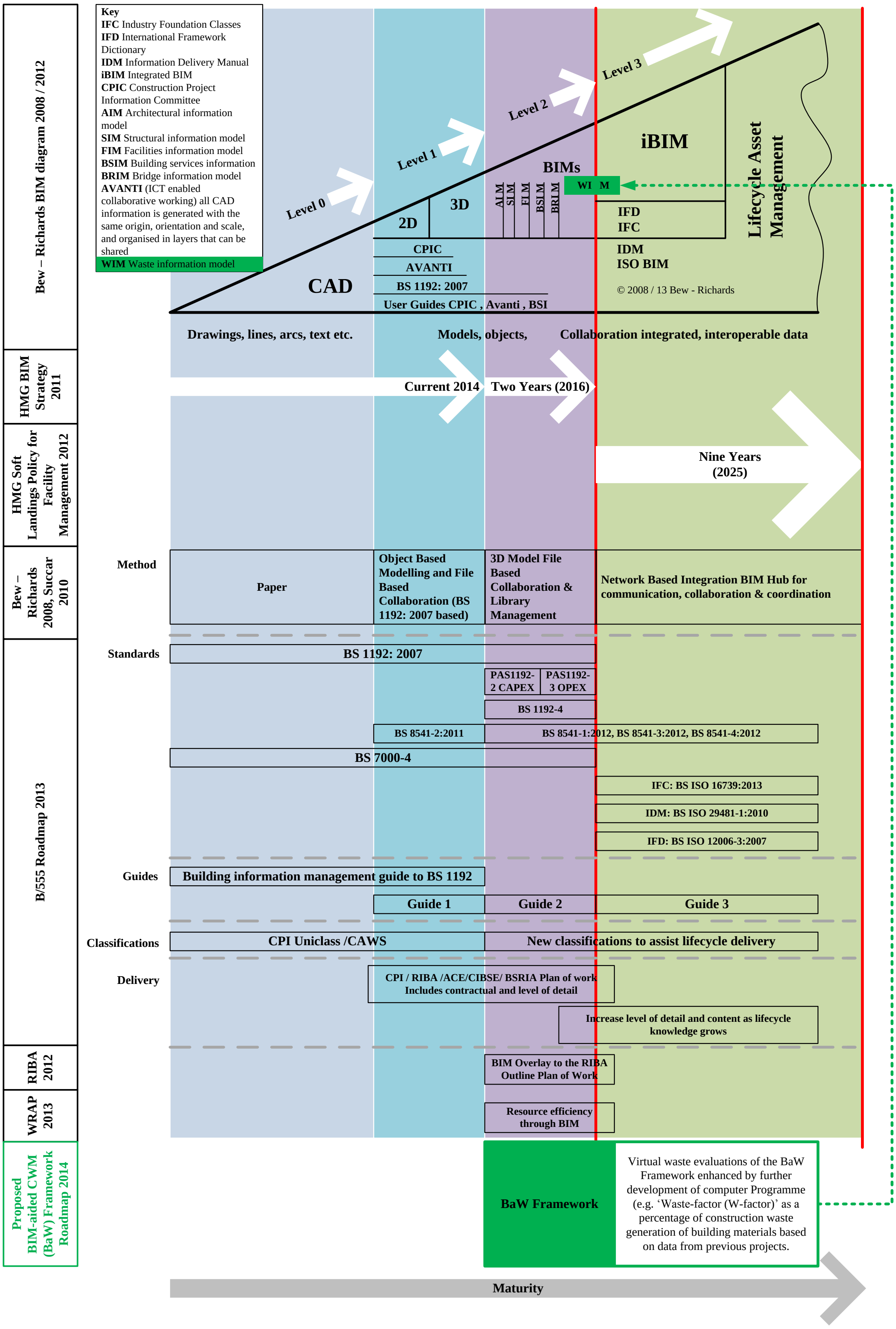


Figure 7.14 Diagram of the BaW Framework in current UK's BIM maturity roadmap (devised by the author based on the literature and the research findings)

Moreover, strategical CWM improvements were embedded within briefing requirements during Briefing stage (Appraisal and Design Brief stages) for CWM decision making in the High-level BaW Framework, as shown in Figure 7.8. These strategical CWM improvements were aimed to provide efficient and effiective steps for achieving better waste minimisation performance from the commencing of the project regardless the use of BIM. Hence, the Briefing stage of the validated High-level BaW Framework is suitable for architects to implement for waste reduction in building design, who have not adopted BIM.

Furthermore, the validated BaW Framework was developed aligning with RIBA Work of Plan stages, where the process of using BIM is outlined to aid waste reduction. Thus, the implementation of the validated BaW Framework can enhanced the both of RIBA Green Overlay and BIM Overlay in building design industry.

Finally, implementing the validated BaW Framework in building design industry have a direct impact on improving on-site waste management plan, and even help with re-installing the SWMP, which was recently repealed as a legislation owing to the lack of engagement of architects for waste reduction during design.

7.5. Summary

The proposed BaW Framework development and validation process are described in this chapter. It presents results from the BaW Framework validation process and the overall feedback on the Framework design, including clarity, structure, content and flow.

The validation results revealed that the BaW Framework has a clear structure and flow and that the content presented in the two High-level and Low-level component related evaluation process are appropriate. The adopted validation approach helped to refine and enhance the BaW Framework based on feedback and recommendations from participants.

The validation results indicated that the BaW Framework is useful and suitable for implementation with any type of procurement system or building types. A Framework implementation strategy has been proposed by participating architects confirming that it could be implemented and led by the lead designer and in line with the RIBA BIM overlay. The validation results also suggest that it is also possible for the validated BaW Framework to be used to enhance BREEAM construction waste minimisation ratings; and that it could be further developed for FM use as a potential component of Government Soft Landings. It could also be applied to potential third-party computer software plug-ins of current BIM packages or W-factors of materials that could be developed to assist waste estimation to encourage the BaW Framework adoption.

The next chapter presents the conclusions of this research and recommendations for further research.

CHAPTER EIGHT

Conclusions and Recommendations

8.1. Introduction

This chapter outlines the conclusions and recommendations drawn from the research findings. The first section presents the research achievements based upon the research aim and objectives. The second section provides key research contributions to existing knowledge. Subsequently, research limitations are discussed. The final section forwards recommendations for the industry, policy-makers and further research.

8.2. Achievement of the research aim and objectives

The aim of the research was to investigate the use of BIM as a platform to minimise construction waste, and to develop and validate a BIM-aided waste minimisation (BaW) Framework during design. Six objectives were developed to address the research aim. The fulfilment of objectives is discussed in the following sections.

8.2.1 Fulfilment of the first objective

The first objective was to review existing literature on CWM drivers and construction waste causes. This was accomplished through the literature review and interviews, and is presented in Chapters 2 and 5.

A comprehensive examination of CWM drivers (e.g. environmental drivers, business drivers, economical drivers, and legislative and policy drivers) was performed. Chapter 2 identified and classified waste causes (as shown in Table 2.2, 2.3 and 2.4) in line with Briefing, Design, Procurement, and Construction stages.

The fulfilment of the first objective was the basis of further investigation of construction waste causes during design, and how these causes could be addressed through BIM (see Chapters 4 and 5).

8.2.2 Fulfilment of the second objective

The second objective was to review current CWM practices including approaches, techniques and tools. This was accomplished through the literature review, and is presented in Chapter 2.

Most current CWM approaches, techniques and tools, focus on the Construction stage for handling on-site waste, rather than the Design stages which hold the greatest waste reduction opportunities. There was a consensus in the literature that Briefing and Design stages have the greatest opportunities to implement construction waste reduction. There is a growing trend for the development of CWM techniques and tools, including online and integrated methods (e.g. GIS) that have recently been explored although design related construction waste issues have caught the attention of the construction industry, few BIM practices have been established to help with the problem. There are no studies that have yet investigated how CWM practices could be improved through the use of BIM throughout the design process.

Further investigation was required to assess CWM practices and examine the potential of BIM to aid CWM during building design (see Chapters 4 and 5).

8.2.3 Fulfilment of the third objective

The third objective was to provide a detailed review of the current BIM practices including approaches, techniques and tools. This was accomplished through the literature review, questionnaire and interviews, and is presented in Chapter 2, 4 and 5.

Currently, BIM has been implemented during building design to improve simulation and analysis, enhanced coordination and communication for collaborative working, lifecycle information assessment and management, and information management across project lifecycle stages. Current BIM techniques and tools have been used to enhance design and construction related issues, including sustainable design (e.g. energy efficiency, and carbon reduction) during Briefing and Design stages. There are few current BIM approaches, techniques or tools that attempted to reduce design related construction waste during the design process.

BIM related literature findings were used to perform further investigation to examine BIM practices and their potential relationship with CWM (see Chapters 4 and 5).

8.2.4 Fulfilment of the fourth objective

The fourth objective was to explore the relationship between CWM and BIM during design. This was accomplished through literature review and questionnaire, and is presented in Chapters 2 and 4.

The most widely used BIM practices for design related activities were identified. These included: clash detection, detailing, visualisation and simulation to improve communication and coordination (see section 4.3.1). In terms of sustainable building design, BIM has been frequently used to enhance energy efficiency, carbon reduction, and building material specification (see section 4.3.3). BIM was regarded by participating respondents as having a significant potential to facilitate CWM during design stages (see section 4.4.1). BIM was also deemed as an appropriate platform to address construction waste causes, such as ineffective coordination and communication, and design changes (see section 4.4.2). Interoperability, resistance to change, and not being used by all project partners, were identified as major barriers in the adoption of BIM in building design (see section 4.3.5).

The questionnaire findings were employed to further investigate CWM and BIM via follow-up interviews that were presented in Chapter 5.

8.2.5 Fulfilment of the fifth objective

The fifth objective was to identify the relationship between construction waste causes and the use of BIM, and define potential improvements for CWM through BIM to assist architects to minimise waste. This was accomplished through interviews and presented in Chapter 5.

The waste causes during building Design and Procurement stages were identified in Table 5.1 (see section 5.3.1).

The results of the interviews identified the main employed BIM practices to enhance building design activities, such as detailing, clash detection, visualisation and simulation, and improved coordination and communication (see section 5.4), and sustainable building design (e.g. energy efficiency, carbon reduction and building material specification). The interview results revealed that BIM-enhanced design activities could benefit CWM during building design (see section 5.4). The results also suggested that BIM-associated improved coordination and communication approach would be the most appropriate in reducing construction waste (see section 5.5.3.5).

Interview findings suggested that the use of BIM has the potential to reduce construction waste generation throughout all design stages, particularly at Concept and Design Development stages; and help addressing construction waste causes during design. However, the interviewees argued that culture change related barriers to construction waste and BIM need to be addressed.

Findings obtained from literature review, questionnaire, and interviews were used to structure and design the BIM-aided waste minimisation (BaW) Framework (see Chapter 7).

8.2.6 Fulfilment of the sixth objective

The sixth objective was to develop and validate a BaW Framework. This was accomplished through the Framework design, development, and validation, as presented in Chapter 7.

The aim of the BaW Framework was to provide improvements to construction waste reduction during design stages through the use of BIM. The Framework development process was based upon key findings that emerged from the research (see section 7.2). The BaW Framework was developed and comprised two levels. These are a strategic High-level, and a detailed Low-level having two related evaluation process components. The BaW Framework guides the user by providing step-by-step process actions on BIM-associated CWM improvements to minimise design-related waste causes during building design.

The aim of the Framework validation was to determine the clarity and appropriateness of the BaW Framework content and the practicability of proposed action improvements. Results of validation indicated that it has a clear structure and flow. It also confirmed that the content presented in the High-level and Low-level (including two evaluation processes) are appropriate (see section 7.3.2). The BaW Framework underwent further improvements based on suggestions from the validation respondents (see section 7.3.3). The Framework validation identified the most appropriate implementation strategy in line with the RIBA BIM overlay to be led by the project lead designer (see section 7.3.4).

8.3. Contribution to knowledge

The research provides three key contributions to knowledge: (1) contribution to the theoretical understanding of BIM, and the relationship between BIM and CWM; (2) insight into addressing construction waste causes through BIM; (3) BIM-aided CWM (BaW) Framework.

8.3.1 Contribution to the theoretical understanding of BIM and construction waste minimisation

The research has not only added value to existing knowledge by enhancing the understanding of how BIM can be used in building design by mapping the processes (see Figure 5.1) such as visualisation and simulation, detailing, clash detection, and coordination and communication; but has also extended the existing knowledge towards a clear understanding of the actual process in the use of BIM for sustainable building design (i.e. energy efficiency, carbon reduction, and building material specification), by providing detailed roadmaps as shown in Figure 5.3.

The literature has failed to identify specific BIM implementation barriers and incentives for CWM, which has emerged from the research. These included: (1) technological barrier, such as slow uptake of family libraries for building products to BIM, and knowledge barriers; and (2) design decision making, cost and environmental, and marketing incentives. The research findings (see sections 4.3.5, 5.4.5.2, and 7.3.4) suggested a method to overcome technological barrier, which is that manufacturers and suppliers should develop their own database of 3D building material libraries for architects to use directly in BIM via a 3D process of material specification for coordination.

The research has obtained subjective views of architects regarding to the relationship between CWM and BIM. By adopting a mixed-method research strategy and employing sequential questionnaire and interviews, the current study contributes to the knowledge of mixed method research for investigation of the use of BIM for CWM in construction management.

8.3.2 Contribution to BIM assisted construction waste minimisation knowledge

Only one study explored the BIM for specific waste causes, such as design changes. However, nothing has been known regarding the impact of the use of BIM on construction waste causes associated with project stages in building design. The research has proposed a number of actions through BIM-enhanced design activities (e.g. visualisation and simulation, detailing, clash detection, and coordination and communication) and processes (e.g. energy efficiency) to address construction waste causes. Potentially, this helps to improve current CWM and BIM practices.

8.3.3 Contribution to knowledge for development of BaW Framework

This research has presented a BaW Framework to provide BIM related process actions to reduce construction waste throughout building design stages. The BaW Framework also provides the foundation for the use of BIM for CWM decision making during design. Therefore, the BaW Framework is a novel contribution to the field of CWM innovation and BIM application.

The BaW Framework includes BIM-enhanced design related activities, such as visualisation and simulation, detailing, clash detection, and coordination and communication for a integrated BIM-aided CWM process that provides CWM performance consideration throughout all design stages, including waste minimisation evaluation for the CWM decision making across each design stages. The BaW Framework also supports architects to make informed CWM decisions throughout the design stages.

8.4. Research limitations

The research limitations are related to research design, data collection, sampling frame, and the BaW Framework design and development, which are discussed below.

There are insufficient prior research studies in relation to CWM and BIM, which could help to lay a foundation to understand the research problem. Hence, the adopted research design used an exploratory rather than an explanatory method. Time and resource limitations were taken into consideration along with the current status of CWM and BIM knowledge when selecting and designing the appropriate method to address the research aim and objectives. The research produced findings based upon the opinions of respondents by using a mixed research method of sequential procedures (i.e. a questionnaire survey and interviews). Hence, the data collected in relation to CWM and BIM could have resulted in different research outcomes if other research designs, such as case studies, were employed.

The questionnaire sample was drawn from the UK's top 100 architectural practices, and interviews' sample was based on BIM users from the questionnaire respondents. Although the research attempted to draw a suitable representative sample, it could have been slightly different if a larger sample size and a different sample frame methodology were implemented.

The data used to design and develop the BaW Framework is limited to findings from the reviewed literature, questionnaire and interviews. As such, the BaW Framework is specific to architects when using BIM to reduce construction waste during building design rather than other building designers, such as structural engineers and service engineers. In addition, the BaW Framework is limited to the use within building projects rather than other construction project types such as infrastructure. Moreover, the BaW Framework focused on building design stages, of which Concept and Design Development stages were of particular focus. The Framework was only implemented for the Briefing and Design stages, not in relation to other building project stages such as Procurement, Construction and Post-construction. Furthermore, the BaW Framework was not specifically designed to focus on the process of BIM tools implementation, but on a more detailed strategic framework related to building design decision making.

8.5. Recommendations to stakeholders

8.5.1 Recommendations to industry

The research suggests that CWM and BIM related training should be provided to project stakeholders, such as architects, structural engineers, services engineers, and quantity surveyors, in order to achieve outcome of the BaW Framework implementation.

The research recommends that the contractor should be involved in the project throughout the building design stages as a consultant, which is a key element of the BaW Framework and its implementation. As such, CWM-related experience of the contractor, including the use of BIM in both building design and construction, is ensured to gain the best CWM performance through the building design. Similarly, the database of the BaW Framework should be used in future project, as such comparison of CWM performance from project to project can help with improving CWM target setting and benchmarking. Further, a 'Waste-factor (W-factor)', which stands for a generation of percentage of construction waste (according to data of on-site waste auditing), of the building materials based on the database for the virtual waste estimation of the BaW Framework has been proposed to encourage the adoption of the Framework. The development of a BIM software package or third party packages (e.g. API or plug-ins) are produced to add to the current widely used BIM packages to assist the estimation of virtual waste content within the Framework including the 'W-factor'.

8.5.2 Recommendations to policy makers

1) The research reported that cultural issues in the building design industry have a considerable impact not only on the performance of CWM, such as unawareness of waste causes during building design, inexperience of efficient CWM practices, and attitudes toward CWM. Hence, the research recommends that policy makers should focus on a wider cultural change toward CWM at both strategic and project level in the building design industry. This is whereby policy documents could be made to encourage implementation of CWM through incentives, such as rewarding environmental credits for building design at strategic level and building design activities at project level.
2) The research suggests that client-led initiatives are essential for successful implementation of both CWM and BIM in building design. Thus, the research recommends that Government should commission best practice demonstration projects to encourage the use of BIM to facilitate CWM. New-build public projects could be set as examples for private clients regarding aspects of the implementation of CWM through BIM. Such initiatives could encourage the dissemination of best the practice to other building types and sectors (e.g. private, refurbishment, commercial, residential, and industrial).

8.6. Recommendations for further research

1) The BaW Framework is mainly focused on the Concept and Design Development stages of building design. Hence, the research could be extended to the study of other building design stages in more depth (i.e. Briefing, Technical Design, and Production Information); and project lifecycle stages such as Procurement, Construction, Operation and Maintenance.
2) Further research could also be recommended to improve the validated BaW Framework in terms of its wider adoption. The BaW Framework is a decision making tool and does not specifically relate to existing BIM packages (e.g. Revit, Bentley, ArchiCAD, and Vectorworks). Hence, the research recommends the mapping of existing BIM tools to incorporate into the BaW Framework in order to create different versions for execution to align with each current BIM packages.
3) It is also recommended to investigate possibilities and deliverables that are associated with project environmental assessment and credit rewarding systems such as BREEAM and Code for Sustainable Homes.
4) Follow-up research is also required to develop BIM-aided CWM Frameworks related to building design disciplines, which would involve structural engineers, service engineers and quantity surveyors.
5) Further research could also investigate the potential use of BIM for water efficiency in building design, which has not yet been investigated in currently available literature.

REFERENCES

Agopyan, V., Souza, U., Paliari, J.C. & Andrade, A.C. 1998, "Alternatives for Reducing Material Waste on Building Sites", *Research report*, Sa˜o Paulo, USP.

Ahankoob, A., Khoshnava, S. M., Rostami, R. & Preece, C. 2012, "BIM perspectives on construction waste reduction", *Management in Construction Research Association (MiCRA) Postgraduate Conference*, pp. 195-199.

Akintoye, A., McIntosh, G. & Fitzgerald, E. 2000, "A survey of supply chain collaboration and management in the UK construction industry", *European Journal of Purchasing & Supply Management*, vol. 6, no. 3-4, pp. 159-168.

Alarcon, L.F. 1993, "Modelling waste and performance in construction" in *Lean Construction* A.A. Balkema, Rotterdam, Netherlands.

Al-Hajj, A. & Hamani, K. 2011, "Material Waste in the UAE Construction Industry: Main Causes and Minimisation Practices", *Architectural Engineering and Design Management*, vol 7, no. 4, pp. 221-235., http://dx.doi.org/10.1080/17452007.2011.594576

Ali, S. 2010, "Analysis of procedures and workflow for conducting energy analysis using autodesk revit, gbxml and trace 700", *Fourth National Conference of IBPSA-USA*, New York.

Al-Sari, M. I., Al-Khatib, I. A., Avraamides, M. & Fatta-Kassinos, D. 2012, "A study on the attitudes and behavioural influence of construction waste management in occupied Palestinian territory". *Waste Management & Research*, vol. 30, no. 2, pp. 122-136.

Alwi, S., Hampson, K. & Mohamed, S. 2002, "Waste in the Indonesian Construction Project". *Proceedings of the 1st International Conferences of CIB W107 – Creating a Sustainable Construction Industry in Developing Countries*, pp. 305-315, November 2002, South Africa.

Alwisy, A., Al-Hussein, M. & Al-Jibouri, S. H. 2012, "BIM Approach for Automated Drafting and Design for Modular Construction Manufacturing". *In: Computing in Civil Engineering*, 17-20 June 2012, Reston, Virginia , USA.

AIA. 2007, *Integrated project delivery: a guide*, [Online]. Available: http://www.aia.org/groups/aia/documents/pdf/aiab083423.pdf [2011, 17 Jan] .

Amaratunga, D., Baldry, D., Sarshar, M. & Newton, R. 2002, "Quantitative and Qualitative Research in Built Environment: Application of 'Mixed' Research Approach", *Work Study*, vol. 51, no. 1, pp. 17-31.

Aouad, G., Lee, A. & Wu, S. 2005, "nD Modelling for Collaborative Working in Construction". *Architectural Engineering and Design Management*, vol. 1, no. 1, pp. 33-44.

Arayici, Y. 2008, "Towards building information modelling for existing structures", *Structural Survey*, vol. 26, no. 3, pp. 210-222.

Arayici, Y., Coates, P., Koskela, L., Kagioglou, M., Usher, C. & O'Reilly, K. 2011, "BIM adoption and implementation for architectural practices". *Structural Survey*, vol. 29, no. 1, pp. 7-25.

Arensman, D. B. & Ozbek, M. E. 2012, "Building Information Modeling and Potential Legal Issues". *International Journal of Construction Education and Research*, vol. 8, no. 2, pp. 146-156.

Axinn, W.G. & Pearce, L.D. 2006, *Mixed Method Data Collection Strategies*, Cambridge University Press, New York.

Autodesk. 2002, *Building Information Modeling: White Paper*,[Online]. Available: http://www.laiserin.com/features/bim/autodesk_bim.pdf [2011, 17 Jan].

Autodesk. 2008, *Improving building industry results through integrated project delivery and building information modeling*, [Online]. Available: http://images.autodesk.com/adsk/files/bim_and_ipd_whitepaper.pdf [2011, 17 Jan].

Azhar, S. 2011, "Building Information Modeling (BIM): Trends, Benefits, Risks, and Challenges for the AEC Industry". *Leadership and Management in Engineering*, vol. 11, pp. 241-252.

Azhar, S. & Behringer, A. 2013, "A BIM-based Approach for Communicating and Implementing a Construction Site Safety Plan". *49th ASC Annual International Conference Proceedings*.

Azhar, S. & Brown, J. 2009, "BIM for Sustainability Analyses". *International Journal of Construction Education and Research*, vol. 5, pp. 276-292.

Azhar, S., Nadeem, A., Mok, Y. N. & Leung, H. Y. 2008, "Building Information Modeling (BIM): A New Paradigm for Visual Interactive Modeling and Simulation for Construction Projects". *First International Conference on Construction in Developing Countries (ICCIDC–I)*, August 4-5, Karachi, Pakistan.

Babatunde, S. O. 2012, "Quantitative Assessment of Construction Materials Wastage in the Nigerian Construction Sites". *Journal of Emerging Trends in Economics and Management Sciences*, vol. 3, no. 3, pp. 238-241.

Babič, N., Podbreznik, P. & Rebolj, D. 2010, "Integrating resource production and construction using BIM", *Automation in Construction*, vol. 19, pp. 539-543.

Baker, F. 2001, *The Basics of Item Response Theory*, ERIC Clearinghouse on Assessment and Evaluation.

Baldwin, A.N., Austin, S.A., Hassan, T.M. & Thorpe, A. 1998, "Planning building design by simulating information flow", *Automation in Construction*, vol. 8, no. 2, pp. 149-163.

Baldwin, A.N., Shen, L.Y., Poon, C.S., Austin, S.A. & Wong, I. 2008, "Modelling design information to evaluate pre-fabricated and pre-cast design solutions for reducing construction waste in high rise residential buildings", *Automation in Construction*, vol. 17, no. 3, pp. 333-341.

Baldwin, A.N., Shen, G.Q. & Brandon, P. 2009a, "Collaborative construction information management - evolution and revolution" *in Collaborative Construction Information Management*, eds. G.Q. Shen, P. Brandon & A. Baldwin, Spon press, New York, pp. 1-17.

Baldwin, A.N., Poon, C., Shen, L., Austin, S. & Wong, I. 2009b, "Designing out waste in high-rise residential buildings: Analysis of precasting methods and traditional construction", *Renewable Energy*, vol. 34, no. 9, pp. 2067-2073.

Ball, J. 2002, "Can ISO 14000 and eco-labelling turn the construction industry green?", *Building and Environment*, vol. 37, no. 4, pp. 421-428.

Bansal, V. K. 2011, "Application of geographic information systems in construction safety planning", *International Journal of Project Management*, vol. 29, pp. 66-77, DOI:10.1016/j.ijproman.2010.01.007.

Basbagill, J., Flager, F., Lepech, M. & Fischer, M. 2013, "Application of life-cycle assessment to early stage building design for reduced embodied environmental impacts", *Building and Environment*, vol. 60, pp. 81-92.

Bassanino, M., Fernando, T. & Wu, K. 2013, "Can virtual workspaces enhance team communication and collaboration in design review meetings?", *Architectural Engineering and Design Management*, Taylor & Francis, pp. 1-35.

Baumard, P. & Ibert, J. 2001, "What approach with which data?" in *Doing management research, a comprehensive guide*, ed. R. Thiétart, Sage Publications, London, pp. 76-83.

Bazjanec, V. 2004, "Building energy performance simulation as part of interoperable software environments", *Building and Environment*, vol. 39, no. 8.

Bazjanac, V. & Kiviniemi, A. 2007, “Reduction, simplification, translation and interpretation in the exchange of model data”. *Proceedings of the 24th Conference on Bringing ITC Knowledge to Work*, pp. 293-313, Moribar, Slovenia.

Begum, R.A. 2006, "A benefit-cost analysis on the economic feasibility of construction waste minimisation: The case of Malaysia", *Resources conservation and recycling*, vol. 48, no. 1, pp. 86-98.

Begum, R.A., Siwar, C., Pereira, J.J. & Jaafar, A.H. 2009, "Attitude and behavioral factors in waste management in the construction industry of Malaysia", *Resources, Conservation and Recycling*, vol. 53, no. 6, pp. 321-328.

Bernstein, P.G. & Pittman, J.H. 2004, “Barriers to the Adoption of Building Information Modelling in the Building Industry”. *Autodesk Building Solutions*, San Rafael, CA.

Bertram, M., Graedel, T.E., Rechberger, H. & Spatari, S. 2002, "The contemporary European copper cycle: waste management subsystem", *Ecological Economics*, vol. 42, no. 1-2, pp. 43-57.

Bew, M., & Underwood, J. 2010, "Delivering BIM to the UK Market", *In J. Underwood & I. Umit (Eds.), Handbook of Research on Building Information Modeling and Construction Informatics: Concepts and Technologies*, IGI Global, pp. 30-64.

BIS. 2012, *INDUSTRIAL STRATEGY: UK SECTOR ANALYSIS*, [Online]. Available: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/34607/12-1140-industrial-strategy-uk-sector-analysis.pdf [2013, 22 September].

BIM Task Group. 2013, 2013 update, *What is COBie UK 2012?* [COBie UK 2012 / BIM Task Group], [Online]. Available: http://www.bimtaskgroup.org/cobie-uk-2012/ [2013, 30 April].

Bjork, B.C. 1989, "Basic Structure of a Building Product Model", *Computer aided Design*, vol. 21, no. 2, pp. 71-78.

Blaxter, L., Hughes, C. & Tight, M. 2010, *How to research*, 4th edn, Open University Press, Berkshire.

Blengini, G.A. & Garbarino, E. 2010, "Resources and waste management in Turin (Italy): the role of recycled aggregates in the sustainable supply mix", *Journal of Cleaner Production*, vol. 18, no. 10-11, pp. 1021-1030.

BLIS. 2004, *BLIS-Building Lifecycle Interoperable Software* [Homepage of Building Lifecycle Interoperable Software], [Online]. Available: http://www.blis-project.org/ [2010, 02 November].

BlueWise. 2010, *ConstructCLEAR*, [Online]. Available: http://www.constructclear.co.uk/ [2011, 17 Jan] .

Bogdan, R. C., & Biklen, S. K. 1982, *Qualitative research for education: An introduction to theory and methods*, Allyn and Bacon, Inc., Boston.

Bosché, F. 2012, "Plane-based registration of construction laser scans with 3D/4D building models", *Advanced Engineering Informatics*, vol. 26, no. 1, pp. 90-102.

Bossink, B.A.G. & Brouwers, H.J.H. 1996, "CONSTRUCTION WASTE: QUANTIFICATION AND SOURCE EVALUATION", *Journal of Construction Engineering and Management*, vol. 122, no. 1, pp. 55-60.

Boukamp, F. & Akinci, B. 2007, “Automated processing of construction specifications to support inspection and quality control”. *Automation in Construction*, vol. 17, no. 1, pp. 90-106.

Bourdeau, L. 1999, “Sustainable development and the future of construction: acomparison of visions from various countries”. *Building Research & Information*, vol. 27, no. 6, pp. 354-366.

Bowman, D.A., Ray, A.A. Gutierrez, M.S., Mauldon, M., Dove, J.E. Westman, E. & Setareh, M. 2006, “Engineering in three dimensions: immersive virtual environments, interactivity, and 3D user interfaces for engineering applications”. *ASCE Proceedings of GeoCongress 200*.

Bozdoc, M. 2003, 3 June-last update, *Marian Bozdoc's History of CAD* [Homepage of MB design], [Online]. Available: http://www.mbdesign.net/mbinfo/CAD-History.htm [2010, 29 October].

Brace, I. 2008, *Questionnaire design*, 2nd edn, Kogan Page Ltd, London.

Braun, J., Cho, Y. K. & Li, H. 2010, “Editorial: Expanding BIM to Meet the Grand Challenges in Buildings—What is Needed?”. *HVAC&R Research*, vol. 16, no. 5, pp. 543-544.

BRE. 2001, *SMARTWaste* [Homepage of Building Research Establishment (BRE)], [Online]. Available: http://www.smartwaste.co.uk/ [2011, 17 Jan] .

BRE. 2006, *BRE joins forces with RDAs in blitz on construction waste* [news from BRE], [Online]. Available: http://www.bre.co.uk/news/BRE-joins-forces-with-RDAs-in-blitz-on-construction-waste--400.html [2013, 22 September].

BRE. 2007, *SMARTStart*, [Homepage of Building Research Establishment (BRE)], [Online]. Available: http://www.smartwaste.co.uk/smartstart/about.jsp [2011, 17 Jan].

BRE. 2008, *SMARTAudit*, [Homepage of Building Research Establishment (BRE)], [Online]. Available: http://www.smartwaste.co.uk/smartaudit.jsp?id=27 [2011, 17 Jan].

BRE. 2009, *Sustainable construction of buildings*, [Homepage of Building Research Establishment (BRE)], [Online]. Available: http://www.bre.co.uk/page.jsp?id=9 [2011, 17 Jan].

BRE. 2010, *True cost of waste calculator,* [Homepage of Building Research Establishment (BRE)], [Online]. Available: http://www.wastecalculator.co.uk/login.jsp [2011, 17 Jan].

Brewer, G. & Gajendran, T. 2012, “Attitudes, behaviours and the transmission of cultural traits: Impacts on ICT/BIM use in a project team”. *Construction Innovation: Information, Process, Management*, vol. 12, no. 2, pp. 198-215.

Brilakis, I., Lourakis, M., Sacks, R., Savarese, S., Christodoulou, S., Teizer, J. & Makhmalbaf, A. 2010, "Toward automated generation of parametric BIMs based on hybrid video and laser scanning data", *Advanced Engineering Informatics*, vol. 24, no. 4, pp. 456-465.

Briscoe, G., Dainty, A.R.J. & Millett, S. 2001, "Construction supply chain partnerships: skills, knowledge and attitudinal requirements", *European Journal of Purchasing & Supply Management*, vol. 7, no. 4, pp. 243-255.

Bryde, D., Broquetas, M. & Volm, J. M. 2013, "The project benefits of Building Information Modelling (BIM)", *International Journal of Project Management*, vol. 31, no. 7, pp. 971-980.

Bryman, G. H. 1987, *Report of the World Commission on Environment and Development: Our Common Future*, Transmitted to the General Assembly as an Annex to document A/42/427 - Development and International Co-operation: Environment, United Nations.

Bryman, A. 2008, *Social Research Methods*, 3rd edn, Oxford University Press, Oxford.

Bryman, A. & Bell, E. 2007, *Business Research Methods*, 2nd edn, Oxford University Press, Oxford.

Bryman, A. & Cramer, D. 2005, *Quantitative Data Analysis with SPSS 12 and 13*, Routledge, East Sussex.

Bryne, M. 2001, "Data analysis strategies for qualitative research", *AORN*, vol. 74, no. 6, pp. 904-905.

BSi. 2008, *BS1192:2007 Collaborative production of architectural, engineering and construction information - Code of practice*, BSi, London, UK.

BSi. 2012, *B/555 Roadmap - Design, Construction & Operational Data & Process Management for the Built Environment*, BSi, London, UK.

BSi. 2013, *PAS 1192-2:2013 Incorporating Corrigendum No. 1 - Specification for information management for the capital/delivery phase of construction projects using building information modelling*, BSi, London, UK.

Building Magazine. 2010, *Top 100 Architects*, [Online]. Available: http://www.building.co.uk/Journals/43/Files/2010/10/7/054_BUILDING40.pdf [2011, 16 June].

Bugher, W. 1980, *Polling Attitudes of Community on Education Manual (PACE)*, Delta Kappan, Bloomington, Indiana .

Cavieres, A., Gentry, R. & Al-Haddad, T. 2011, “Knowledge-based parametric tools for concrete masonry walls: Conceptual design and preliminary structural analysis”. *Automation in Construction*, vol.20, pp. 716-728.

CBI. 2013, *Building Britain’s future - An industrial strategy for construction*, [Online]. Available: http://www.cbi.org.uk/media/2118883/building_britains_future.pdf [2013, 22 September].

Chen, Z., Li, H., & Wong, C.T.C. 2002, “An application of bar-code system for reducing construction wastes”. *Automation in Construction*, vol.11, no. 5, pp. 521-533.

Chen, Z., Li, H., Kong, S.C.W., Hong, J. & Xu, Q. 2006, "E-commerce system simulation for construction and demolition waste exchange", *Automation in Construction*, vol. 15, no. 6, pp. 706-718.

Cheng, C. P. & Ma, Y.H. 2013, “A BIM-based system for demolition and renovation waste estimation and planning”. *Waste Management*, vol.33, no. 6, pp. 1539-1551.

Cheng, T. & Teizer, J. 2013, "Real-time resource location data collection and visualization technology for construction safety and activity monitoring applications", *Automation in Construction*, vol. 34, pp. 3-15.

Cheung, F.K.T., Rihan, J., Tah, J.H.M., Duce, D. & Kurul, E. 2012, "Early stage multi-level cost estimation for schematic BIM models", *Automation in Construction*, vol. 27, pp. 67-77.

Choi, J. & Kim, I. 2008, “An Approach to Share Architectural Drawing Information and Document Information for Automated Code Checking System”. *TSINGHUA SCIENCE AND TECHNOLOGY*, vol. 13, no. 1, pp. 171-178.

Chua, K.H., Nguyen, T.Q. & Yeoh, K.W. 2013, "Automated construction sequencing and scheduling from functional requirements", *Automation in Construction*, vol. 35, pp. 79-88.

CIRIA. 1995, "Waste Minimization and Recycling in Construction - A Review", *Special Publication SP122*, CIRIA, London.

CIRIA. 1999, "Waste Minimization and Recycling in Construction - Design Manual", *Special Publication SP134*, CIRIA, London.

CIRIA. 2001, *Waste minimisation in construction: training pack*, 2nd edn, CIRIA, London .

CITA. 2012, *BIM | Building Information Modelling | Ireland’s Opportunity*, [Online]. Available: http://www.cita.ie/images/assets/cita%20pres_gccc_2nd%20may%202012.pdf [2011, 17 Jan].

Conrad, P. & Reinarz, S. 1984, "Qualitative computing: approaches and issues", *Qualitative Sociology*, vol. 7, no. 34, pp. 60.

Conway, F. 1967, *Sampling: an introduction for social scientists*, George Allen & Unwin Ltd, London.

Costa, A., Keane, M. M., Torrens, J. I. & Corry, E. 2013, “Building operation and energy performance: Monitoring, analysis and optimisation toolkit”, *Applied Energy*, vol. 101, pp. 310-316.

Costa, A. A. & Tavares, L. V. 2012, “Social e-business and the Satellite Network model: Innovative concepts to improve collaboration in construction”, *Automation in Construction*, vol. 22, pp. 387-397.

Costin, A., Pradhananga, N., Teizer, J. & Marks, E. 2012a, “Real-Time Resource Location Tracking in Building Information Models (BIM)”, *LECTURE NOTES IN COMPUTER SCIENCE : Cooperative Design, Visualization, and Engineering*, vol. 7467, pp. 41-48, SPRINGER-VERLAG, Germany.

Costin, A., Pradhananga, N. & Teizer, J. 2012b, “Leveraging passive RFID technology for construction resource field mobility and status monitoring in a high-rise renovation project”, *Automation in Construction*, vol. 24, pp. 1-15.

Coventry, S. 2001, *Demonstrating waste minimisation benefits in construction*, CIRIA, London.

Craven, D.J., Okraglik, H.M. & Eilenberg, I.M. 1994, "Construction waste and a new design methodology", *Sustainable Construction: Proceedings of the 1st Conference of CIB TG16 Tampa*, FL, pp. 89-98.

Creswell, J.W. 2007, *Qualitative inquiry and research design: choosing among five traditions*, Sage Publications, Thousand Oaks, CA.

Creswell, J.W. 2009, *Research design: Qualitative, quantitative, and mixed methods approaches*, 3rd edn, SAGE Publication, Inc.

Crittenden, B.D. & Kolaczkowski, S.T. 1995, *Waste minimization : a practical guide*, Institution of Chemical Engineers, Rugby.

Crocker, L. & Algina, J. 1986, *Introduction to classical & modern test theory*, Harcourt Brace Jovanovich, Fort Worth, TX.

Cronbach, L. J. & Meehl, P. E. 1955, "Construct validity in psychological tests", *Psychological Bulletin*, vol. 52, no. 4, pp. 281-302.

Cronbach, L.J. 1984, *Essentials of Psychological Testing*, 4th edn, Harper and Raw, New York, USA.

Crosbie, T., Dawood, N. & Dawood, S. 2011, “Improving the energy performance of the built environment: The potential of virtual collaborative life cycle tools”, *Automation in Construction*, vol. 20, pp. 205-216.

Crotty, M. 1998, *The foundations of social research: Meaning and perspective in the research process*, Sage Publication, Thousand Oaks, CA.

C.S.U 2011a, *Advantages and Disadvantages of Experimental Research: Quick Reference List* [Homepage of Colorado State University], [Online] Available: http://edu-net.net/bus-writing/writing/guides/research/experiment/pop5d.html [2011, 17 Jan].

C.S.U 2011b, *Advantages and Disadvantages of the Survey Method* [Homepage of Colorado State University], [Online]. Available: http://writing.colostate.edu/guides/research/survey/com2d1.cfm [2011, 17 Jan].

Dainty, A. 2008, "Methodological Pluralism in Construction Management Research" *in Advanced Research Methods in the Built Environment*, eds. A. Knight & L. Ruddock, Blackwell Publishing Ltd, , pp. 1-13.

Dainty, A.R.J. & Brooke, R.J. 2004, "Towards improved construction waste minimisation: a need for improved supply chain integration?", *Structural Survey*, vol. 22, no. 1, pp. 20-29.

Dania, A. A., Kehinde, J.O. & Bala, K. 2007, “A study of construction material waste management practices by construction firms in Nigeria”. *Building Research Reports series*, Caledonia University, Scotland UK, pp.121-129.

Davies, M.B. 2007, *Doing a successful research project: Using qualitative or quantitative methods*, Palgrave Macmillan, New York.

Davis, K. A. 2008, “Assessing individuals’ resistance prior to it implementation in the AEC industry”. *CIB W78 2008: International Conference on Information Technology in Construction*, Santiago, Chile.

Davies, R. & Harty, C. 2013, “Implementing ‘Site BIM’: A case study of ICT innovation on a large hospital project”, *Automation in Construction*, vol. 30, pp. 15-24.

Dayal, M. & Timmermans, J. 2004, "Analysedes 3D-Datenaustausches via IFC-Modell amBeispiel komplexer Objektdokumentation", *der Automobilindustrie mit dem Ziel der Optimierung von Planungsprozessen*, Fraunhofer IRB Verlag, Stuttgart.

Defra. 2004, *e-Digest Environment Statistics, Waste and recycling*, [Online]. Available: http://archive.defra.gov.uk/evidence/statistics/environment/waste/kf/wrkf02.htm [2013, 25 September].

Defra. 2007, *Waste Strategy for England 2007*, [Online]. Available: http://archive.defra.gov.uk/environment/waste/strategy/strategy07/documents/waste07-strategy.pdf [2013, 22 September].

Defra. 2008, *Construction Resources and Waste Roadmap 2008*, Building Research Establishment (BRE), Watford, UK.

Defra. 2011, *Government Review of Waste Policy in England 2011*, [Online]. Available: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/69401/pb13540-waste-policy-review110614.pdf [2013, 16 September].

Defra. 2013a, *Review of Defra's funding for WRAP in England – Opportunity to comment*, [Online]. Available: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/193917/wrap-funding-review-comment-20130503.pdf [2013, 17 September].

Defra. 2013b, *Defra Public Consultations: Proposed repeal of construction Site Waste Management Plan Regulations (2008) - Summary of responses and Government response*, [Online]. Available: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/237398/site-waste-manage-consult-sum-resp-20130830.pdf [2013, 22 September].

Defra. 2013c, *Waste Prevention Programme for England Call for evidence*, [Online]. Available: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/221130/wpp-consult-doc-20130311.pdf [2013, 22 September].

Denzin, N.K. & Lincoln, Y.S. 1994, *Handbook of qualitative research*, Sage Publications, Thousand Oaks, CA.

Denzin, N.K. & Lincoln, Y.S. 2003, *Collecting and Interpreting Qualitative Materials*, Sage Publication, New York.

Deutsch, R. 2011, *BIM and Integrated Design: Strategies for Architectural Practice*, John Wiley & Sons, Inc., Hoboken, New Jersey.

Department of Trade and Industry (DTI). 2007, *Meeting the energy challenge. a white paper on energy*, The Stationery Office, London.

DFP 2011, 13 January-last update, T*he Energy Performance of Buildings (EPB)* [Homepage of Department of Finance and Personnel], [Online]. Available: http://www.dfpni.gov.uk/index/buildings-energy-efficiency-buildings/energy-performance-of-buildings.htm [2011, 13 January].

Diao, Y., Kato, S. & Hiyama, K. 2011, "Development of an optimal design aid system based on building information modeling". *Building Simulation*, vol. 4, no. 4, pp. 315-320.

Ding, L.Y. & Zhou, C. 2013, "Development of web-based system for safety risk early warning in urban metro construction", *Automation in Construction*, vol. 34, pp. 45-55.

Ding, L.Y., Zhou, Y., Luo, H.B. & Wu,X.G. 2012, "Using nD technology to develop an integrated construction management system for city rail transit construction", *Automation in Construction*, vol. 21, pp. 64-73.

Directive. 2008, 02 Jun-last update, *EC on waste (Waste Framework Directive) - Environment - European Commission* [Homepage of European Commission], [Online]. Available: http://ec.europa.eu/environment/waste/framework/ [2011, 17 Jan] .

Domingo, D. 2008, *Reduction construction waste in healthcare facilities: a project lifecycle approach -- First year report*, Loughborogh University, Loughborough.

Dong, B., Lam, K.P., Huang, Y.C. & Dobbs, G.M. 2007, "A comparative study of the IFC and gbXML informational infrastructures for data exchange in computational design support environments", *Proceedings: Building Simulation 2007*.

Dossick, C. S. & Neff, G. 2011, "Messy talk and clean technology: communication, problem solving and collaboration using Building Information Modelling". *Engineering Project Organization Journal*, vol. 1, no. 2, pp. 83-93.

Dye, A. & McEvoy, M. 2008, *Environmental Construction Handbook*, RIBA Publishing, London, UK.

East, E. W. 2012, 2012 update, *Construction-Operations Building information exchange (COBie), buildingSMART alliance, National Institute of building Sciences, Washington*, [Online]. Available: http://www.buildingsmartalliance.org/index.php/projects/activeprojects/25 [2013, 30 April].

Easterby-Smith, M., Thorpe, R. & Lowe, A. 2002, *Management Research: An Introduction*, Sage Publication, London.

Eastman, C. 1976, "General purpose building description systems", *Computer-Aided Design*, vol. 8, no. 1, pp. 17-26.

Eastman, C.M. 1992, "Modeling of buildings: evolution and concepts", *Automation in Construction*, vol. 1, pp. 99-109.

Eastman, C. 1999, *Building Product Models: Computer Environments Supporting Design and Construction*, CRC Press LLC, Florida, USA.

Eastman, C. 2009, "Automated Assessment of Early Concept Designs". *Architectural Design*, vol. 79, no. 2, pp. 52-57.

Eastman, C., Lee, J., Jeong, Y. & Lee, J. 2009, "Automatic rule-based checking of building designs", *Automation in Construction*, vol.18, pp. 1011-1033.

Eastman, C., Teicholz, P., Sacks, R. & Liston, K. 2008, *BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors*, John Wiley & Sons, Inc., Canada.

E.C.Environment. 2010, 02 Jun-last update, *European Commission: Environment* [Homepage of European Commission], [Online]. Available: http://ec.europa.eu/environment/waste/legislation/a.htm [2011, 17 Jan] .

E.C.Environment. 2012, 20 Jun-last update, *Review of the Thematic Strategy on the prevention and recycling of waste* [Waste - Environment - European Commission], [Online]. Available: http://ec.europa.eu/environment/waste/strategy.htm [2012, 17 Sep] .

Ekanayake, L.L. & Ofori, G. 2000, "Construction material waste source evaluation", *In Proceedings of 2nd Southern African Conference on Sustainable Development in the Built Environment: Strategies for a sustainable built environment*, Pretoria, South Africa, August 23-25.

Ekanayake, L. L. & Ofori, G. 2004, "Building waste assessment score: design-based tool". *Building and Environment*, vol. 39, pp. 851-861.

Emmitt, S. 2010, *Managing Interdisciplinary Projects: A primer for architecture, engineering and construction*, Spon press, Oxon.

Enshassi, A. 1996, "Material Control and Waste on Building Sites", *Building Research and Information*, vol. 24, no. 1, pp. 31-34.

Environment Agency. 1997, *Waste minimisation and waste management: an environmental good practice guide for industry*. Solihull. E.A.

Environment Agency. 2003, *Sustainable Construction: Position Statement* [Online]. Available: http://www.environment-agency.gov.uk/cy/ymchwil/llyfrgell/safbwynt/41239.aspx [2013, 20 Feb].

Environment Agency. 2004, *Sustainable Procurement Product Guidance*, Environment Agency, UK.

Environment Agency. 2008, *The economic and environmental benefits Science Report – SC050041/SR2 of resource efficiency in construction* [Online]. Available:

http://a0768b4a8a31e106d8b0-50dc802554eb38a24458b98ff72d550b.r19.cf3.rackcdn.com/scho0308bnrx-e-e.pdf [2013, 22 September].

Environment Agency. 2010, *Environment Agency - Landfill* [Online]. Available: http://www.environment-agency.gov.uk/business/sectors/32445.aspx [2013, 22 September].

Environmental Protection Department. 2009, 24 November-last update, *Implementation of Waste Disposal Plan*, [Online]. Available: http://www.epd.gov.hk/epd/english/environmentinhk/waste/prob_solutions/iwdp.html [2010, 25 september] .

Envirowise. 1998, *Waste minimisation clubs: setting them up for success*. Harwell.

Esin, T. & Cosgun, N. 2007, "A study conducted to reduce construction waste generation in Turkey", *Building and Environment*, vol. 42, no. 4, pp. 1667-1674.

Faniran, O.O. & Caban, G. 1998, "Minimizing waste on construction project sites", *Engineering Construction and Architectural Management*, vol. 5, no. 2, pp. 182-188.

Fellows, R. & Liu, A. 2008, *Research Methods for Construction*, 3rd edn, Blackwell Science Ltd.

Feng, C., Chen, Y. & Huang. J. 2010, “Using the MD CAD model to develop the time–cost integrated schedule for construction projects”, *Automation in Construction*, vol. 19, no. 3, pp. 347-356.

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

Flick, U. 2002, *An Introduction to Qualitative Research*, 2nd edn, SAGE Publication, Inc.

Fink, A. 2006, *How to Conduct Surveys – A step by step guide*, 3rd edn, Thousand Oaks, Sage Publications, California and UK.

Fitzgerald, B. & Howcroft, D. 1998, "Towards dissolution of the IS research debates: from polarisation to polarity", *Journal of Information Technology*, vol. 13, no. 4, pp. 313-326.

Forgues, D., Iordanova, I., Valdivesio, F. & Staub-French, S. 2012, "Rethinking the Cost Estimating Process through 5D BIM: A Case Study", *Construction Research Congress 2012*, pp. 778-786.

Formoso, C.T., Isatto, E.L. & Hirota, E.H. 1999, "Method for waste control in the building industry", *Proceedings IGLC-7, 7th Conference of the International Group for Lean Construction*, Berkeley, CA, 26-28 July.

Formoso, C.T., M.ASCE, L.S., Cesare, C.D. & Isatto, E.L. 2002, "Material Waste in Building Industry: Main Causes and Prevention", *JOURNAL OF CONSTRUCTION ENGINEERING AND MANAGEMENT*, pp. 316-325.

Forsythe, P., and Marsden, P. K. 1999, “Material Waste in the UAE Construction Industry: Main Causes and Minimization Practices”. *Profitable partnering in construction procurement, CIB W92 (Procurement Systems) and CIB TG23 (Culture in Construction) Joint Symposium*, Spon, London, pp. 679-688.

Forza,C. 2002, "Survey research in operations management: a process-based perspective", *International Journal of Operations & Production Management*, vol. 22, no. 2, pp. 152-194.

Fowler, F.J. 2002, *Survey Research Methods*, 3rd edn, SAGE Publications Ltd, Thousand Oaks, California.

Franklin Associates. 1998, "CHARACTERIZATION OF BUILDING-RELATED CONSTRUCTION AND DEMOLITION DEBRIS IN THE UNITED STATES", *The U.S. Environmental Protection Agency, Municipal and Industrial Solid Waste Division, Office of Solid Waste*, Prairie Village, KS.

Frazer, L. & Lawley, M. 2000, *Questionnaire Design and Administration: A Practical Guide*, Wiley, Brisbane, Chichester.

Froese, T. 2003, "Future directions for IFC-based interoperability", *Special Issue IFC – Product Models for the AEC Arena*, vol. 8, pp. 231-246.

Fruchter, R., Clayton, M.J., Krawinkler, H., Kunz, J. & Teicholz, P. 1996, "Interdisciplinary communication medium for collaborative conceptual building design", *Advances in Engineering Software*, vol. 25, no. 2-3, pp. 89-101.

Gabbar, H.A., Aoyama, A. & Naka, Y. 2004, “Model-based computer-aided design environment for operational design”. *Computers & Industrial Engineering*, vol. 46, no. 3, pp. 413-430.

Gaito, J. 1980, "Measurement scales and statistics: Resurgence of an old misconception". *Psychological Bulletin*, vol. 87, no. 3, pp. 564-567.

Gamage, I.S.W., Osmani, M. & Glass, J. 2009, "An investigation into the impact of procurement systems on waste generation: the contractors' perspective". *In: DAINTY., A., Proceedings of 25th Annual ARCOM Conference*, 7-9 September 2009, Nottingham, UK, Association of Researchers in Construction Management, pp.1031-1040.

Ganah, A. & John, G. A. 2013, "Suitability of BIM for enhancing value on PPP projects for the benefit of the public sector". *PPP International Conference 2013 Body of Knowledge*, 18-19 March 2013, Preston, UK, pp.347-356.

Garrick, B.J. 2002, "The use of risk assessment to evaluate waste disposal facilities in the United States of America", *Safety Science*, vol. 40, no. 1-4, pp. 135-151.

Gavilan, R.M. & Bernold, L.E. 1994, "Source Evaluation of Solid Waste in Building Construction", *JOURNAL OF CONSTRUCTION ENGINEERING AND MANAGEMENT*, vol. 120, no. 3, pp. 536-552.

gbXML. 2013, 2012 update, *About gbXML*, [Online]. Available: http://www.gbxml.org/aboutgbxml.php [2013, 30 April].

gbXML. 2014, *History - Green Building XML Schema* [Online]. Available: http://www.gbxml.org/history.php [2014, 04 January].

Geyer, P. 2012, "Systems modelling for sustainable building design", *Advanced Engineering Informatics*, vol. 26, no. 4, pp. 656-668.

Gibson, W.J. & Brown, A. 2009, *Working with Qualitative Data*, SAGE Publications Ltd, London.

Gielingh, W. 1988, ""General AEC Reference Model (GARM)" Conceptual Modeling of Buildings", *CIB W74+W78 Seminar*, CIB Publication 126, Lund, Sweden.

Gillham, B. 2000, *The research interview*, 1st edn, Continum, London.

Glesene, C. 1999, *Becoming Qualitative Researchers - An Introduction*, 2nd edn, Longman, New York, USA.

Gökçe, H. U. & Gökçe, K. U. 2013, "Holistic system architecture for energy efficient building operation", *Sustainable Cities and Society*, vol. 6, pp. 77-84.

González-Aguilera, D., Rodriguez-Gonzalvez, P., Armesto, J. & Lagüela, S. 2012, "Novel approach to 3D thermography and energy efficiency evaluation", *Energy and Buildings*, vol. 54, pp. 436-443.

Grabowski, H. & Eigner, M. 1979, "Semantic data-model requirements and realization with a relational data-structure", *Computer-Aided Design*, vol. 11, no. 3, pp. 158-168.

Graham, P. & Smithers, G. 1996, "Construction Waste Minimization for Australian Residential Development", *Asia Pacific Building and Construction Management Journal*, vol. 2, no. 1, pp. 14-19.

Grayling, A.C. 1998, *Philosophy 1: A Guide through the Subject*, Oxford University Press.

Grbich, C. 2007, *Qualitative data analysis: an introduction*, Sage Publications Inc, London.

Green Construction Board. 2013, *CD&E WASTE: Halving Construction, Demolition and Excavation Waste to Landfill by 2012 compared to 2008*, [Online]. Available: http://www.greenconstructionboard.org/otherdocs/CD&E_waste_from_landfill_2011_Report.pdf [2013, 30 April].

Greenwood, R. 2003, *Construction Waste Minimisation Good Practice Guide*, The Welsh Assembly Government, Cardiff.

Greenwood, D., Horne, M., Thompson, E. M., Allwood, C. M., Wernemyr, C. & Westerdahl, B. 2008, “Strategic Perspectives on the Use of Virtual Reality within the Building Industries of Four Countries”. *Architectural Engineering and Design Management*, vol. 4, no. 2, pp. 85-98.

Grice, A. 2010, 8 July-last update, *UK warned it will run out of landfill sites in eight years* [Homepage of Independent news], [Online]. Available: http://www.independent.co.uk/news/uk/home-news/uk-warned-it-will-run-out-of-landfill-sites-in-eight-years-2021136.html [2010, 25 september].

Grilo, A. & Jardim-Goncalves, R. 2010, "Building information modeling and collaborative working environments", *Automation in Construction*, vol. 19, no. 5, pp. 521-521.

Grilo, A. & Jardim-Goncalves, R. 2011, “Challenging electronic procurement in the AEC sector: A BIM-based integrated perspective”. *Automation in Construction*, vol.20, pp. 107-114.

Grilo, A. & Jardim-Goncalves, R. 2013, “Cloud-Marketplaces: Distributed e-procurement for the AEC sector”, *Advanced Engineering Informatics*, vol.27, pp. 160-172.

Grilo, A., Zutshi, A., Jardim-Goncalves, R. & Steiger-Garcao, A. 2013, “Construction collaborative networks: the case study of a building information modelling-based office building project”. *International Journal of Computer Integrated Manufacturing*, vol. 26, no. 1-2, pp. 152-165.

Gruen, A., Behnisch, M. & Kohler, N. 2009, “Perspectives in the reality-based generation, nD modelling, and operation of buildings and building stocks”. *Building Research & Information*, vol. 37, no. 5-6, pp. 503-519.

Guffond, L.E. & Leconte, G. 1995, "Le 'disposif': un outil de mire en orme et de conduite du changement industrial", *Sociologie du Travail*, vol. 3, pp. 435-457.

Gurevich, U. & Sacks, R. 2014, “Examination of the effects of a KanBIM production control system on subcontractors' task selections in interior works”, *Automation in Construction*, vol. 77, pp. 81-87.

Hakim, C. 1987, *Research design: strategies and choices in the design of social research*, Routledge, London.

Hamassaki, L.T. & Neto, C.S. 1994, "Technical and economic aspects of construction/demolition waste utilization", *Sustainable construction (Proc. 1st Conf. of CIB TG 16)*, pp. 395-403, Gainesville, Fla.

Hamil, S. 2013, *The potential of BIM to reduce waste during design and construction* [Online]. Available: http://constructioncode.blogspot.co.uk/2013/03/the-potential-of-bim-to-reduce-waste.html [2013, 04 May].

Hammersley, M. & Gomm, R. 2000, "Introduction of Case Study Method" in *Case Study Method*, eds. R. Gomm, M. Hammersley & P. Foster, SAGE Publications Ltd., London, pp. 1-16.

Hamza, N. & DeWilde, P. 2014, “Building simulation visualization for the boardroom: an exploratory study”. *Journal of Building Performance Simulation*, vol. 7, no. 1, pp. 52-67.

Han, G.S.A., Bektaş, N. & Öncel, M.S. 2010, "Separate collection practice of packaging waste as an example of Küçükçekmece, Istanbul, Turkey", *Resources, Conservation and Recycling*, vol. 54, no. 12, pp. 1317-1321.

Hannabuss, S. 1996, "Research Interviews", *New Library World 97*, vol. 1129, pp. 22-30.

Hao, J.L., Hills, M.J. & Huang, T. 2007, "A simulation model using system dynamic method for construction and demolition waste management in Hong Kong", *Construction Innovation: Information, Process, Management*, vol. 7, no. 1, pp. 7-21.

Hao, J.L., Hill, M.J. & Shen, L.Y. 2008, "Managing construction waste on-site through system dynamics modelling: the case of Hong Kong", *Engineering, Construction and Architectural Management*, vol. 15, no. 2.

Hao, J.L.J., Tam, V.W.Y., Yuan, H.P., Wang, J.Y. & Li, J.R. 2010, "Dynamic modeling of construction and demolition waste management processes: An empirical study in Shenzhen, China", *Engineering, Construction and Architectural Management*, vol. 17, no. 5, pp. 476-492.

Hardin, B. 2009, *BIM and construction management: proven tools, methods, and workflows*, 1st edn, Wiley Publish, Inc, Canada.

Henry, G. T. 1990, *Practical sampling*, Sage Publications Inc., USA.

Hewage, K. & Porwal, A. 2012, *Sustainable Construction: An Information Modelling Approach for Waste Reduction* [Online]. Available: http://www.iiirr.ucalgary.ca/files/iiirr/148.pdf [2012, 04 May].

Hijazi, I. H., Ehlers, M. & Zlatanova, S. 2012, “a new approach to representing and analysing interior utility networks within 3D geo-information systems”. *International Journal of Digital Earth*, vol. 5, no. 1, pp. 22-42.

Hijazi, I., Zlatanova, S. & Ehlers, M. 2011, “NIBU: An integrated framework for representing the relation among building structure and interior utilities in micro-scale environment”. *Geo-spatial Information Science*, vol. 14, no. 2, pp. 98-108

Hjelseth, E. 2010, " Exchange of Relevant Information in BIM Objects Defined by the Role- and Life-Cycle Information Model", *Architectural Engineering and Design Management*, vol. 6, no. 4, pp. 279-287.

HM Government 2008, *Strategy for sustainable construction*, London.

HM Government. 2009, *Strategy for Sustainable Construction Progress Report* [Online]. Available: http://www.bis.gov.uk/files/file52843.pdf [2013, 22 September].

HM Government. 2011, *Environment*, [Online]. Available: http://www.redtapechallenge.cabinetoffice.gov.uk/themehome/environment-2/ [2013, 22 September].

HM Government. 2011b, *Government Construction Strategy 2011* [Online]. Available: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/61152/Government-Construction-Strategy_0.pdf [2013, 22 September].

HM Government. 2012, "Building Information Modelling". *Industrial strategy: government and industry in partnership*, BSi, London.

HM Government. 2013a, *Construction 2025: Industrial Strategy: government and industry in partnership* [Online]. Available: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/210099/bis-13-955-construction-2025-industrial-strategy.pdf [2013, 22 September].

HM Government. 2013b, 2013 update, *Budget 2013 policy decisions table* [HM Treasury], [Online]. Available: https://www.gov.uk/government/publications/budget-2013-policy-decisions-table/budget-2013-policy-decisions-table [2013, 22 September].

HM Revenue & Customs. 2013, 2013 update, *A general guide to Landfill Tax* [HM Revenue & Customs], [Online]. Available: http://customs.hmrc.gov.uk/channelsPortalWebApp/channelsPortalWebApp.portal?_nfpb=true&_pageLabel=pageExcise_ShowContent&propertyType=document&id=HMCE_CL_000509 [2013, 22 September].

Ho, P. & Fischer, M. 2009, "Validating Renovation Phasing Schedules Using 4D Model Based Methods". *Construction Research Congress 2009*, pp. 926-935.

Hoekstra, J. 2003, "Big buzz for BIM". *Architecture*, vol. 92, no. 7, pp. 79-82.

Hogwood, B.W. & Gunn, L.A. 1985, *Policy Analysis for the Real World*, Oxford University Press Inc., New York, USA.

Honderich, T. 1995, *The Oxford Companion to Philosophy*, Oxford University Press Inc., New York, USA.

Hong, T., Buhl. F., Haves, P., Selkowitz, S. & Wetter, M. 2008, "Comparing computer run time of building simulation programs". *Building simulation*, vol. 1, pp. 210-213.

Howard, R. & Björk, B. 2008, "Building information modelling – Experts' views on standardisation and industry deployment", *Advanced Engineering Informatics*, vol. 22, no. 2, pp. 271-280.

Howe, K.R. 1988, "Against the quantitative-qualitative incompatibility thesis or dogmas die hard", *Educational Researcher*, vol. 17, pp. 10-16.

Howell, I. & Batcheler, B. 2005, "Building Information Modeling Two Years Later — Huge Potential, Some Success and Several Limitations". *The Laiserin Letter*.

Hsieh, Y. & Lu, Y. 2012, "Visualization system for field monitoring data and its effectiveness", *Automation in Construction*, vol. 26, pp. 54-68.

Hu, Z. & Zhang, J. 2011, "BIM- and 4D-based integrated solution of analysis and management for conflicts and structural safety problems during construction: 2. Development and site trials", *Automation in Construction*, vol. 20, pp. 167-180.

IAI. 2008, *buildingSMART* [Homepage of International Alliance for Interoperability], [Online]. Available: http://www.buildingsmart.com/ [2010, 02 November].

IAI. 2010, 23 July-last update, *Model - Industry Foundation Classes (IFC)* [Homepage of Alliance for Interoperability], [Online]. Available: http://www.buildingsmart.com/bim [2010, 02 November].

Ibrahim, M., Krawczyk, R. & Schipporeit, G. 2004, "A web-based approach to transferring architectural information to the construction site based on the BIM object concept", *CAADRIA 2004 Conference*, pp. 1-10.

Ilal, M.E. 2007, "The quest for integrated design system: a brief survey of past and current efforts", *Middle East Technical University Journal of the Faculty of Architecture*, vol. 24, no. 2, pp. 10.

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

Irizarry, J., Karan, E. P. & Jalaei, F. 2013a, “Integrating BIM and GIS to improve the visual monitoring of construction supply chain management”. *Automation in Construction*, vol. 31, pp. 241-254.

Irizarry, J., Gheisari, M., Williams, G. & Walker, B. N. 2013b, “InfoSPOT: A mobile Augmented Reality method for accessing building information through a situation awareness approach”. *Automation in Construction*, vol. 33, pp. 11-23.

Isaac, S. & Navon, R. 2013, “A graph-based model for the identification of the impact of design changes”. *Automation in Construction*, vol. 31, pp. 31-40.

ISG. 2010, *IFC-Compliant Software -IAI-ISG* [Homepage of Implementer Support Group], [Online]. Available: http://www.iai.hm.edu/ifc-compliant-software [2010, 02 November].

Ishiwata, J. 1997, *IE for the Shop Floor: Productivity through Process Analysis*, Thomson Shore, Inc.

Isikdag, U., Underwood, J. & Aouad, G. 2008, "An investigation into the applicability of building information models in geospatial environment in support of site selection and fire response management processes", *Advanced Engineering Informatics*, vol. 22, no. 4, pp. 504-519.

Isikdag, U. & Underwood, J. 2010, “Two design patterns for facilitating Building Information Model-based synchronous collaboration”, *Automation in Construction*, vol. 19, pp. 544-553.

Jaillon, L., Poon, C.S. & Chiang, Y.H. 2009, "Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong", *Waste Management*, vol. 29, no. 1, pp. 309-320.

Jardim-Goncalves, R. & Grilo, A. 2010, "Building information modeling and interoperability", *Automation in Construction*, vol. 19, no. 4, pp. 387-387.

Jensen, P. A. 2009, “Design Integration of Facilities Management: A Challenge of Knowledge Transfer”. *Architectural Engineering and Design Management*, vol. 5, no. 3, pp. 124-135.

Jeong,S. & Ban, Y. 2011, “Developing a topological information extraction model for space syntax analysis”. *Building and Environment*, vol.46, pp. 2442-2453.

Jeong, Y., Eastman, C.M., Sacks, R. & Kaner, I. 2009, "Benchmark tests for BIM data exchanges of precast concrete", *Automation in Construction*, vol. 18, no. 4, pp. 469-484.

Jiao, Y., Zhang, S., Li, Y., Wang, Y. & Yang, B. 2013a, “Towards cloud Augmented Reality for construction application by BIM and SNS integration”. *Automation in Construction*, vol. 33, pp. 37-47.

Jiao, Y., Wang, Y., Zhang, S., Li, Y., Yang, B. & Yuan, L. 2013b, “A cloud approach to unified lifecycle data management in architecture, engineering, construction and facilities management: Integrating BIMs and SNS”. *Advanced Engineering Informatics*, vol. 27, no. 2, pp. 173-188.

Jick, T.D. 1979, "Mixing qualitative and quantitative methods: Triangulation in action", *Adiministrative Science Quarterly*, vol. 24, pp. 602-611.

Johnson, R. E. & Foote, B. 1988, " Designing reusable classes", *Journal of Object-Oriented Programing*, vol. 1, no. 2, pp. 22-35.

Kalay, Y. 1989, *Modeling Objects and Environments*, John Wiley & Sons, Inc., New York.

Kalton, G. 1983, *Introduction to survey sample*, Sage Publications, Inc., USA.

Kamardeen, I. 2010, “8D BIM modelling tool for accident prevention through design”, *In: Egbu, C. (Ed) Procs 26th Annual ARCOM Conference*, 6-8 September 2010, Leeds, UK, Association of Researchers in Construction Management, pp. 281-289.

Kang, L. S., Kim, S., Moon, H. S. & Kim, H. S. 2013, “Development of a 4D object-based system for visualizing the risk information of construction projects”, *Automation in Construction*, vol. 31, pp. 186-203.

Kelle, U. & Laurie, H. 1995, "Computer use in qualitative research and issues of validity" in *Computer-Aided Qualitative Data Analysis: Theory, Methods and Practice*, ed. U. Kelle, 1st edn, Sage, London.

Keller, T. & Tergan, S.O. 2005, “Visualizing knowledge and information: an introduction”. *Knowledge and Information Visualization*, vol. 3426, pp. 1-23.

Kemper, E. A., Stringfield, S. & Teddlie, C. 2003, “Mixed Method Sampling Strategies in Social Science Research”, *Handbook of mixed methods in social & behavioural research*, Sage Publications, pp. 273-296, Thousand Oaks, CA.

Kerlinger, F. 1964, *Foundations of beheavioral research*, Holt, Rinehart & Winston, New York.

Keys, A., Baldwin, A.N. & Austin, S.A. 2000, "Designing to encourage waste minimisation in the construction industry". CIBSE (Chartered Institute of Building Services Engineers).

Khosrowshahi, F. & Alani, A. 2011, “Visualisation of impact of time on the internal lighting of a building”, *Automation in Construction*, vol. 20, no. 2, pp. 145-154.

Kim, H. & Grobler, F. 2009, “Design Coordination in Building Information Modeling (BIM) Using Ontological Consistency Checking”, *COMPUTING IN CIVIL ENGINEERING - ASCE*, pp. 410-420.

Kim, T. W., Rajagopal, R., Fischer, M. & Kam. C. 2013a, “A knowledge-based framework for automated space-use analysis”. *Automation in Construction*, vol.32, pp. 165-176.

Kim, K., Kim, G. Yoo, D. & Yu, J. 2013b, “Semantic material name matching system for building energy analysis”. *Automation in Construction*, vol.30, pp. 242-255.

Kim, C., Son, H. & Kim, C. 2013c, “Automated construction progress measurement using a 4D building information model and 3D data”, *Automation in Construction*, vol. 31, pp. 75-82.

King, N. 1994, “The Qualitative Research Interviews”, *Qualitative Methods in Organisational Research: A Practical Guide*, Sage Publications, London.

Kiviniemi, M., Sulankivi, K., Kähkönen, K., Mäkelä, T. & Merivirta, M. 2011, “BIM-based Safety Management and Communication for Building Construction”, *Espoo 2011*, VTT Tiedotteita – Research Notes 2597.

Klein, L., Li, N. & Becerik-Gerber, B. 2012, “Imaged-based verification of as-built documentation of operational buildings”, *Automation in Construction*, vol. 21, pp. 161-171.

Knight, A. & Ruddock, L. 2008, *Advanced research methods in the built environment*, Wiley-Blackwell.

Knight, D., Roth, S. & Rosen, S.L. 2010, “Using BIM in HVAC Design”, *ASHRAE Journal*, vol. 52, no. 6, pp. 24-32.

Koo, B. & Fischer, M. 2000, “Feasibility study of 4D CAD in commercial construction”. *Constr. Eng*. M. ASCE, vol. 126, no. 4, pp. 251-261.

Koskela, L. 1992, *Application of the new production philosophy to construction*, CIFE, Stanford University, Stanford, CA.

Kovacic,I., Oberwinter,L., Müller, C. & Achammer, C. 2013, “The “BIM-sustain” experiment – simulation of BIM-supported multi-disciplinary design”. *Visualization in Engineering*, vol. 1, no. 1, Article.13, DOI:10.1186/2213-7459-1-13.

Krygiel, E. & Nies, B. 2008, *Green BIM: Successful Sustainable Design with Building Information Modeling*, John Wiley & Sons, Inc., Canada.

Ku, K. & Taiebat, M. 2011, “BIM Experiences and Expectations: The Constructors' Perspective”. *International Journal of Construction Education and Research*, vol. 7, no. 3, pp. 175-197.

Kuhn, T. S. 1996, *The Structure of Scientific Revolutions*, 3rd edn, University of Chicago Press, Chicago.

Kulatunga, U., Amaratunga, D. Haigh, R. and Rameezden, R. 2006, "Attitudes and Perceptions of construction workforce on Construction Waste in Sri Lanka", *Management and Environmental Quality: An International Journal*, Emerald Group Publishing Limited, United Kingdom. Vol 17, No. 1, pp. 57-72.

Kulasekara, G., Jayasena, H. S. & Ranadewa, K. A. T. O. 2013, "Comparative effectiveness of quantity surveying in a building information modelling implementation", *The Second World Construction Symposium 2013: Socio-Economic Sustainability in Construction*, 14-15 June, Colombo, Sri Lanka.

Kulahcioglu, T., Dang, J. & Toklu, C. 2012, "A 3D analyzer for BIM-enabled Life Cycle Assessment of the whole process of construction", *HVAC&R Research*, vol 18, no. 1-2, DOI:10.1080/10789669.2012.634264.

Kumar, R. 1999, *Research Methodology- Step by Step Guide*, Sage Publication, London.

Kuo, C., Tsai, M. & Kang, S. 2011, “A framework of information visualization for multi-system construction”, *Automation in Construction*, vol.20, pp. 247-262.

Kvale, S. & Brinkmann, S. 2009, *Interviews: Learning the Craft of Qualitative Research Interviewing*, Sage Publication, Los Angeles, Calif.

Kymmell, W. 2008, *Building Information Modeling: Planning and Managing Construction Projects with 4D CAD and Simulations*, McGraw-Hill, United States.

Lagüela, S., Díaz-Vilariño, L., Martínez, J. & Armesto, J. 2013, “Automatic thermographic and RGB texture of as-built BIM for energy rehabilitation purposes”, *Automation in Construction*, vol. 31, pp. 230-240.

Laiserin, J. 2010, "DESIGNER’S BIM: Vectorworks Architect keeps design at the center of BIM process", *LAISERINLETTER*, vol. 26.

Lancaster, F. & Tobin, J. 2010, “Integrated Project Delivery: Next-Generation BIM for Structural Engineering”, *Structures Congress 2010*, pp. 2809-2818.

Lee, S. & Akin, Ö. 2011, “Augmented reality-based computational fieldwork support for equipment operations and maintenance”, *Automation in Construction*, vol.20, pp. 338-352.

Lee, R.M. & Fielding, N.G. 1995, "Users' Experiences of Qualitative Data Analysis Software" in *Computer-Aided Qualitative Data Analysis: Theory, Methods and Practice*, ed. U. Kelle, 1st edn, Sage, London.

Lee, S., Diekmann, J., Songer, A.D. & Brown, H. 1999, "Identifying waste: applications of construction process analysis", *Proceedings IGLC-7*, pp. 63-72, University of California, Berkeley, CA, USA.

Lee, J., Min, K., Lee, Y., Kim, J. & Kim, J. 2008, “Building ontology to implement the bim(building information modeling) focused on Briefing stage”. *The 25th International Symposium on Automation and Robotics in Contruction*, Vilnius, Lithuania.

Lee, G., Sacks, R. & Eastman, C.M. 2006, “Specifying parametric building object behavior (BOB) for a building information modeling system”. *Automation in Construction*, vol. 15, no. 6, pp. 758-776.

Lee, G., Park, H. K. & Won, J. 2012a, “D3 City project — Economic impact of BIM-assisted design validation”. *Automation in Construction*, vol.22, pp. 577-586.

Lee, S., Bae, J. & Cho, Y. S. 2012b, “Efficiency analysis of Set-based Design with structural building information modeling (S-BIM) on high-rise building structures”. *Automation in Construction*, vol.23, pp. 20-32.

Leedy, P.D. & Ormrod, J.E. 2005, *Practical research: Planning and design*, 8th edn, Pearson Merrill Prentice Hall, New Jersey.

Leite, P.R. 2003, *Logistica Reversa (Reverse Logistics)*, Prentice Hall, Sa˜o Paulo.

Leite, F., Akcamete, A., Akinci, B., Atasoy, G. & Kiziltas, S. 2011, “Analysis of modeling effort and impact of different levels of detail in building information models”, *Automation in Construction*, vol.20, pp. 601-609.

Lewin, K. 1946, "Action research and minority problem", *Journal of Social Issues*, vol. 2, pp. 34-36.

LGA Media Office. 2007, 26 April-last update, *Landfill space will run out in nine years warn council leaders* [Homepage of Local Government Association], [Online]. Available: http://www.lga.gov.uk/lga/core/page.do?pageId=41793 [2010, 25 september] .

Li, H., Chen, Z., Yong, L. & Kong, S.C.W. 2005, "Application of integrated GPS and GIS technology for reducing construction waste and improving construction efficiency", *Automation in Construction*, vol. 14, no. 3, pp. 323-331.

Li, H., Huang, T., Kong, C.W., Guo, H.L., Baldwin, A., Chan, N. & Wong, J. 2008, “Integrating design and construction through virtual prototyping”, *Automation in Construction*, vol.17, pp. 915-922.

Lincoln, Y.S. & Guba, E.G. 1985, *Naturalistic inquiry*, Sage Publication, Thousand Oaks, CA.

Lingard, H., Graham, P. & Smithers, G. 2000, "Employee perceptions of the solid waste management system operating in a large Australian contracting organization: implications for company policy implementation", *Construction Management and Economics*, vol. 18, no. 4, pp. 383.

Lingard, H., Gilbert, G. & Graham, P. 2001, "Improving solid waste reduction and recycling performance using goal setting and feedback", *Construction Management and Economics*, vol. 19, no. 8, pp. 809-817.

London, K. & Singh, V. 2013, “Integrated construction supply chain design and delivery solutions”. *Architectural Engineering and Design Management*, vol. 9, no. 3, pp. 135-157.

Loosemore M., Dainty, A. & Lingard, H. 2002, *Strategic human resource management in the construction industry*, Taylor and Francis, London.

Love, P. E., Edwards, D. J., Han, S. & Goh, Y. M. 2011, “Design error reduction : toward the effective utilization of building information modeling”. *Research in engineering design*, vol. 22, no. 3, pp. 173-187, SPRINGER VERLAG KG, Germany.

Love, P.E.D., Holt, G.D. & Li, H. 2002, "Triangulation in Construction Management Research", *Engineering, Construction and Architectural Management*, vol. 9, no. 4, pp. 294-303.

Love, P.E.D., Li, H. & Mandal, P. 1999, "Rework: a symptom of a dysfunctional supplychain", *European Journal of Purchasing and Supply Management*, vol. 5, pp. 1-11.

Love, P. E., Lopez, R. & Kim, J. T. 2013a, “Design error management: interaction of people, organisation and the project environment in construction”, *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*, DOI:10.1080/15732479.2013.767843.

Love, P. E., Lopez, R. & Edwards, D. J. 2013b, “Reviewing the past to learn in the future: making sense of design errors and failures in construction”. *Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance*, vol. 9, no. 7, pp. 675-688.

Ma, Z., Wei, Z. & Zhang, X. 2013, “Semi-automatic and specification-compliant cost estimation for tendering of building projects based on IFC data of design model”, *Automation in Construction*, vol.30, pp. 126-135.

Mah, D., Manrique, J. D., Yu, H., Al-Hussein, M. & Nasseri, R. 2011, “House construction CO2 footprint quantification: a BIM approach”. *Construction innovation*, vol. 11, no. 2, pp. 161-178.

Male, S., Kelly, J., Fernie, S., Gronqvist, M. & Bowles, G. 1998, *The value management benchmark: A framework for clients and practitioners*, Thomas Telford, London.

Malkin, R. 2010, “building information modelling (BIM) for efficient sustainable design”. *ARCHITECTURE AUSTRALIA*, vol. 99, no. 5, pp. 105-107.

Martins, J. P. & Monteiro, A. 2013, “LicA: A BIM based automated code-checking application for water distribution systems”, *Automation in Construction*, vol.29, pp. 12-23.

Mayring, P. 2000, “Qualitative Content Analysis” [Online]. Available: http://www.qualitative-research.net/index.php/fqs/article/view/1089/2385 [2013, 20 Feb].

McDonald, B. & Smithers, M. 1998, "Implementing a waste management plan during the construction phase of a project: a case study", *Construction Management and Economics*, vol. 16, no. 1, pp. 71-78.

McGraw-Hill 2007, *Interoperability in the construction industry*, McGraw-Hill Construction, New York.

McGraw-Hill 2008, *Building Information Modeling (BIM): Transforming Design and Construction to Achieve Greater Industry Productivity*, McGraw-Hill Construction, New York.

McGraw-Hill 2010, *Green BIM Smart Market Report: How Building Information Modeling is Contributeing to Green Design and Construction*, McGraw-Hill construction, New York.

McKechnie, E. & Brown, E. 2007, "Achieving effective waste minimisation through design", [Online]. Available: http://www2.wrap.org.uk/downloads/Design_FINAL.a4fded37.4821.pdf [2013, 20 Feb].

McKinney, K. & Fischer, M. 1998, "Generating, evaluating and visualizing construction schedules with CAD tools", *Automation in Construction*, vol. 7, no. 6, pp. 433-447.

Mertens, D.M. 1998, *Education; Psychology; Research; Methodology*, Sage Publications, CA.

Messick, S. 1989, *Validity: Educational Measurement*, Macmillan, New York, USA.

Messick, S. 1995, "Validity of psychological assessment: Validation of inferences from persons' responses and performances as scientific inquiry into score meaning", *American Psychologist*, vol. 50, no. 9, pp. 741-749.

Mihindu, S. & Arayici, Y. 2008, "Digital construction through BIM systems will drive the re-engineering of construction business practices". *Proceedings of the International Conference Visualisation, IEEE Computer Society*, Los Alamitos, CA.

Mikulakova, E., König, M., Tauscher, E. & Beucke, K. 2010, "Knowledge-based schedule generation and evaluation", *Advanced Engineering Informatics*, vol. 24, no. 4, pp. 389-403.

Mills, T.H., Showalter, E. & Jarman, D. 1999, "A Cost-Effective Waste Management Plan", *Cost Engineering*, vol. 41, no. 3, pp. 35-43.

Moore, N. 2000, *how to do research: The complete guide to designing and managing research projects*, 3rd edn, Library Association, London.

Morgan, D.L. & Krueger, R.A. 1998, *The Foucs Group Kit*, Sage Publication, Thousand Oaks, CA.

Motawa, I. & Almarshad, A. 2013, "A knowledge-based BIM system for building maintenance", *Automation in Construction*, vol.29, pp. 173-182.

Moum, A. 2010, "Design team stories Exploring interdisciplinary use of 3D object models in practice", *Automation in Construction*, vol.19, pp. 554-569.

Muhwezi, L., Chamuriho, L. M., & Lema, N. M. 2012, "An investigation into Materials Wastes on Building Construction Projects in Kampala-Uganda", *Scholarly Journal of Engineering Research*, vol. 1, no. 1, pp. 11-18.

Murphy, M., McGovern, E. & Pavia, S. 2013, " Historic Building Information Modelling – Adding intelligence to laser and image based surveys of European classical architecture", *ISPRS Journal of Photogrammetry and Remote Sensing*, vol. 76, pp. 89-102.

Nagapan, S., Rahman, I.A., Asmi, A., Memon, A.H. & Zin, R.M. 2012, "Identifying Causes of Construction Waste - Case of Centra Region of Peninsula Malaysia", *International Journal of Integrated Engineering*, vol. 4, no. 2, pp. 22-28.

Naoum, S.G. 2002, *Dissertation Research Writing for Construction Students*, Butterworth-Heinemann, Oxford.

Nassar, K. 2010, “A model for assessing occupant flow in building spaces”. *Automation in Construction*, vol.19, pp. 1027-1036.

Nawari, N.O. 2012, “BIM-Model Checking in Building Design”. *PROCEEDINGS OF STRUCTURES CONGRESS*, vol. 2, pp. 941-952.

NBS. 2011, *Building Information Modelling Report*, Newcastle. UK.

NBS. 2012, *National BIM Report 2012*, Newcastle. UK.

NBS. 2013, *National BIM Report 2013*, Newcastle. UK.

Neff, G., Fiore-Silfvast, B. & Dossick, C. S. 2010, “A case study of the failure of digital communication to cross knowledge boundaries in virtual construction”. *Information, Communication & Society*, vol. 13, no. 4, pp. 556-573.

Neo, R. B. & Koh, T. J. 1995, “Accounting for waste in construction”. *Proceedings of the First International Conference on Construction Project Management*, Singapore, pp.399-406.

Nepal, M. P., Staub-French, S., Pottinger, R. & Webster, A. 2012, “Querying a building information model for construction-specific spatial information”. *Advanced Engineering Informatics*, vol.26, pp. 904-923.

Neuman, W.L. 2006, *Social Research Methods: Qualitative and Quantitive Approaches*, 6th edn, Pearson Education, Boston.

Newman, I. & Benz, C.R. 1998, *Qualitative-Quantitative Research Methodology: Exploring the Interactive Continuum*, Southern Illinois University Press.

Ningappa, G. 2011, "Use of Lean and Building Information Modeling (BIM) in the Construction Process; Does BIM make it Leaner?", *Master degree thesis*, Georgia Institute of Technology.

Nisbet, N. & Dinesen, B. 2010, *Building information modelling: construction the business case*, British Standards Institution, London.

Novick, G. 2008, "Is there a bias against telephone interviews in qualitative research?", *Researching in Nursing and Health*, vol. 31, no. 4, pp. 391-398.

NSCC. 2007, *Reduce, Reuse, Recycle Managing your waste*, [Online]. Available: http://www.nscc.org.uk/docs/general/002fGuidanceonwaste.pdf [2013, 22 September].

Nunes, K.R.A., Mahler, C.F. & Valle, R.A. 2009, "Reverse logistics in the Brazilian construction industry", *Journal of environmental management*, vol. 90, no. 12, pp. 3717-3720.

Odman, P. 1988, "Hermeneutics" in *Educational research methodology and measurement: An international handbook*, ed. J.P. Keeves, Pergamon Press, New York, pp. 63-70.

Ofori, G. 2000, "Greening the construction supply chain in Singapore", *European Journal of Purchasing & Supply Management*, vol. 6, no. 3-4, pp. 195-206.

O’Keeffe, S. E. 2012, "Developing 6D BIM Energy Informatics for GDL LEED IFC Model Elements", *Proceedings of the 2012 International Conference on Industrial Engineering and Operations Management*, 3-6 July, Istanbul, Turkey.

O'Keeffe, S., Shiratuddin, M.F. & Fletcher, D. 2009, "LEED certification review in a Virtual Environment", *In: 9th International Conference on Construction Applications of Virtual Reality*, 5-6 November, Sydney, Australia.

ONS. 2011, *Annual Business Survey*, [Online]. Available: http://www.ons.gov.uk/ons/dcp171778_286414.pdf [2013, 22 September].

O'Reilly, A. 2012, “Using BIM as a tool for cutting construction waste at source”. *CIOB Construction Research and Innovation*, vol. 3, no. 1, pp. 28-31.

Osello,A., Cangialosi,G., Dalmasso, D., Paolo,A. D., Turco,M. L., Piumatti,P. & Vozzola, M. 2011, “Architecture data and energy efficiency simulations: BIM and interoperability standards”. *Proceedings of Building Simulation 2011: 12th Conference of International Building Performance Simulation Association*, 14-16 November, Sydney.

Osmani, M. 2005, "Potential for construction waste minimisation through design", *Sustainable Development and Planning II, Vols 1 and 2*, vol. 84, pp. 575-584.

Osmani, M. 2012, “A Kaleidoscope Evaluation of Construction Waste Management in the UK", *CRETE 2012: 3rd International Conference on Industrial and Hazardous Waste Management.*

Osmani, M. 2013, "Design waste mapping: a project life cycle approach", *Proceedings of the ICE - Waste and Resource Management*, vol. 166, no. 3, pp. 114-127.

Osmani, M., Glass, J. & Price, A. 2006, "Architect and contractor attitudes to waste minimisation", *Proceedings of the Institution of Civil Engineers*: Waste and Resource Managament, vol. 159, pp. 65-72.

Osmani, M., Glass, J. & Price, A.D.F. 2008, "Architects' perspectives on construction waste reduction by design", *Waste Management*, vol. 28, no. 7, pp. 1147-1158.

Panos, K. & Danai, G. I. 2012, "Survey Regarding Control and Reduction of Construction Waste", *PLEA2012 - 28th Conference, Opportunities, Limits & Needs Towards an environmentally responsible architecture*, Lima, Perú.

Papakyriakou, A. & Hopkinson, L. 2012, “The potential of integrating Design for Deconstruction as a waste minimization strategy into the profession of the architect", *Proceedings of 2nd Conference: People and Buildings*, London Metropolitan University, London, UK.

Park, C. & Kim, H. 2013, "A framework for construction safety management and visualization system", *Automation in Construction*, vol. 33, pp. 95-103.

Park, C., Lee, D., Kwon, O. & Wang, X. 2013, “A Framework for Proactive Construction Defect Management using BIM, Augmented Reality and Ontology-based Data Collection Template”, *Automation in Construction*, vol. 33, pp. 61-71.

Patton, M.Q. 1990, *Qualitative evaluation and research methods*, 2nd edn, Sage Publications, Newbury Park, CA.

Patton, M.Q. 2003, *Qualitative Evaluation and Research Methods*, 3rd edn, Sage Publications Inc, Newbury Park, CA.

Paul, H. 1993, *Reconstructing Scientific Revolutions: Thomas S. Kuhn's Philosophy of Science*. Translated by Alexander T. Levine. (With a Foreword by Thomas S. Kuhn.), 2nd edn, University of Chicago Press, Chicago.

Pauwels, P., Van Deursen, D., Verstraeten, R., De Roo, J. De Meyer, R., Van de Walle, R. & Van Campenhout, J. 2011, “A semantic rule checking environment for building performance checking”, *Automation in Construction*, vol.20, pp. 506-518.

Peng, C., Scorpio, D.E. & Kibert, C.J. 1997, "Strategies for successful construction and demolition waste recycling operations", *Construction Management and Economics*, vol. 15, no. 1, pp. 49-58.

Penttilä, H. 2006, "Describing the changes in architectural information technology to understand design complexity and free-form architectural expression", *ITCON 11 (Special Issue The Effects of CAD on Building Form and Design Quality)*, pp. 395-408.

Penttilä, H. 2007, "Early Architectural Design and BIM". *Computer-aided architectural design futures conference; CAAD Futures 2007*, pp. 291-302, Sydney.

Perry, C. 1994, "A structureed approach to presenting PhD theses: notes for candidates and their supervisors.", Paper presented to the ANZ doctorial consortium.

Phillips, D.C. & Burbules, N.C. 2000, *Postpositivism and educational research*, Rowman & Littlefield publishers, Lanham, MD.

Pickering, A. 1992, *Science as Practice and Culture*. University of Chicago Press, Chicago.

Pidd, M. 2009, *Tools for Thinking: Modelling in Management Science*, John Wiley & Sons, Inc., West Sussex, United Kingdom.

Pinto, T.P. 1989, "‘‘Perda de materiais em processos construtivos tradicionais’’(Material waste in traditional construction processes)", *Research Rep*., Federal Univ of Sa˜o Carlos,, Sa˜o Carlos (in Portuguese).

Plume, J. & Mitchell, J. 2007, "Collaborative design using a shared IFC building model—Learning from experience", *Automation in Construction*, vol. 16, no. 1, pp. 28-36.

Polat, G. & Ballard, G. 2004, "Waste in Turkish construction: need for lean construction techniques", *12th Annual Conference on lean construction, Denmark*, IGLC, Copenhagen, Denmark.

Polesie, P., Frödell, M., & Josephson, P. 2009, "Implementing standardisation in medium-sized construction firms: facilitating site managers' feeling of freedom through a bottom-up approach", *Proceedings for the 17th Annual Conference of the International Group for Lean Construction*.

Poon, C.S. 2007, "Reducing construction waste", *Waste Management*, vol. 27, no. 12, pp. 1715-1716.

Poon, C.S. & Jaillon, L. 2010, "Designing for Waste Minimization in High-Density Cities" in *Designing High-Density Cities: For Social and Environmental Sustainability*, ed. E. Ng, Earthscan, London, pp. 195-207.

Poon, C.S., Yu, A.T.W. & Jaillon, L. 2004, "Reducing building waste at construction sites in Hong Kong", *Construction Management and Economics*, vol. 22, no. 5, pp. 461-470.

Poon, C.S., Yu, A.T.W. & Ng, L.H. 2001, "On-site sorting of construction and demolition waste in Hong Kong", *Resources, Conservation and Recycling*, vol. 32, no. 2, pp. 157-172.

Poon, C.S., Yu, A.T.W., & Ng, L.H. 2003, "Comparison of low waste building technologies adopted in public and private housing projects in Hong Kong". *Engineering, Construction and Architectural Management*, vol.10, no. 2, pp. 88-98.

Popov, V., Juocevicius, V., Migilinskas, D., Ustinovichius, L. & Mikalauskas, S. 2010, "The use of a virtual building design and construction model for developing an effective project concept in 5D environment". *Automation in Construction*, vol.19, pp. 357-367.

Porwal, A. 2013, "Construction waste management at source: a building information modeling based system dynamics approach", *Doctoral Thesis*, the University of British Columbia.

Porwal, A. & Hewage, K. N. 2012, "Building Information Modeling–Based Analysis to Minimize Waste Rate of Structural Reinforcement". *Journal of construction engineering and management*, vol.138, pp. 943-954.

Porwal, A. & Hewage, K. N. 2013, “Building Information Modeling (BIM) partnering framework for public construction projects”. *Automation in Construction*, vol. 31, pp. 204-214.

Prins, M. & Owen, R. 2010, “Integrated Design and Delivery Solutions”, *Architectural Engineering and Design Management*, vol. 6, no. 4, pp. 227-231.

Punch, K.F. 1998, *Introduction to Social Research: Quantitative and Qualitative Approaches*, Sage Publications, London.

Qi, G.Y., Shen, L.Y., Zeng, S.X. & Jorge, O.J. 2010, "The drivers for contractors’ green innovation: an industry perspective", *Journal of Cleaner Production*, vol. 18, no. 14, pp. 1358-1365.

Rawlinson, S. & Weight, D. 2007, *Sustainability — Embodied carbon* [BuildingMagazine], [Online]. Available: http://www.building.co.uk/data/sustainability-%E2%80%94-embodied-carbon/3097160.article#ixzz0R4kkECS1 [2013, 30 April].

Razavi, S. N. & Haas, C. T. 2010, “Multisensor data fusion for on-site materials tracking in construction”, *Automation in Construction*, vol. 19, no. 8, pp. 1037-1046.

Redmond, A., Hore, A., Alshawi, M. & West, R. 2012, “Exploring how information exchanges can be enhanced through Cloud BIM”. *Automation in Construction*, vol. 24, pp. 175-183.

Rekola, M., Kojima, J. & Mäkeläinen, T. 2010, “Towards Integrated Design and Delivery Solutions: Pinpointed Challenges of Process Change”, *Architectural Engineering and Design Management*, vol. 6, no. 4, pp. 264-278.

Ren, Y., Skibniewski, M. J. & Jiang, S. 2012, “Building information modeling integrated with electronic commerce material procurement and supplier performance management system”. *Journal of Civil Engineering and Management*, vol. 18, no. 5, pp. 642-654.

RIBA. 2008, *RIBA Outline Plan of Work 2007* [architecture], [Online]. Available: http://www.architecture.com/Files/RIBAProfessionalServices/Practice/Archive/OutlinePlanofWork%28revised%29.pdf [2013, 30 April].

RICS. 2013, 2013 update, *Building4Change _ Survey finds lack of client demand is biggest barrier to BIM* [Building4Change], [Online]. Available: http://www.building4change.com/page.jsp?id=1795 [2013, 30 April].

Riemer, J. & Kristoffersen, M. 1999, *Information on waste management practices, European Environmental Agency*, Copenhagen, Denmark.

Robson, C. 2002, *Real World Research*, 2nd edn, Blackwell Publications, Oxford.

Roh, S., Aziz, Z. & Peña-Mora, F. 2011, “An object-based 3D walk-through model for interior construction progress monitoring”, *Automation in Construction*, vol. 20, pp. 66-75.

Roorda, D. & Liu, M. K. 2008, "Implementation of Building Information Modeling (BIM) on the Renovation of the Art Gallery of Alberta in Edmonton, Alberta", *In: 18th Analysis and Computation Speciality Conference*, 2008, Vancouver, Canada.

Rounce, G. 1998, "Quality, waste and cost considerations in architectural building design management", *International Journal of Project Management*, vol. 16, no. 2, pp. 123-127.

Royat, S. 1994, "Development Strategy of Construction Industry in Indonesia", *Workshop on Strategic Management in Construction Industry*, Bandung.

Royer, I. & Zarlowski, P. 2001, "Research design" in *Doing Management Research: A Comprehensive Guide*, ed. R. Thiétart, Sage Publications, London, pp. 111-131.

Rüppel,U. & Schatz, K. 2011, " Designing a BIM-based serious game for fire safety evacuation simulations", *Advanced Engineering Informatics*, vol. 25, no. 4, pp. 600-611.

Ruwanpura, J.Y., Hewage, K.N. & Silva, L.P. 2012, “Evolution of the i-Booth© onsite information management kiosk”, *Automation in Construction*, vol. 21, pp. 52-63.

Saad, M., Jones, M. & James, P. 2002, "A review of the progress towards the adoption of supply chain management (SCM) relationships in construction", *European Journal of Purchasing & Supply Management*, vol. 8, no. 3, pp. 173-183.

Sacks, R., Eastman, C. & Lee, G. 2004, “Parametric 3D modeling in building construction with examples from precast concrete”. *Automation in Construction*, vol. 13, pp. 291-312.

Sacks, R., Treckmann, M. & Rozenfeld, O. 2009, “Visualization of Work Flow to Support Lean Construction”. *Journal of construction engineering and management*, vol. 135, no. 2, pp. 1307-1315.

Sacks, R., Koskela, L. J., Dave, B. A. & Owen, R. 2010, "The interaction of lean and building information modeling in construction", *Journal of Construction Engineering and Management*, vol. 136, no. 9, pp. 968-980.

Sacks, R., Kaner, I., Eastman, C.M. & Jeong, Y. 2010a, "The Rosewood experiment — Building information modeling and interoperability for architectural precast facades", *Automation in Construction*, vol. 19, no. 4, pp. 419-432.

Sacks, R., Radosavljevic, M. & Barak, R. 2010b, “Requirements for building information modeling based lean production management systems for construction”, *Automation in Construction*, vol. 19, pp. 641-655.

Sanguinetti, P., Abdelmohsen, S., Lee, J., Lee, J., Sheward, H. & Eastman, C. 2012, “General system architecture for BIM: An integrated approach for design and analysis”. *Advanced Engineering Informatics*, vol.26, pp. 317-333.

Santos, A. Formoso, C. T. & Tookey J. E. 2002, “Expanding the meaning of standardisation within construction processes”. *The TQM Magazine*, vol.14, no. 1, pp. 25-33.

Sapsford, R. & Jupp, V. 1996, *Data collection and analysis*, Sage Publications, London.

Saunders, J. & Wynn, P. 2004, "Attitudes towards waste minimisation amongst labour only sub-contractors", *Structural Survey*, Vol. 22 Iss: 3, pp.148 – 15.

Saunders, M., Lewis, P. & Thornhill, A. 2007, *Research methods for business students*, 4th edn, Prentice Hall, London.

Schade, J., Olofsson, T. & Schreyer, M. 2011, “Decision‐making in a model‐based design process”, *Construction Management and Economics*, vol. 29, no. 4, pp. 371-382.

Scherer, R.J. & Schapke, S. E. 2011, “A distributed multi-model-based Management Information System for simulation and decision-making on construction projects”, *Automation in Construction*, vol. 25, pp. 582-599.

Schlueter, A. & Thesseling, F. 2009, "Building information model based energy/exergy performance assessment in early design stages", *Automation in Construction*, vol. 18, no. 2, pp. 153-163.

Sealey, B.J., Phillips, P.S. & Hill, G.J. 2001, "Waste management issues for the UK ready-mixed concrete industry", *Resources, Conservation and Recycling*, vol. 32, no. 3-4, pp. 321-331.

Sebastian, R. 2010, “Integrated Design and Engineering using Building Information Modelling: A Pilot Project of Small-Scale Housing Development in The Netherlands”, *Architectural Engineering and Design Management*, vol. 6, no. 2, pp. 103-110.

Sekaran, U. 2002, *Research Methods for Business: A Skill Building Approach*, 3rd edn, Wiley, New York.

Selltiz, C., Jahoda, M. & Deutsch, M. 1965, *Research Methods in Social Relations*, Methuen, London.

Serpell, A., Venturi, A. & Contreras, J. 1995, "Characterization of waste in building construction projects" in *Lean Construction*, ed. Alarcon , A.A. Balkema, Rotterdam, Netherlands.

Sharma, S. & Fisher, A. 2013, “Simulating the User Experience Design Optimisation for Visitor Comfort”. *ARCHITECTURAL DESIGN*, vol. 83, no. 2, pp. 62-65, John Wiley & Sons, United Kingdom.

Shelden, D. 2013, “Networked Space”. *ARCHITECTURAL DESIGN*, vol. 83, no. 2, pp. 36-41, John Wiley & Sons, United Kingdom.

Shen, W., Shen, Q. & Sun, Q. 2012a, “Building Information Modeling-based user activity simulation and evaluation method for improving designer–user communications”. *Automation in Construction*, vol.21, pp. 148-160.

Shen, W., Hao, Q. & Xue, Y. 2012b, “A loosely coupled system integration approach for decision support in facility management and maintenance”. *Automation in Construction*, vol.25, pp. 41-48.

Shen, L.Y. & Tam, V.W.Y. 2002, "Implementation of environmental management in the Hong Kong construction industry", *International Journal of Project Management*, vol. 20, no. 7, pp. 535-543.

Shen, L.Y., Tam, V.W.Y., Tam, C.M. & Drew, D. 2004, "Mapping approach for examining waste management on construction sites", *JOURNAL OF CONSTRUCTION ENGINEERING AND MANAGEMENT*, vol. 130, pp. 472-481.

Shen, W., Zhang, X., Shen, G. Q. & Fernando, T. 2013, “The User Pre-Occupancy Evaluation Method in designer–client communication in early design stage: A case study”, *Automation in Construction*, vol. 32, pp. 112-124.

Shin, D. H. & Dunston, P. S. 2010, “Technology development needs for advancing Augmented Reality-based inspection”, *Automation in Construction*, vol.19, pp. 169-182.

Shin, D. H., Park, J., Woo, S. & Jang, W. 2013, “Representations for imagining the scene of non-existing buildings in an existing environment”, *Automation in Construction*, vol. 33, pp. 86-94.

Silva, N.D. & Vithana, S.B.K.H. 2008, "Use of PC elements for waste minimization in the Sri Lankan construction industry", *Structural Survey*, vol. 26, no. 3, pp. 188-198.

Silverman, D. 2010, *Doing Qualitative Research,* 3rd edn, SAGE Publication Ltd.

Sinclair, K. M. 2005, *Construction and Demolition Waste Reduction Project-SMF 4194* [Online]. Available: http://www.branz.co.nz/cms_show_download.php?id=f41f5e4783639c1e94058911d9cf6caca3fb2cb2 [2013, 22 September].

Sinclair, D. 2012, *BIM Overlay to the RIBA Outline Plan of Work*, RIBA, London, UK.

Singh, V., Gu, N. & Wang, X. 2011, “A theoretical framework of a BIM-based multi-disciplinary collaboration platform”, *Automation in Construction*, vol. 20, pp. 134-144.

Skoyles, E.R. 1976, "Materials wastage - a misuse of resources", *Building Research & Information*, vol. 4, no. 4, pp. 232.

Skoyles, E.R. & Skoyles, J.R. 1987, *Waste Prevention on Site*, Mitchell Publishing, London.

Smith, D.K. & Tardif, M. 2009, *Building information modeling: a strategic implementation guide for architects, engineers, constructors, and real estate asset managers*, John Wiley & Sons, Inc., Canada.

Snook, K., Turner, A. & Ridout, R. 1995, *Recycling waste from the construction site*, Chartered Institute of Building.

Soibelman, L., Formosa, C.T. & Franchi, C.C. 1994, "A study on the waste of materials in the building industry in Brazil", *in Proceedings of the First International Conference of CIB TG16*, pp. 555-563, Sustainable construction, Gainesville, Florida.

Song, S., Yang, J. & Kim, N. 2012, “Development of a BIM-based structural framework optimization and simulation system for building construction”. *Computers in Industry*, vol.63, pp. 895-912.

Spivey, D.A. 1974, "Construction Solid Waste", *Journal of the Construction Division*, vol. 100, no. 4, pp. 501-506.

Stake, R. 1995, *The art of case study research*, Sage Publications, Thousand Oaks, CA.

Steel, J., Drogemuller, R. & Toth, B. 2012, “Model interoperability in building information modelling”. *Software and Systems Modeling*, vol. 11, no. 1, pp. 99-109.

STEP Tools 2010, *ISO 10303 STEP Standards*, [Homepage of STEP Tools Incorporated], [Online]. Available: http://www.steptools.com/library/standard/ [2010, 02 November].

Steptools. 2013, *STEP standard* [Online]. Available: http://www.steptools.com/library/standard/ [2013, 22 September].

Stopher, P. R. & Meybury, A. H. 1979, *Survey sampling and multivariate analysis for social scientists and engineers*, D.C. Heath and Company, Canada.

Strategic Forum for Construction. 2010, *CD&E WASTE: Halving Construction, Demolition and Excavation Waste to Landfill by 2012 compared to 2008* [Online]. Available: http://www.strategicforum.org.uk/pdf/Waste_report_4_draft_22-3-10V4.pdf [2013, 04 January].

Strategic Forum for Construction. 2011, *Waste Action Plan* [Online]. Available: http://www.strategicforum.org.uk/pdf/10WasteActionPlan.pdf [2013, 04 January].

Strategic Forum for Construction. 2012, 2012 update, *The 2010 Assessment for CD&E Waste to Landfill in England*, [Online]. Available: http://www.strategicforum.org.uk/pdf/CD&E-waste-to-landfill-figures2010.pdf [2013, 22 September].

Studer, R., Benjamins, V.R. & Fensel, D. 1998, "Knowledge engineering: principles and methods", *Data & Knowledge Engineering*, vol. 25, no. 1-2, pp. 161-197.

Succar, B. 2009, "Building information modelling framework: A research and delivery foundation for industry stakeholders", *Automation in Construction*, vol. 18, no. 3, pp. 357-375.

Sulankivi, K., Mäkelä, T. & Kiviniemi, M. 2009, "BIM-based Site Layout and Safety Planning", *Proceedings of the First International Conference on Improving Construction and Use through Integrated Design Solutions*, CIB IDS 2009, 10-12 June 2009 Espoo, Finland. VTT Symposium 259, pp. 125-140.

Surrey county council. 2010, 07 september-last update, *Landfill sites*, [Online].Available: http://www.surreycc.gov.uk/sccwebsite/sccwspages.nsf/LookupWebPagesByTITLE_RTF/Landfill+sites?opendocument [2010, 25 september].

Tam, V.W.Y., Shen, L.Y. & Tam, C.M. 2002, "The practices of implementing governmental control in managing construction wastes in Hong Kong", *CIB W107: Creating a Sustainable Construction Industry in Developing Countries*, pp. 113-124.

Tam, V.W.Y., & Tam, C.M. 2006, "A review on the viable technology for construction waste recycling". *Resources, Conservation and Recycling*, vol.47, no. 3, pp. 209-221.

Tam, V.W.Y., Tam, C.M. & Ng, W.C.Y. 2007, "On prefabrication implementation for different project types and procurement methods in Hong Kong", *Journal of Engineering, Design and Technology*, vol. 5, no. 1, pp. 68-80.

Tan, W. 2002, *Practical research methods*, Pearson Education Asia Pte Ltd., Singapore.

Tang, P., Huber, D., Akinci, B., Lipman, R. & Lytle, A. 2010, " Automatic reconstruction of as-built building information models from laser-scanned point clouds: A review of related techniques", *Automation in Construction*, vol. 19, no. 7, pp. 829-843.

Tashakkori, A. & Teddlie, C. 2003, *Handbook of mixed methods in social and behavioral research*, Sage Publications, Thousand Oaks, CA.

Tashakkori, A. & Teddlie, A. 2009, *Foundation of Mixed Methods Research: Integrating Quantitative and Qualitative Approaches in the Social and Behavioural Sciences*, Sage Publications, Los Angeles.

Tauber, R. 1997, *Self-fulfilling prophecy: A Practical guide to its use in education*, Praeger, Westport, CT.

Taylor, C. 2010, "Construction waste - The road to resource efficiency", *recycle and waste management exhibition*, NEC, Birmingham, UK.

Teddlie, C. & Tashakkori, A. 2009, *Foundations of Mixed Methods Research : Integrating Quantitative and Qualitative Approaches in the Social and Behavioral Sciences*, SAGE Publication, Inc.

Teichmann, J. & Evans, K.C. 1999, *Philosophy: A Beginner's Guide*, Blackwell Publishing.

Teo, M.M.M. & Loosemore, M. 2001, "A theory of waste behaviour in the construction industry", *Construction Management and Economics*, vol. 19, no. 7, pp. 741-751.

Teo, M.M.M., Loosemore, M., Masosszeky, M. & Karim, K. 2000, "Operatives Attitudes Towards Waste on a Construction Project", *Annual Conference – ARCOM 2000*, vol. 2, pp. 509-517.

Thuesen, N., Kirkegaard, P.H. & Jensen, R.L. 2010, "Evaluation of BIM and Ecotect for conceptual architectural designanalysis", *Proceedings of the International Conference on Computing in Civil and Building Engineering*, Nottingham University, UK.

Travers, M. 2001, *Qualitative Research Through Case Studies*, SAGE Publications Ltd.

Tse, T. K., Wong, K. A. & Wong, K. F. 2005, "The utilization of building information models in nD modeling: a study of data interfacing and adoption barriers". *ITcon*, vol. 10, pp. 85-110.

Turkan, Y., Bosche, F., Haas, C. T. & Haas, R. 2012, "Automated progress tracking using 4D schedule and 3D sensing technologies", *Automation in Construction*, vol. 22, pp. 414-421.

Udhayakumar, R. & Karthikeyan, P. 2014, "Career Advancement of Civil Engineers through Application of BIM in Construction Industry", *Journal of Engineering, Computers & Applied Sciences (JEC&AS)*, vol. 3, no. 1, pp. 6-11.

UKCG. 2009, *Construction in the UK Economy: The Benefits of Investment*, [Online]. Available: http://www.nasc.org.uk/NASC/files/ea/eabc21b4-91d3-4e44-8f0f-ab27a7a0a4b1.pdf [2013, 22 September].

UK Environment Agency. 2013, *Sustainable Construction: Position Statement* [Online]. Available: http://www.environment-agency.gov.uk/cy/ymchwil/llyfrgell/safbwynt/41239.aspx [2013, 20 Feb].

UK Green Building Council. 2013, *Waste*, [Online]. Available: http://www.ukgbc.org/content/waste [2013, 22 September].

UK Legislation. 2010, *The Environmental Permitting (England and Wales) Regulations 2010*, [Online]. Available: http://www.legislation.gov.uk/ukdsi/2010/9780111491423/contents [2013, 22 September].

Uschold, M. 1996, "Building ontologies: towards a unified methodology, expert systems", *the 16th Annual Conference of the British Computer Society Specialist Group on Expert Systems*, Cambridge, UK.

USGBC. 2010, *USGBC: U.S. Green Building Council* [Homepage of U.S. Green Building Council], [Online]. Available: http://www.usgbc.org/ [2010, 25 October].

Vanlande, R., Nicolle, C. & Cruz, C. 2008, “IFC and building lifecycle management”. *Automation in Construction*, vol.18, no. 1, pp. 70-78.

Walliman, N. 2006, *Social Research Methods*, SAGE Publication Ltd, London.

Wang, X. & Love, P.E.D. 2012, “BIM + AR: Onsite Information Sharing and Communication via Advanced Visualization”. *Proceedings of the 2012 IEEE 16th International Conference on Computer Supported Cooperative Work in Design*, pp. 850-855.

Wang, X., Love, P. E. D., Kim, M. J., Park, C., Sing, C. & Hou, L. 2013, “A conceptual framework for integrating building information modeling with augmented reality”, *Automation in Construction*, vol.34, pp. 37-44.

Weber, R. P. 1990, *Basic content analysis*, Sage Publications Inc, London.

Welle, B., Rogers, Z. & Fischer, M. 2012, “BIM-Centric Daylight Profiler for Simulation (BDP4SIM): A methodology for automated product model decomposition and recomposition for climate-based daylighting simulation”, *Building and Environment*, vol. 58, pp. 114-134.

Wellel, B., Haymaker, J & Rogers, Z. 2011, “ThermalOpt: A methodology for automated BIM-based multidisciplinary thermal simulation for use in optimization environments”. *Building simulation*, vol. 4, pp. 293-313.

Whyte, J. 2012, " Building Information Modelling in 2012: Research Challenges, Contributions, Opportunities", *Working Paper*, vol. 5, Design Innovation Research Centre, University of Reading, UK.

Wirfs-Brock, R., Wilkerson, B. & Wiener, L. 1990, *Designing Object-Oriented Software*, Prentice Hall.

Wong, K. & Fan, Q. 2013, “Building information modelling (BIM) for sustainable building design”. *Facilities*, vol. 31, pp. 138-157.

Wong, F.W.H., Lam, P.T.I., Chan, A.P.C. & Chan, E.H.W. 2006, “A Review of Buildability Performance in Hong Kong and Strategies for Improvement”. *Surveying and Built Environment*, vol.17, no. 2, pp. 37-48.

Wong, J. K.W., Li, H., Wang, H., Huang, T., Luo, E. & Li, V. 2012, “Toward low-carbon construction processes: the visualisation of predicted emission via virtual prototyping technology”, *Automation in Construction*, vol.33, pp. 72-78.

Wong, E.O.W. & Yip, R.C.P. 2004, "Promoting sustainable construction waste management in Hong Kong", *Construction Management and Economics*, vol. 22, no. 6, pp. 563-566.

WRAP. 2007a, *Reducing material wastage in construction* [Online]. Available: http://www2.wrap.org.uk/downloads/Reducing_Material_Wastage_in_Construction.6bf7495b.4711.pdf [2013, 22 September].

WRAP. 2007b, *Material Logistics Plan Good Practice Guidance*, Waste & Resources Action Programme, Oxon.

WRAP 2007c, *Current practices and future potential in modern methods of construction*, Waste & Resources Action Programme, Oxon.

WRAP. 2008, *TRUE COST of waste in whole life costing*, [Online]. Available: http://www.wrap.org.uk/sites/files/wrap/True%20Cost%20of%20Waste%20in%20Whole%20Life%20Costing%20report.pdf [2013, 22 September].

WRAP. 2009, *Designing out Waste: a design team guide for buildings*, [Online]. Available: http://www.wrap.org.uk/content/designing-out-waste-design-team-guide-buildings-0 [2013, 22 September].

WRAP. 2010, *WRAP SWMP Tracker*, [Online]. Available: http://swmptracker.wrap.org.uk/ [2013, 22 September].

WRAP. 2011, *Welcome to WRAP’s Waste forecasting tools*, [Homepage of Waste & Resources Action Programme], [Online]. Available: http://nwtool.wrap.org.uk/ [2011, 17 Jan].

WRAP. 2013a, *BIM (Building Information Modelling) utilisation to achieve resource efficiency in construction: Leeds Arena* [Online]. Available: http://www.wrap.org.uk/sites/files/wrap/Leeds_Arena_FINAL.pdf [2013, 04 January].

WRAP. 2013b, *What is Halving Waste to Landfill?* [Online]. Available: http://www.wrap.org.uk/content/what-halving-waste-landfill [2013, 22 September].

WRAP. 2013, *Review of the factors causing waste soil to be sent to landfill, 2007 to 2011* [Online]. Available: http://www.wrap.org.uk/sites/files/wrap/CIS101-301%20Final%20Report%20final%2017%20april%2013.pdf [2013, 22 September].

WRAP. 2013c, *Construction procurement guidance*, [Online]. Available: http://www.wrap.org.uk/content/procurement-guidance [2013, 22 September].

WRAP. 2013d, 2013 update, *BIM and Resource Efficiency, WRAP*, [Online]. Available: http://www.wrap.org.uk/content/bim-and-resource-efficiency [2013, 21 May].

Wu, I. & Chang, S. 2013, “Visual Req calculation tool for green building evaluation in Taiwan”, *Automation in Construction*, vol.35, pp. 608-617.

Wu, I. & Hsieh, S. 2012, “A framework for facilitating multi-dimensional information integration, management and visualization in engineering projects”, *Automation in Construction*, vol.23, pp. 71-86.

Xie, H., Shi, W. & Issa, R.R.A. 2010, “Implementation of BIM/RFID in computer-aided design-manufacturing-installation process”. *Computer Science and Information Technology (ICCSIT), 2010 3rd IEEE International Conference*, vol. 2, pp. 107-111, July 2010, Chengdu

Xiong, X., Adan, A., Akinci, B. & Huber, D. 2013, “Automatic creation of semantically rich 3D building models from laser scanner data”. *Automation in Construction*, vol.31, pp. 325-337.

Yahya, K. & Boussabaine, A.H. 2006, "Eco-costing of construction waste", *Management of Environmental Quality: An International Journal*, vol. 17, no. 1, pp. 6-19.

Yan, W., Culp, C. & Graf, R. 2011, “Integrating BIM and gaming for real-time interactive architectural visualization”. *Automation in Construction*, vol.20, no. 4, pp. 446-458.

Yin, R.K. 2008, *Case study research: Design and methods*, 3rd edn, Sage Publications, Thousand Oaks, CA.

Yoon, S., Park, N. & Choi, J. 2009, “A BIM-based design method for energy-efficient building”. *Fifth International Joint Conference on INC, IMS and IDC*, 25-27 Aug. 2009, Seoul, pp. 376-381.

Yuan, H. & Shen, L. 2011, “Trend of the research on construction and demolition waste management”. *Waste Management*, vol. 31, pp. 670-679.

Yurchyshyna, A. & Zarli, A. 2009, “An ontology-based approach for formalisation and semantic organisation of conformance requirements in construction”, *Automation in Construction*, vol.18, pp. 1084-1098.

Zakar, S. 2008, *Wastage Rate Report*, Building Research Establishment (BRE), Garston.

Zhang, J. & Li, D. 2010, “Research on 4D virtual construction and dynamic management system based on BIM”. *Proceedings of the international conference on computing in civil and building engineering*.

Zhang, X., Wu,Y. & Shen, L. 2012, “Application of low waste technologies for design and construction: A case study in Hong Kong”. *Renewable and Sustainable Energy Reviews*, vol.16, pp. 2973-2979.

Zhang, S., Teizer, J., Lee, J., Eastman, C. M. & Venugopal, M. 2013, “Building Information Modeling (BIM) and Safety: Automatic Safety Checking of Construction Models and Schedules”, *Automation in Construction*, vol. 29, pp. 183-195.

Zhao, W., Leeftink, R.B. & Rotter, V.S. 2010, "Evaluation of the economic feasibility for the recycling of construction and demolition waste in China—The case of Chongqing", *Resources, Conservation and Recycling*, vol. 54, no. 6, pp. 377-389.

Zhong, B.T., Ding, L.Y., Luo, H.B., Zhou, Y., Hu, Y.Z. & Hu, H.M. 2012, “Ontology-based semantic modeling of regulation constraint for automated construction quality compliance checking”, *Automation in Construction*, vol.28, pp. 58-70.

Zhou,Y., Ding, L.Y. & Chen, L.J. 2013, "Application of 4D visualization technology for safety management in metro construction", *Automation in Construction*, vol. 34, pp. 25-36.

Zimmermann, G., Lu, Y. & Lo, G. 2012, “Automatic HVAC fault detection and diagnosis system generation based on heat flow models”. *HVAC&R Research*, vol. 18, no. 1-2, pp. 112-125

APPENDICES

List of Publications

- Liu, Z., Osmani, M., Demian, P., & Baldwin, A. N. 2011, "The potential use of BIM to aid construction waste minimalisation". *IN: Proceedings of the CIB W78-W102 2011: International Conference. 26th-28th October 2011*, Sophia Antipolis, France, paper 53.
- Post-viva publication plan:

  A paper "A BIM-aided-construction waste minimisation framework" was scheduled to be submitted to Journal Automation in Construction.

THE POTENTIAL USE OF BIM TO AID CONSTRUCTION WASTE MINIMISATION

Zhen Liu, Doctoral Student, Z.Liu2@lboro.ac.uk
Mohamed Osmani, Senior Lecturer, m.osmani@lboro.ac.uk
Peter Demian, Lecturer, P.Demian@lboro.ac.uk
Andrew N Baldwin, Director of IMCRC, a.n.baldwin@lboro.ac.uk
Department of Civil and Building Engineering, Loughborough University, Loughborough, Leicestershire LE11 3TU, United Kingdom

ABSTRACT

It is widely acknowledged that the construction industry has a major impact on the environment, both in terms of resource consumption and waste production. The construction industry is responsible for producing a whole variety of different onsite wastes; the amount and type of which depends on factors such as the stage of construction, type of construction work, direct or indirect stakeholders' design change contribution, and practices throughout the project lifecycle. A number of construction waste minimisation (CWM) techniques and tools are currently available to assist contractors to divert waste away from landfill. However, literature reveals that there are insufficient techniques and tools for reducing construction waste during the design and procurement stages. The last few years saw the emergence of Building Information Modelling (BIM) techniques, which can be adopted to improve sustainable construction performance. BIM is a maturing modelling philosophy, which has been applied to several building-related functions such as visualising designs, automating quantity takeoffs, checking compliance with regulations, and scheduling construction processes. Furthermore, BIM, as a real-time interactive and collaborative communication system, has the potential to help project stakeholders to collaboratively attain waste minimisation for sustainable construction and building throughout design, construction and throughout the lifecycle by improving building construction performance. Hence, this paper, which is part of an ongoing doctoral study, explores the potential application of BIM to design out waste. An in-depth literature review was conducted to provide a foundation for the doctoral study that aims to investigate the use of BIM as a potential platform for building design waste minimisation. The paper explores construction waste origins and causes, current waste reduction practices; examines current industry BIM practices and investigates BIM tools for sustainable project construction and management; and identifies the knowledge gaps in existing literature that pave the way for the subsequent data collection stages.

Keywords: Environmental impact, Sustainable construction, Construction waste minimisation (CWM), Building Information Modelling (BIM), Designing out waste.

1. INTRODUCTION

Sustainability is becoming a major catalyst for change in the built environment owing to its ever increasing energy consumption and material usage, which leads to waste and pollution. Waste generated from construction and demolition (C&D) activities in the UK accounts for 32% of total waste generation (WRAP 2011a). In addition, the last five years saw a striking increase in C&D waste in the UK. Indeed, In C&D activities generated 90 million tonnes of physical waste in 2005 (Zakar 2008); while recent figures from WRAP (2011a) revealed that this has increased to 120 million tones. Similarly, the current estimation of C&D waste disposed off to landfill is 40% (WRAP 2011a); whilst it was 30% in 2005 (Edgar 2007). The UK Waste Strategy for England 2007 identified the construction industry as a priority sector to move forward with the waste minimisation agenda (Defra 2007). Furthermore, the UK has set the ambitious target of zero construction waste to landfill by 2020 (WRAP 2011b). From a financial perspective, it has been estimated that the true cost of waste could as much as 10 times that of disposal (WRAP 2011a). Thus, the construction industry is under an ever-increasing pressure to explore and develop effective and efficient techniques and tools to minimise its escalating waste production. A comprehensive literature review was conducted to explore the extent of the relationship between Building Information Modelling (BIM) and construction waste minimisation (CWM). The review examined construction waste origins and causes, current waste reduction practices; assessed current industry BIM practices, BIM tools for sustainable project construction and management; and discussed the knowledge gaps in existing literature that pave the way for the subsequent data collection stages of this ongoing research that will lead to the development of BIM aided CWM framework.

2. CONSTRUCTION WASTE MINIMISATION (CWM)

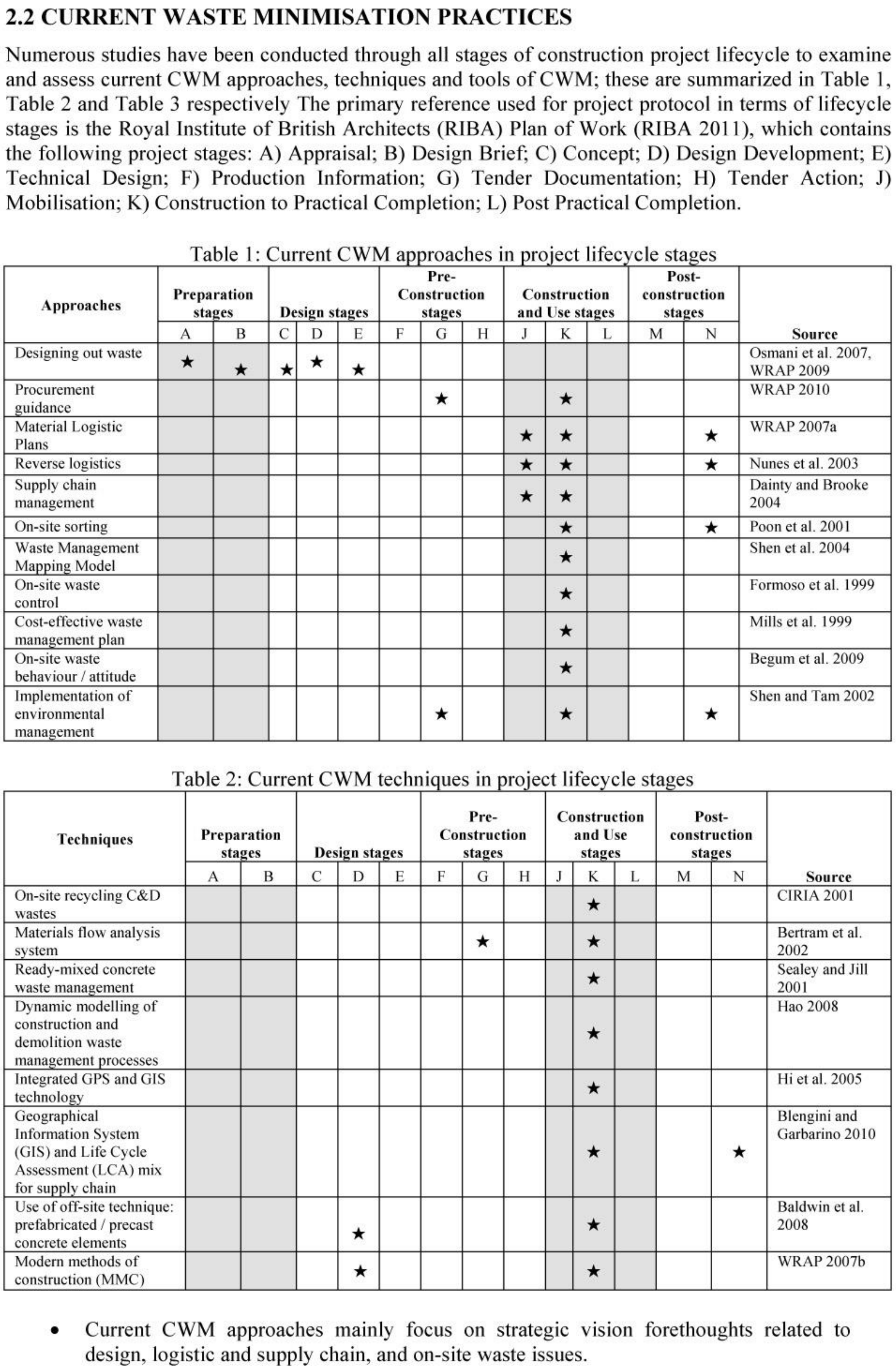
CWM has been defined by the UK Environment Agency (1997) as reducing construction waste by preventive measures (prevention, reduction at source, and reuse of products) and waste management measures (quality improvement, and recycling). Similarly, Envirowise (1998) defined CWM as the process of systematic waste reduction at source, by preventing and reducing waste before its physical generation, and encouraging reuse, recycling and recovery. Therefore, CWM is a process which avoids, eliminates or reduces waste at its sources or permits reuse and recycling of the waste for benign purposes in construction (Riemer and Kristoffersen 1999).

2.1 CONSTRUCTION WASTE CAUSES AND ORIGINS

By and large, construction waste origins are related to design changes, leftover material scraps, no-recyclable/re-useable packaging waste, design/detailing errors, and poor weather (Faniran and Caban 1998). Further, a study of attitudes of architects and contractors toward origins of construction waste indicates that construction waste is related to design, site operation, procurement routes, material handling and sub-contractor's practices (Osmani et al. 2006). Osmani et al. (2007) went further to compile and group the main sources of waste factors in terms of construction lifecycle stages, comprising contractual, design, procurement, transportation, on-site management and planning, material storage, material handling, site operation, residual, and other.

There is a consensus in literature that a significant portion of waste is caused by problems which occur in stages that precede production, and design stage is one of the major construction waste sources (Keys et al. 2000, Osmani 2011). That said literature failed to identify a clear linkage or relationship between consequences of amount of construction waste generated and their corresponding causes and origins. Additionally, Agopyan et al. (1998) argued that the lack of knowledge of waste generators is a noteworthy cause of waste. Furthermore, there are no forecasting comprehensive and reliable methods and tools to predict and estimate the amount of constructed waste before projects start on site (Formoso et al. 1999). Therefore, an accountable top-down dynamic relationship between main causes and origins of construction waste and their respective amount of construction waste generated. This was supported by Teo (2001) who acknowledged that there are limited construction waste reduction methods that specifically address known causes and origins of waste. On the other hand, the analysis of sources of waste indicated that a large quantity of material waste is due to flow activities, such as material delivery, inventories, and internal transportation and handling (Formoso et al. 2002). The transformational approach suggests that an independent control of each stage of production is required, whereas flow processes' approach suggests that a focus on the control of the total flow of production is needed (Koskela 1999).

There is a consensus in literature that all construction stages directly or indirectly contribute to onsite waste generation. However, the level and severity of waste production varied from stage to stages depending on a number of variables that include type of procurement, project brief, stakeholders' engagement and commitment, etc. That said, it is widely argued that waste reduction intervention should focus on pre-construction stages, particularly design, where 'virtual waste' (simulated waste generation during design stages), as opposed to 'actual waste' (physical onsite waste), could be effectively identified, evaluated and reduced.



2.2 CURRENT WASTE MINIMISATION PRACTICES

Numerous studies have been conducted through all stages of construction project lifecycle to examine and assess current CWM approaches, techniques and tools of CWM; these are summarized in Table 1, Table 2 and Table 3 respectively The primary reference used for project protocol in terms of lifecycle stages is the Royal Institute of British Architects (RIBA) Plan of Work (RIBA 2011), which contains the following project stages: A) Appraisal; B) Design Brief; C) Concept; D) Design Development; E) Technical Design; F) Production Information; G) Tender Documentation; H) Tender Action; J) Mobilisation; K) Construction to Practical Completion; L) Post Practical Completion.

Table 1: Current CWM approaches in project lifecycle stages

Approaches	**Preparation stages**		**Design stages**			**Pre-Construction stages**			**Construction and Use stages**			**Post-construction stages**		
	A	B	C	D	E	F	G	H	J	K	L	M	N	**Source**
Designing out waste	★	★	★	★	★									Osmani et al. 2007, WRAP 2009
Procurement guidance							★			★				WRAP 2010
Material Logistic Plans									★	★			★	WRAP 2007a
Reverse logistics									★	★			★	Nunes et al. 2003
Supply chain management									★	★				Dainty and Brooke 2004
On-site sorting										★			★	Poon et al. 2001
Waste Management Mapping Model										★				Shen et al. 2004
On-site waste control										★				Formoso et al. 1999
Cost-effective waste management plan										★				Mills et al. 1999
On-site waste behaviour / attitude										★				Begum et al. 2009
Implementation of environmental management							★			★			★	Shen and Tam 2002

Table 2: Current CWM techniques in project lifecycle stages

Techniques	**Preparation stages**		**Design stages**			**Pre-Construction stages**			**Construction and Use stages**			**Post-construction stages**		
	A	B	C	D	E	F	G	H	J	K	L	M	N	**Source**
On-site recycling C&D wastes										★				CIRIA 2001
Materials flow analysis system							★			★				Bertram et al. 2002
Ready-mixed concrete waste management										★				Sealey and Jill 2001
Dynamic modelling of construction and demolition waste management processes										★				Hao 2008
Integrated GPS and GIS technology										★				Hi et al. 2005
Geographical Information System (GIS) and Life Cycle Assessment (LCA) mix for supply chain										★			★	Blengini and Garbarino 2010
Use of off-site technique: prefabricated / precast concrete elements				★						★				Baldwin et al. 2008
Modern methods of construction (MMC)				★						★				WRAP 2007b

- Current CWM approaches mainly focus on strategic vision forethoughts related to design, logistic and supply chain, and on-site waste issues.

- Current CWM techniques developed by the industry are mainly concerned with on on-site, off-site, and logistic waste minimisation issues.
- Current CWM tools, such as SMARTWaste, are related waste audit and better onsite practices to comply with waste regulations, such as Site Waste Management Plans (SWMPs) (WRAP 2011d).

Table 3: Current CWM tools in project lifecycle stages

Tools	**Preparation stages**		**Design stages**			**Pre-Construction stages**			**Construction and Use stages**			**Post-construction stages**		
	A	B	C	D	E	F	G	H	J	K	L	M	N	**Source**
Waste forecasting tool (online tool)			★	★										WRAP 2011b
On-site waste auditing: SMARTWaste										★				McGrath 2001
Waste management planning (WMP)										★				McDonald and Smithers 1998
On-site waste control tools										★				Formoso et al. 1999
Site waste management plans (SWMPs)										★				WRAP 2011d
ConstructCLEAR (online tool)										★				BlueWise 2010
True cost of waste calculator (online tool)										★				BRE 2010
SMARTAudit										★				BRE 2008
BreMap (online GIS tool)										★			★	BRE 2009
SMARTStart										★			★	BRE 2007
Webfill (online tool)										★			★	Chen et al. 2006

The current CWM approaches, techniques and tools focus on separate project stages with overwhelming endeavours to manage waste onsite. However, limited effort is invested to concentrate on pre-construction waste generation related to supply chain management issues and procurement, design and tender stages. These offer substantial waste reduction opportunities on McKechnie's (2007) waste reduction opportunity curve. More recently, BRE (2011) called for the development of online CWM techniques and tools. Yet, there are no research studies on integrated e-waste minimisation or IT related approaches, techniques and tools across all life cycle stages of construction projects. These would particularly be suited to design out waste, since 33% of construction waste might be directly influenced by inappropriate design decision making and design changes (Innes 2004), which contribute to more than 50% of the total onsite waste production in construction projects (Faniran and Caban 1998).

3. BUILDING INFORMATION MODELLING (BIM)

BIM has evolved from computer-aid design (CAD) research. However, there is still no single, widely-accepted definition for BIM. BIM is defined in different terms from model and design data to construction management. From a three dimensional (3D) perspective, BIM is defined as a conceptual approach to building design and construction that encompasses 3D parametric modelling of building for design and detailing and computer-intelligible exchange of building information between design, construction and other disciplines (Sacks et al. 2010). From a design and project data management standpoint, BIM is a set of interacting policies, processes and technologies that generate a methodology to manage building design and project data in digital format across all life-cycle stages (Penttilä 2006). In terms of construction management, BIM is an intelligent simulation of architecture to achieve an integrated project delivery (Eastman et al. 2008). However, literature failed to define BIM in relation to sustainable construction performance. Therefore, BIM within the context of this research can be defined as a real-time interactive and collaborative communication system, having the potential to help project stakeholders to collaboratively attain construction waste minimisation throughout the whole lifecycle stages of a building by improving building construction performance.

3.1 BIM-RELATED SOFTWARE APPLICATIONS

A wide range of BIM software applications are currently available for various project performance purposes. As shown in Table 4, the vast majority of BIM related packages focused on design and pre-construction stages. There is a consensus in literature that BIM applications in their current use are vastly superior to 2D and 3D CAD-based tools, which do not maintain comprehensive integrity when changes are made. On the other hand, it is widely acknowledged that associating BIM with the development and use of 3D virtual building modeling techniques and technologies can yield very productive results.

Table 4: Current BIM applications in construction projects

Current BIM	**Preparation stages**		**Design stages**			**Pre-Construction stages**			**Construction and Use stages**			**Post-construction stages**		**Source**
	A	B	C	D	E	F	G	H	J	K	L	M	N	
Beck Technology Dprofiler	√													Beck Technology
Carlson (CVE)	√													Olatunji and Sher 2010
Nemetschek Vectorworks	√		√	√	√	√	√							Nemetschek
Gehry Technologies Digital Project	√		√	√		√	√							Gehry Technologies
Navisworks JetStream v5 Roamer and Clash Detective			√	√										AGC 2006
Autodesk Green Building Studio					√									Autodesk
ArtrA										√		√		ArtrA
Autodesk Revit			√	√	√	√								Autodesk
Graphisoft ArchiCAD			√	√	√	√								Graphisoft
Bentley Systems Architecture			√	√	√	√								Bentley Systems
MasterBill, QSCAD Timberline					√	√	√							Olatunji and Sher 2010
Primavera, Construction Computer Software(CCS)					√	√	√							Olatunji and Sher 2010
PP Manager									√	√				Nemetschek
Navisworks TimeLiner						√			√					AGC 2006
Graphisoft Change Manager				√					√	√				AGC 2006
CostX, Inovayya, Tocoman, CRC estimator, Winest				√	√	√								Olatunji and Sher 2010
BIM and interoperability for precast									√	√				Sacks et al. 2010
Tekla Structures				√	√	√			√	√				Tekla
StructureWorks					√				√	√				StructureWorks
Design Data SDS/2					√				√	√				Design Data 2010

BIM applications in construction projects such as Beck Technology DProfiler and Carlson (CVE) are being used for economic assessments (cost estimating and income forecasting) of project substantive feasibility in the preparation stages. However, there is a lack of BIM tools to help satisfy the client's business requirement; identify potential solutions for feasibility studies; and outline project feasibility requirements.

Furthermore, BIM applications are predominantly used for decision making, and lean or sustainable building construction and performance analysis, such as energy and water analysis are used in pre-construction stages.

Although there are several BIM tools available for construction and post-occupancy stages, such as Tekla Structures (precast/prefabricate solution), StructureWorks (precast solution), Navisworks JetStream v5 (combining and reviewing 3D models), and PP Manager (linkage between CAD, factory and the ERP software); these are mainly used for prefabrication and construction management purposes in the construction stage.

Hence, the existing construction- related BIM applications are used contribute to:

- lower net information costs and risks;
- quick first response in early stage of design to make building safer;
- efficient monitoring lower operation cost;
- better views of facilities for better decision makings;
- reduced project cost and risks; and
- better building environmental performance

3.2 USE OF BIM IN MANAGING SUSTAINABLE CONSTRUCTION

There is an opportunity for BIM to offer valuable controlling features and analysis tools, to manage and maintain the original information of client needs through the design process (Penttilä 2007, Baldwin et al. 1998). BIM enhanced communication and collaboration is an important facet of managing successful sustainable construction (Grilo and Jardim-Goncalves 2010). It has been argued that BIM could enhance communication and collaboration; increase efficiency; and reduces errors, which in turn would reduce resources, energy, materials, and waste (Europe INNOVA 2008). Furthermore, BIM provides the opportunity of testing, revising, rejecting and accepting design ideas in real-time, such as the case for collaborative design methods.

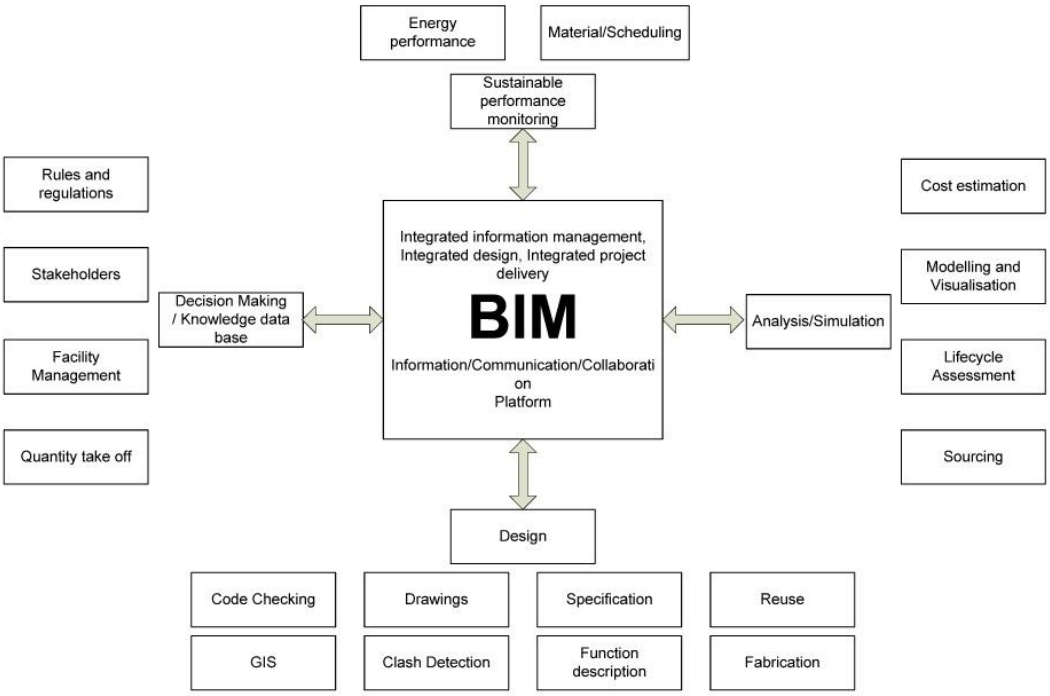


Figure 1: the IICC BIM platform for managing sustainable construction

The integrated information management associated with BIM for construction information would enable modelling, communication, collaboration and integration of sustainable design and construction requirements and actions across all project lifecycle. This would also improve decision making support and other project-related processes by optimising horizontal, vertical, and temporal integration of data and information management to enhance the value added for all project shareholders (Ilal 2007). Further, by adopting BIM technology, integrated project delivery (IPD) (AIA 2007) fosters a great degree of communication and promotes intense collaboration among the project team to enhance profitable, effective, and efficient project management (Hardin 2009). Therefore, integrated information management, integrated design, and IPD enhanced BIM solution can contribute to an efficient approach for managing sustainable construction.

BIM includes transactions at the data; information and knowledge semantic levels and falls within knowledge visualisation; a merger between information visualisation; and visual cognition and communication. (Eppler and Burkhard 2005). Knowledge, players and every component of project concerned will have the opportunity to contribute to managing sustainable construction as a whole; and influence others as individual by using BIM in the form of an integrated information, communication, and collaboration (IICC) platform. The IICC BIM platform for managing sustainable construction is shown as Figure 1. Design; decision making; sustainable performance monitoring; and analysis/simulation are four main application categories of IICC BIM platform for facilitating sustainable construction management.

Although, BIM offers promising methods for energy and resource efficiency, yet BIM methods at present do not consider a way forward for construction waste minimisation.

4. KNOWLEDGE GAP ANALYSIS

There are a number of techniques and tools for waste management that have been developed and introduced to the UK construction industry by leading organisations such as, BRE, WRAP, and CIRIA. These are widely adopted techniques and tools, such as a suite of software packages of SMARTWaste and SWMPs, which can facilitate onsite construction waste management. However, these techniques and tools focus on auditing and managing physical onsite construction waste that has already been generated, without measures to assist designers and other project stakeholders to design out waste. Online waste minimisation methods such as WRAP Waste Forecasting tools, and offsite techniques such as prefabricated/precast and modern methods of construction are being moderately used in construction projects. The extant of literature suggest that there are limited techniques and tools to assess and support construction waste minimisation performance for design decision making in Preparation, Design and Pre-Construction stages. On the other hand, BIM as a mature technique has been widely used in design and construction for many years. BIM applications, which have been supplied by established CAD software companies, concentrate predominantly on solving technical problems throughout all project stages.

Indeed, current BIM techniques and tools have been successfully used to enhance planning and construction relate issues during Preparation, Design and Pre-Construction stages; including improvement of sustainable project performance such as energy and resource efficiency. Although, it is widely accepted that BIM can help reduce waste-related costs and materials in construction projects (Nisbet and Dinesen 2010, Krygiel and Nies 2008, AIA 2007); at present there are no techniques and tools available that explore BIM as a platform to facilitate CWM. Hence this paper, which is part of an ongoing doctoral study, aims to develop a BIM aided CWM framework. The key objective is to improve sustainable construction waste minimisation by using BIM at the very early stages of design. The subsequent stages of this research will include simulating construction waste (virtual waste) through 3D building information (figure 2).

5. CONCLUSIONS

This paper has explored the potential to improve CWM through BIM systems in construction through a critical review of literature, by examining waste origins and causes, current waste reduction practice, and current BIM practices; and examining existing BIM applications that are currently applied to evaluate sustainable project construction and management. The most significant finding that stems from this paper is that although there was an emphasis on the need to explore the use of BIM for CWM; there are no previous attempts to adopt BIM as a vehicle to reduce construction waste. Hence, this research sets out to develop a BIM framework to aid CWM. The next stages of this research will involve designers, contractors and BIM experts to explore the most appropriate approach to adopt BIM as potential platform for CWM; select and customise a suitable BIM software; and develop and validate a BIM aided CWM in a live project.

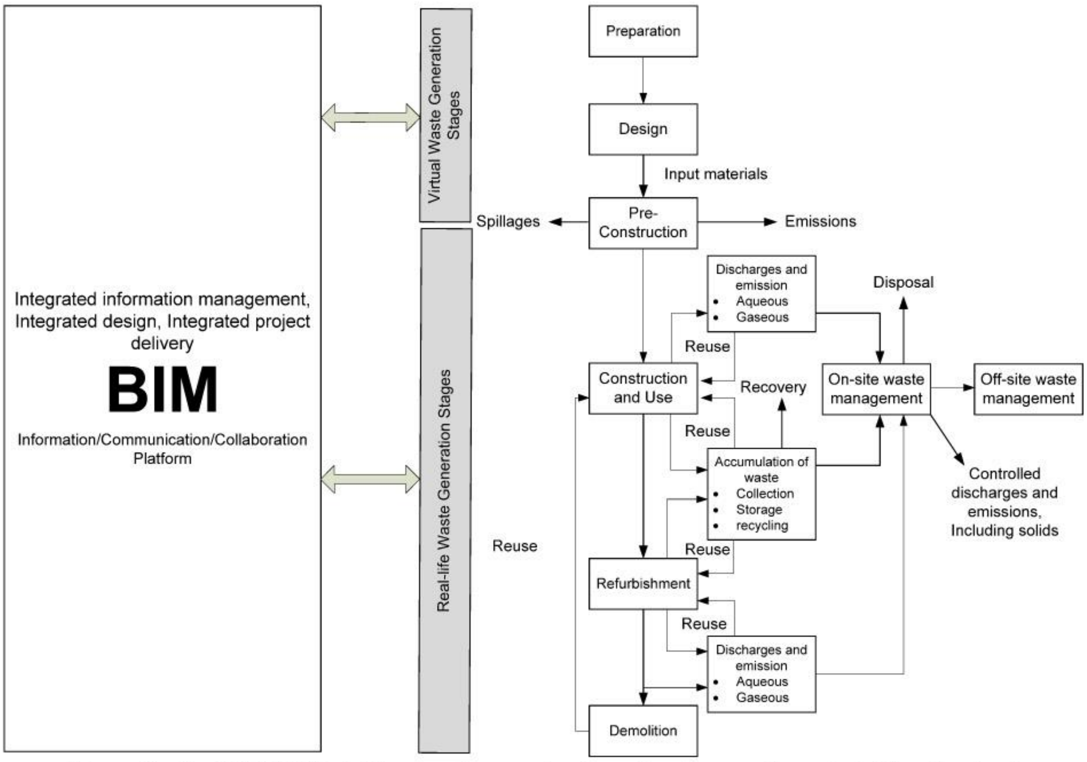


Figure 2: the IICC BIM platform and conceptual construction waste material input-output

REFERENCES

AGC (2006) "Contractors' Guide to BIM" The Associated General Contractors of America.

Agopyan, V. et al. (1998) "Alternatives for Reducing Material Waste on Building Sites", *Research report.*

AIA (2007) "Integrated project delivery: a guide", AIA California Council.

Baldwin, A. N. et al. (1998) "Planning building design by simulating information flow", *Automation in Construction.* 8. 2. 149-163.

Baldwin, A.N. et al. (2008) "Modelling design information to evaluate pre-fabricated and pre-cast design solutions for reducing construction waste in high rise residential buildings", *Automation in Construction.* 17. 3. 333-341.

Begum, R.A. et al. (2009) "Attitude and behavioral factors in waste management in the construction industry of Malaysia", *Resources, Conservation and Recycling.* 53. 6. 321-328.

Bertram, M. et al. (2002) "The contemporary European copper cycle: waste management subsystem", *Ecological Economics.* 42. 1-2. 43-57.

Blengini, G.A. & Garbarino, E. (2010) "Resources and waste management in Turin (Italy): the role of recycled aggregates in the sustainable supply mix", *Journal of Cleaner Production.* 18. 10-11. 1021-1030.

BlueWise (2010) ConstructCLEAR. [Online]. Available: http://www.constructclear.co.uk/ [2011, 17 Jan] .

BRE (2007) SMARTStart [Online]. Available: http://www.smartwaste.co.uk/smartstart/about.jsp [2011, 17 Jan] .

BRE (2008) SMARTAudit [Online]. Available: http://www.smartwaste.co.uk/smartaudit.jsp?id=27 [2011, 17 Jan] .

BRE (2009) BreMap. [Online]. Available: http://www.bremap.co.uk/Default.aspx [2011, 17 Jan]

BRE (2010) True cost of waste calculator. [Online]. Available: http://www.wastecalculator.co.uk/login.jsp [2011, 17 Jan] .

BRE (2011) Waste management tools and training. Available: http://www.bre.co.uk/page.jsp?id=1444 [2011, 22 April].

Chen, Z. et al. (2006) "E-commerce system simulation for construction and demolition waste exchange", *Automation in Construction.* 15. 6. 706-718.

CIRIA (2001) "Waste minimisation in construction: training pack". CIRIA.

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

Defra (2007) "Waste Strategy for England 2007", TSO (The Stationery Office), Norwich.

Design Data (2010) SDS/2 by Design Data. [Online]. Available: http://www.dsndata.com/ [2010, 02 November].

Eastman, C. et al. (2008) "BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors", John Wiley & Sons, Inc., Canada.

Edgar, A. (2007) "W15: Introduction to BIM: People, Processes and Tools", NIBS.

Environment Agency (1997) "Waste minimisation and waste management: an environmental good practice guide for industry ". Solihull. E.A.

Envirowise (1998) " Waste minimisation clubs: setting them up for success". Harwell.

Eppler, M. & Burkhard, R. (2005) "Knowledge visualization", *Encyclopedia of Knowledge Management.* 551-560.

Europe INNOVA (2008) 15 Dec-last update, The STAND-INN HANDBOOK. [Online]. Available: http://standards.eu-innova.org/Pages/NewsDetail.aspx?id=172 [2011, 11 Jan] .

Formoso, C.T. et al. (1999) "Method for waste control in the building industry", *Proceedings IGLC-7, 7th Conference of the International Group for Lean Construction, Berkeley,* CA.

Formoso, C.T. et al. (2002) "Material Waste in Building Industry: Main Causes and Prevention", *Journal of construction engineering and management.* 316-325.

Grilo, A. & Jardim-Goncalves, R. (2010) "Building information modeling and collaborative working environments", *Automation in Construction,* 19. 5. 521-521.

Hao, J.L. et al. (2008) "Managing construction waste on-site through system dynamics modelling: the case of Hong Kong", *Engineering, Construction and Architectural Management.* 15. 2.

Ilal, M.E. (2007) "The quest for integrated design system: a brief survey of past and current efforts", *Middle East Technical University Journal of the Faculty of Architecture.* 24. 2. 10.

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

Keys, A. et al. (2000) "Designing to encourage waste minimisation in the construction industry", CIBSE (Chartered Institute of Building Services Engineers).

Kiviniemi, A. (2005) "Requirements Management Interface to Building Product Models", *CIFE technical report 161.*

Koskela, L. (1999) "Management of production in construction: a theoretical view", *Proceedings of the Seventh Annual Conference of the International Group for Lean Construction IGLC-7,* 241-252.

Krygiel, E. & Nies, B. (2008) "Green BIM: Successful Sustainable Design with Building Information Modeling" John Wiley & Sons, Inc., Canada.

McKechnie, E. & Brown, E. (2007) "Achieving effective waste minimisation through design." Waste & Resources Action Programme, Oxen.

Li, H. et al. (2005) "Application of integrated GPS and GIS technology for reducing construction waste and improving construction efficiency", *Automation in Construction.* 14. 3. 323-331.

McDonald, B. & Smithers, M. (1998) "Implementing a waste management plan during the construction phase of a project: a case study". *Construction Management and Economics*. 16. 1. 71-78.

McGrath, C. (2001) "Waste minimisation in practice", *Resources conservation and recycling.* 32. 3-4. 227-238.

Mills, T.H. et al. (1999) "A Cost-Effective Waste Management Plan". *Cost Engineering.* 41, 3. 35-43.

Nisbet, N. & Dinesen, B. (2010) "Building information modelling: construction the business case" British Standards Institution, London.

Nunes, K.R.A. et al. (2009) "Reverse logistics in the Brazilian construction industry", *Journal of environmental management,* 90. 12. 3717-3720.

Olatunji, O.A. & Sher, W.D. (2010) "A Comparative Analysis of 2D Computer-Aided Estimating Procedures" in *Handbook of research on building information modeling and construction informatics: concepts and technologies*, eds. J. Underwood & U. Isikdag, Information Science Reference. 170-189.

Osmani, M. et al. (2006) "Architect and contractor attitudes to waste minimisation", *Proceedings of the Institution of Civil Engineers : Waste and Resource Managament,* 159. 65-72.

Osmani, M. et al. (2007) "Architects' perspectives on construction waste reduction by design", *Waste Management,* 28. 7, 1147-1158.

Osmani, M. (2011) "Construction Waste", in Letcher T.M. & Vallero D. A. (eds) Waste: A Handbook for Management, Elsevier, 207-218.

Penttilä, H. (2006) "Describing the changes in architectural information technology to understand design complexity and free-form architectural expression", *ITCON 11 (Special Issue The Effects of CAD on Building Form and Design Quality),* 395-408.

Penttilä, H. (2007) "Early Architectural Design and BIM", *Computer-Aided Architectural Design Futures (CAADFutures),* 6. 291-302.

Poon, C.S. et al. (2001) "On-site sorting of construction and demolition waste in Hong Kong". *Resources, Conservation and Recycling.* 32. 2. 157-172.

RIBA (2011) RIBA Plan of work [Online]. Available: http://www.pedr.co.uk/textpage.asp?menu=1a&sortorder=130&area=main [2011, 11 Jan] .

Riemer, J. & Kristoffersen, M. (1999) "Information on waste management practices" European Environmental Agency, Copenhagen, Denmark.

Sacks, R. et al. (2010) "The Rosewood experiment — Building information modeling and interoperability for architectural precast facades", *Automation in Construction,* 19. 4. 419-432.

Sealey, B.J. et al. (2001) "Waste management issues for the UK ready-mixed concrete industry", *Resources, Conservation and Recycling.* 32. 3-4. 321-331.

Shen, L.Y. & Tam, V.W.Y. (2002) "Implementation of environmental management in the Hong Kong construction industry", *International Journal of Project Management.* 20. 7. 535-543.

Shen, L.Y. et al. (2004) "Mapping approach for examining waste management on construction sites", *Journal of construction engineering and management*.

Teo, M.M.M. (2001) "A theory of waste behaviour in the construction industry", *Construction Management and Economics,* 19. 7. 741-751.

WRAP (2007a) "Material Logistics Plan Good Practice Guidance". WRAP.

WRAP (2007b) "Current practices and future potential in modern methods of construction". WRAP.

WRAP (2009) "Designing out Waste: a design team guide for buildings". WRAP.

WRAP (2010) "Setting a requirement for Waste Minimisation and Management". WRAP.

WRAP (2011a) Halving Waste to Landfill [Homepage of Waste & Resources Action Programme], [Online]. Available: http://www.wrap.org.uk/construction/halving_waste_to_landfill/index.html [2011, 17 Jan].

WRAP (2011b) The role of the Net Waste Tool [Online]. Available: http://www.wrap.org.uk/construction/tools_and_guidance/net_waste_tool/the_role_of_the_net.html [2011, 17 Jan].

Zakar, S. (2008) "Wastage Rate Report." Building Research Establishment (BRE), Garston.

Appendix 2.1 Questionnaire survey documents

Appendix 2.1.1 Questionnaire cover page

Zhen Liu
School of Civil and Building Engineering
Loughborough University
Loughborough
Leicestershire LE11 3TU

8th July 2011

Recipient Address

Dear (Sir/Madam name),

RE: Questionnaire: BIM aided Construction Waste Minimisation (CWM)

This questionnaire is a part of a doctoral research study that seeks to develop a BIM aided CWM framework by exploring the potential application of BIM to aid CWM during design. The Top 100 UK architects have been targeted for this questionnaire to capture their views on the potential use of BIM to addressing construction waste during design.

A number of CWM techniques and tools are currently available to assist contractors to divert waste away from landfill. However, there are insufficient techniques and tools for reducing construction waste during the design and procurement stages. The last few years saw the emergence of Building Information Modelling (BIM) techniques, which is currently used Worldwide to integrate the design, construction and operational/post-occupancy phases of buildings; can be adopted to improve sustainable project performance. Further, the latest UK Government Construction Strategy, published in May 2011, calls for fully collaborative 3D BIM for all UK public projects more than £5 million from 2016 onwards (http://www.cabinetoffice.gov.uk/sites/default/files/resources/Government-Construction-Strategy.pdf).

On the other hand, the recently published UK Government Review of Waste Policy in England 2011 emphasizes the importance of waste prevention followed by reuse and recycling. Additionally, a comprehensive Waste Prevention Programme will be published by end of 2013; and the landfill tax will increase to £80 per tonne in 2014/2015.

The Questionnaire should take no longer than 15-20 minutes to complete. If you would like to be sent findings of this research, please tick the relevant section at the end of questionnaire and I shall forward a summary of findings in September 2011.

Please note that the information you provide will be treated in the strictly confidential and no information regarding any individual respondent or organization will be made public. The findings of your questionnaire and others will be used as one of the main data set for my PhD degree study at the Loughborough University.

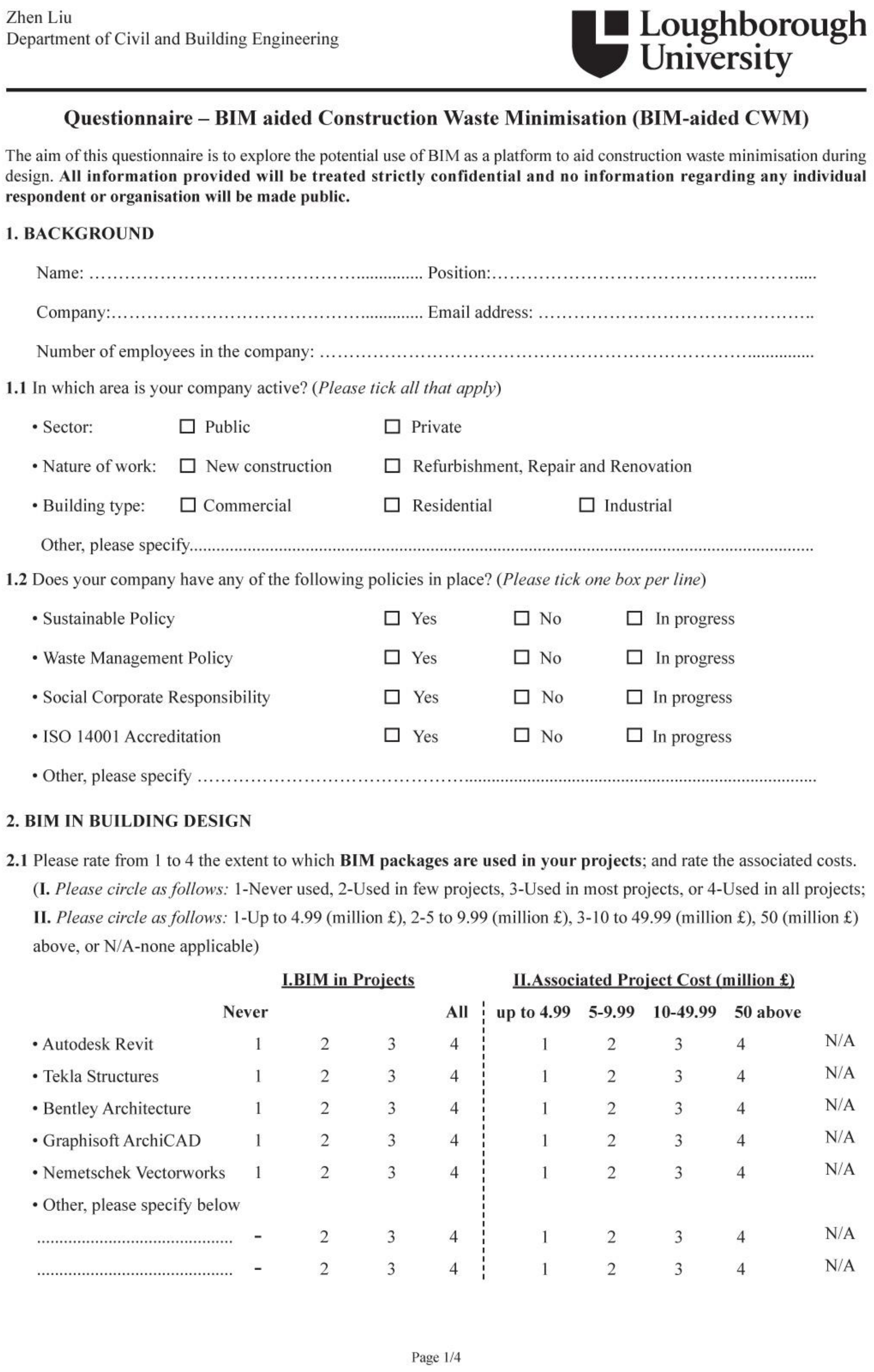
I would be very grateful if you could return the completed questionnaire using the enclosed self addressed envelope by Friday 26th August 2011.

Thank you for your kind participation in this research; and I look forward to receiving the completed questionnaire.

Yours Sincerely,

Zhen Liu
Email: Z.Liu2@lboro.ac.uk

Appendix 2.1.2 Questionnaire template



Zhen Liu
Department of Civil and Building Engineering

Loughborough University

Questionnaire – BIM aided Construction Waste Minimisation (BIM-aided CWM)

The aim of this questionnaire is to explore the potential use of BIM as a platform to aid construction waste minimisation during design. **All information provided will be treated strictly confidential and no information regarding any individual respondent or organisation will be made public.**

1. BACKGROUND

Name: ……………………………………….............. Position:…………………………………………….....

Company:…………………………………….............. Email address: ………………………………………..

Number of employees in the company: ……………………………………………………………….............

1.1 In which area is your company active? (*Please tick all that apply*)

• Sector:	☐ Public	☐ Private	
• Nature of work:	☐ New construction	☐ Refurbishment, Repair and Renovation	
• Building type:	☐ Commercial	☐ Residential	☐ Industrial

Other, please specify...

1.2 Does your company have any of the following policies in place? (*Please tick one box per line*)

• Sustainable Policy	☐ Yes	☐ No	☐ In progress
• Waste Management Policy	☐ Yes	☐ No	☐ In progress
• Social Corporate Responsibility	☐ Yes	☐ No	☐ In progress
• ISO 14001 Accreditation	☐ Yes	☐ No	☐ In progress

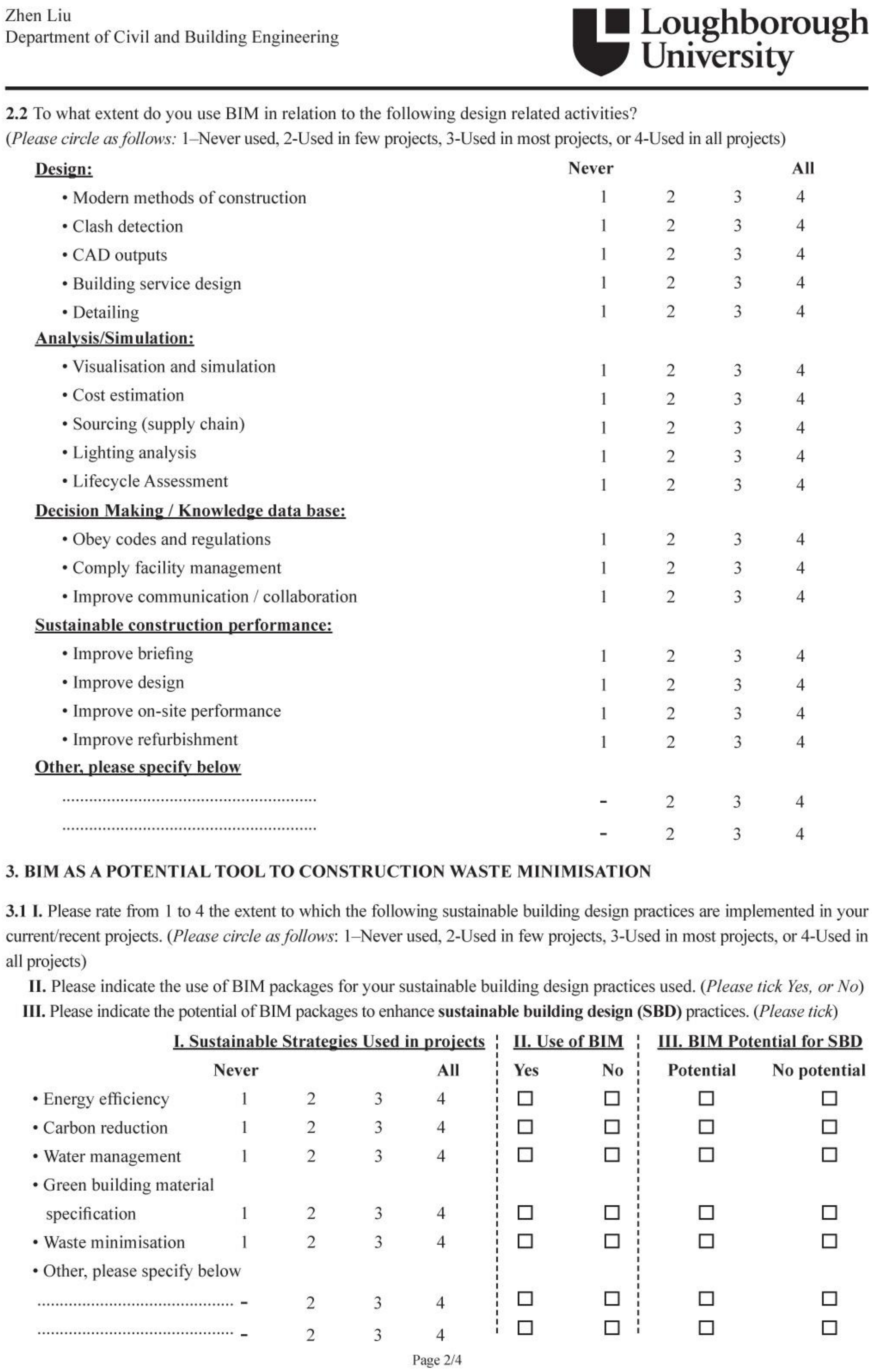
• Other, please specify ………………………………………...

2. BIM IN BUILDING DESIGN

2.1 Please rate from 1 to 4 the extent to which **BIM packages are used in your projects**; and rate the associated costs. (**I.** *Please circle as follows:* 1-Never used, 2-Used in few projects, 3-Used in most projects, or 4-Used in all projects; **II.** *Please circle as follows:* 1-Up to 4.99 (million £), 2-5 to 9.99 (million £), 3-10 to 49.99 (million £), 50 (million £) above, or N/A-none applicable)

	I.BIM in Projects				**II.Associated Project Cost (million £)**				
	Never			**All**	**up to 4.99**	**5-9.99**	**10-49.99**	**50 above**	
• Autodesk Revit	1	2	3	4	1	2	3	4	N/A
• Tekla Structures	1	2	3	4	1	2	3	4	N/A
• Bentley Architecture	1	2	3	4	1	2	3	4	N/A
• Graphisoft ArchiCAD	1	2	3	4	1	2	3	4	N/A
• Nemetschek Vectorworks	1	2	3	4	1	2	3	4	N/A
• Other, please specify below									
....	-	2	3	4	1	2	3	4	N/A
....	-	2	3	4	1	2	3	4	N/A

Page 1/4



Zhen Liu
Department of Civil and Building Engineering

Loughborough University

2.2 To what extent do you use BIM in relation to the following design related activities?
(*Please circle as follows:* 1–Never used, 2-Used in few projects, 3-Used in most projects, or 4-Used in all projects)

	Never			**All**
Design:				
• Modern methods of construction	1	2	3	4
• Clash detection	1	2	3	4
• CAD outputs	1	2	3	4
• Building service design	1	2	3	4
• Detailing	1	2	3	4
Analysis/Simulation:				
• Visualisation and simulation	1	2	3	4
• Cost estimation	1	2	3	4
• Sourcing (supply chain)	1	2	3	4
• Lighting analysis	1	2	3	4
• Lifecycle Assessment	1	2	3	4
Decision Making / Knowledge data base:				
• Obey codes and regulations	1	2	3	4
• Comply facility management	1	2	3	4
• Improve communication / collaboration	1	2	3	4
Sustainable construction performance:				
• Improve briefing	1	2	3	4
• Improve design	1	2	3	4
• Improve on-site performance	1	2	3	4
• Improve refurbishment	1	2	3	4
Other, please specify below				
....	-	2	3	4
....	-	2	3	4

3. BIM AS A POTENTIAL TOOL TO CONSTRUCTION WASTE MINIMISATION

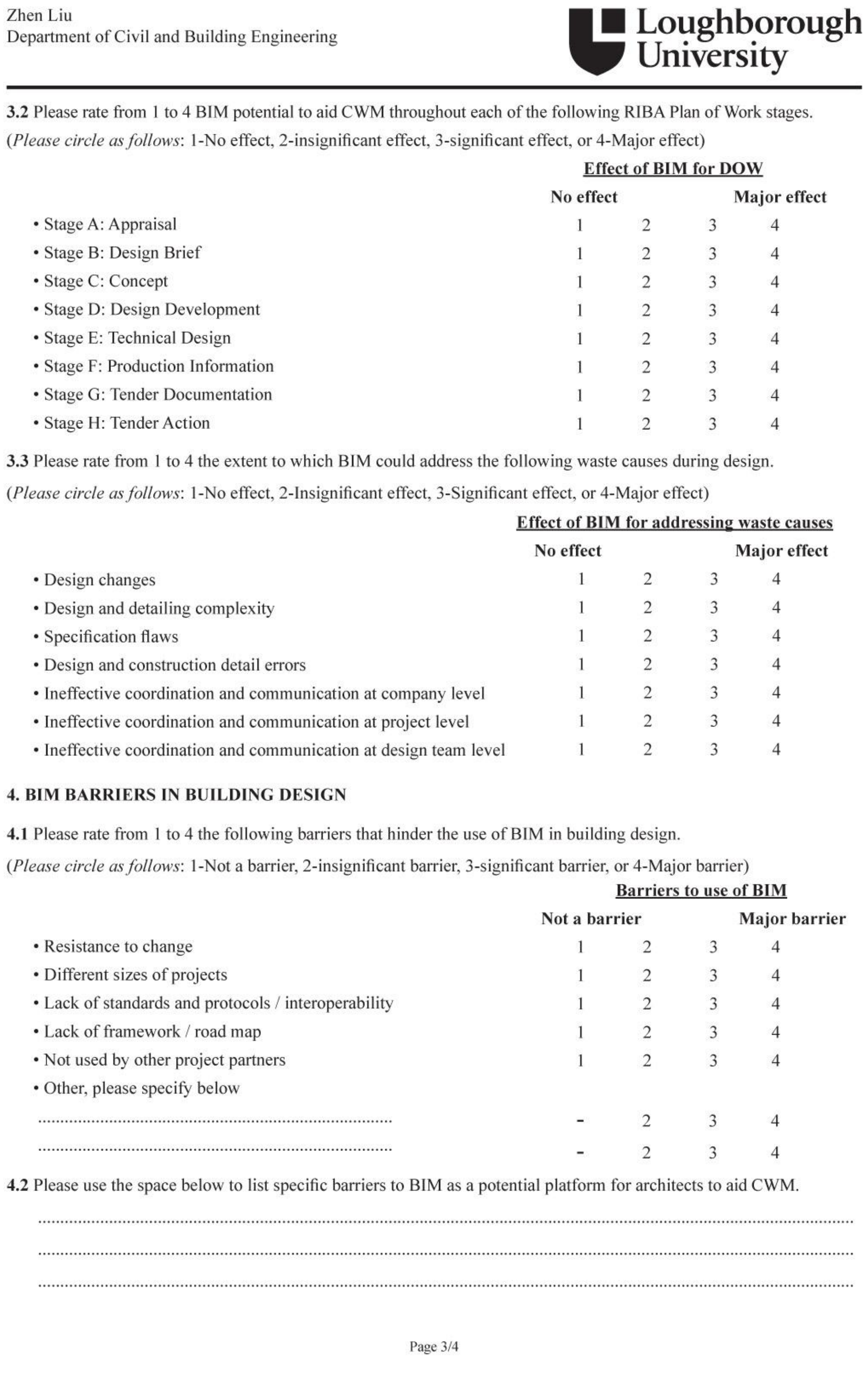
3.1 I. Please rate from 1 to 4 the extent to which the following sustainable building design practices are implemented in your current/recent projects. (*Please circle as follows*: 1–Never used, 2-Used in few projects, 3-Used in most projects, or 4-Used in all projects)

II. Please indicate the use of BIM packages for your sustainable building design practices used. (*Please tick Yes, or No*)

III. Please indicate the potential of BIM packages to enhance **sustainable building design (SBD)** practices. (*Please tick*)

	I. Sustainable Strategies Used in projects				**II. Use of BIM**		**III. BIM Potential for SBD**	
	Never			**All**	**Yes**	**No**	**Potential**	**No potential**
• Energy efficiency	1	2	3	4	☐	☐	☐	☐
• Carbon reduction	1	2	3	4	☐	☐	☐	☐
• Water management	1	2	3	4	☐	☐	☐	☐
• Green building material specification	1	2	3	4	☐	☐	☐	☐
• Waste minimisation	1	2	3	4	☐	☐	☐	☐
• Other, please specify below								
....	-	2	3	4	☐	☐	☐	☐
....	-	2	3	4	☐	☐	☐	☐

Page 2/4



Zhen Liu
Department of Civil and Building Engineering

Loughborough University

3.2 Please rate from 1 to 4 BIM potential to aid CWM throughout each of the following RIBA Plan of Work stages.

(*Please circle as follows*: 1-No effect, 2-insignificant effect, 3-significant effect, or 4-Major effect)

	Effect of BIM for DOW			
	No effect			**Major effect**
• Stage A: Appraisal	1	2	3	4
• Stage B: Design Brief	1	2	3	4
• Stage C: Concept	1	2	3	4
• Stage D: Design Development	1	2	3	4
• Stage E: Technical Design	1	2	3	4
• Stage F: Production Information	1	2	3	4
• Stage G: Tender Documentation	1	2	3	4
• Stage H: Tender Action	1	2	3	4

3.3 Please rate from 1 to 4 the extent to which BIM could address the following waste causes during design.

(*Please circle as follows*: 1-No effect, 2-Insignificant effect, 3-Significant effect, or 4-Major effect)

	Effect of BIM for addressing waste causes			
	No effect			**Major effect**
• Design changes	1	2	3	4
• Design and detailing complexity	1	2	3	4
• Specification flaws	1	2	3	4
• Design and construction detail errors	1	2	3	4
• Ineffective coordination and communication at company level	1	2	3	4
• Ineffective coordination and communication at project level	1	2	3	4
• Ineffective coordination and communication at design team level	1	2	3	4

4. BIM BARRIERS IN BUILDING DESIGN

4.1 Please rate from 1 to 4 the following barriers that hinder the use of BIM in building design.

(*Please circle as follows*: 1-Not a barrier, 2-insignificant barrier, 3-significant barrier, or 4-Major barrier)

	Barriers to use of BIM			
	Not a barrier			**Major barrier**
• Resistance to change	1	2	3	4
• Different sizes of projects	1	2	3	4
• Lack of standards and protocols / interoperability	1	2	3	4
• Lack of framework / road map	1	2	3	4
• Not used by other project partners	1	2	3	4
• Other, please specify below				
....	-	2	3	4
....	-	2	3	4

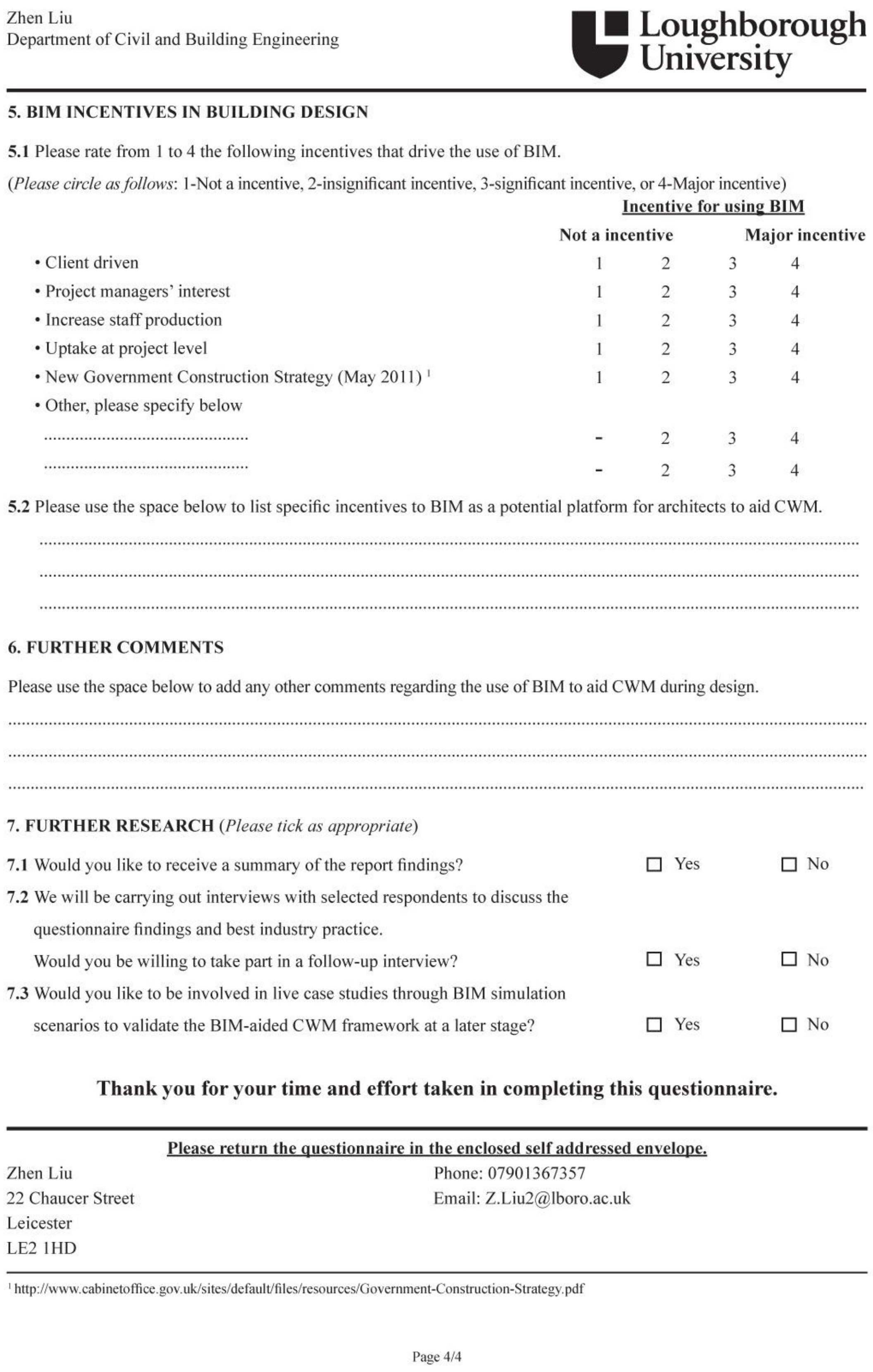
4.2 Please use the space below to list specific barriers to BIM as a potential platform for architects to aid CWM.

....

....

....

Page 3/4



Zhen Liu
Department of Civil and Building Engineering

Loughborough University

5. BIM INCENTIVES IN BUILDING DESIGN

5.1 Please rate from 1 to 4 the following incentives that drive the use of BIM.

(*Please circle as follows*: 1-Not a incentive, 2-insignificant incentive, 3-significant incentive, or 4-Major incentive)

	Incentive for using BIM			
	Not a incentive			**Major incentive**
• Client driven	1	2	3	4
• Project managers' interest	1	2	3	4
• Increase staff production	1	2	3	4
• Uptake at project level	1	2	3	4
• New Government Construction Strategy (May 2011) [1]	1	2	3	4
• Other, please specify below				
....	-	2	3	4
....	-	2	3	4

5.2 Please use the space below to list specific incentives to BIM as a potential platform for architects to aid CWM.

....

....

....

6. FURTHER COMMENTS

Please use the space below to add any other comments regarding the use of BIM to aid CWM during design.

....

....

....

7. FURTHER RESEARCH (*Please tick as appropriate*)

7.1 Would you like to receive a summary of the report findings?	☐ Yes	☐ No
7.2 We will be carrying out interviews with selected respondents to discuss the questionnaire findings and best industry practice. Would you be willing to take part in a follow-up interview?	☐ Yes	☐ No
7.3 Would you like to be involved in live case studies through BIM simulation scenarios to validate the BIM-aided CWM framework at a later stage?	☐ Yes	☐ No

Thank you for your time and effort taken in completing this questionnaire.

Please return the questionnaire in the enclosed self addressed envelope.

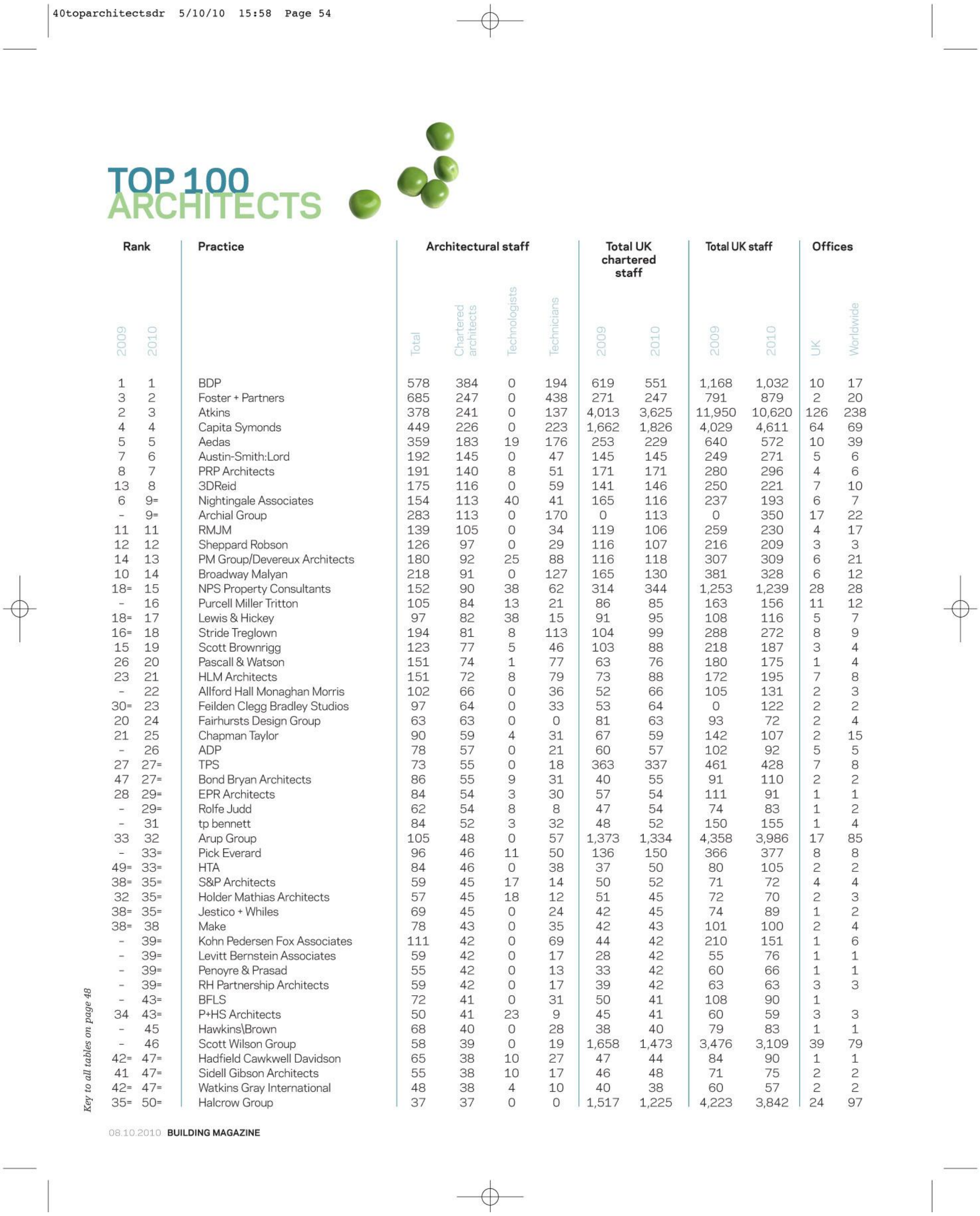
Zhen Liu
22 Chaucer Street
Leicester
LE2 1HD

Phone: 07901367357
Email: Z.Liu2@lboro.ac.uk

---

[1] http://www.cabinetoffice.gov.uk/sites/default/files/resources/Government-Construction-Strategy.pdf

Appendix 2.1.3 Questionnaire sample



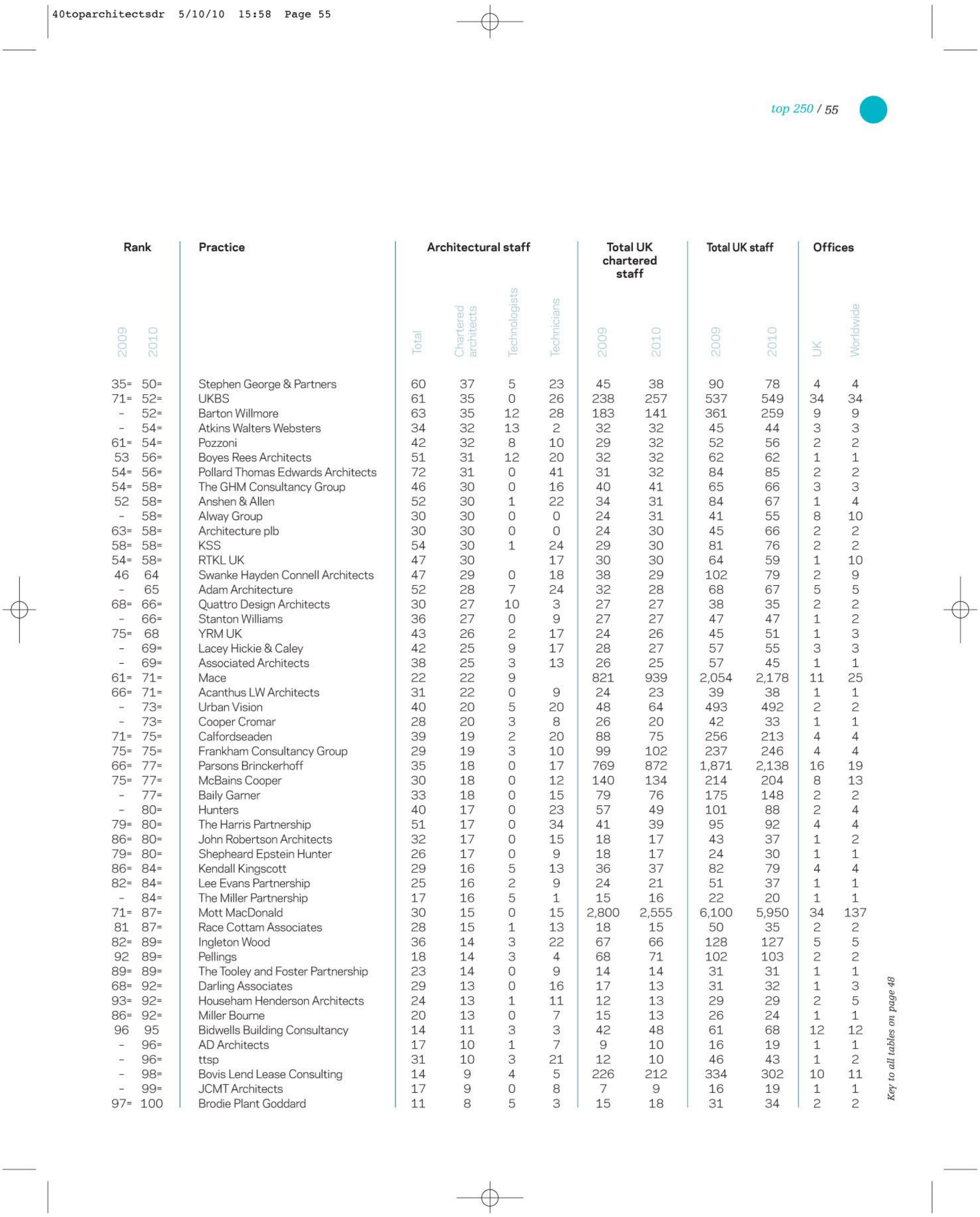
40toparchitectsdr 5/10/10 15:58 Page 54

TOP 100 ARCHITECTS

Rank		Practice	Architectural staff				Total UK chartered staff		Total UK staff		Offices	
2009	2010		Total	Chartered architects	Technologists	Technicians	2009	2010	2009	2010	UK	Worldwide
1	1	BDP	578	384	0	194	619	551	1,168	1,032	10	17
3	2	Foster + Partners	685	247	0	438	271	247	791	879	2	20
2	3	Atkins	378	241	0	137	4,013	3,625	11,950	10,620	126	238
4	4	Capita Symonds	449	226	0	223	1,662	1,826	4,029	4,611	64	69
5	5	Aedas	359	183	19	176	253	229	640	572	10	39
7	6	Austin-Smith:Lord	192	145	0	47	145	145	249	271	5	6
8	7	PRP Architects	191	140	8	51	171	171	280	296	4	6
13	8	3DReid	175	116	0	59	141	146	250	221	7	10
6	9=	Nightingale Associates	154	113	40	41	165	116	237	193	6	7
–	9=	Archial Group	283	113	0	170	0	113	0	350	17	22
11	11	RMJM	139	105	0	34	119	106	259	230	4	17
12	12	Sheppard Robson	126	97	0	29	116	107	216	209	3	3
14	13	PM Group/Devereux Architects	180	92	25	88	116	118	307	309	6	21
10	14	Broadway Malyan	218	91	0	127	165	130	381	328	6	12
18=	15	NPS Property Consultants	152	90	38	62	314	344	1,253	1,239	28	28
–	16	Purcell Miller Tritton	105	84	13	21	86	85	163	156	11	12
18=	17	Lewis & Hickey	97	82	38	15	91	95	108	116	5	7
16=	18	Stride Treglown	194	81	8	113	104	99	288	272	8	9
15	19	Scott Brownrigg	123	77	5	46	103	88	218	187	3	4
26	20	Pascall & Watson	151	74	1	77	63	76	180	175	1	4
23	21	HLM Architects	151	72	8	79	73	88	172	195	7	8
–	22	Allford Hall Monaghan Morris	102	66	0	36	52	66	105	131	2	3
30=	23	Feilden Clegg Bradley Studios	97	64	0	33	53	64	0	122	2	2
20	24	Fairhursts Design Group	63	63	0	0	81	63	93	72	2	4
21	25	Chapman Taylor	90	59	4	31	67	59	142	107	2	15
–	26	ADP	78	57	0	21	60	57	102	92	5	5
27	27=	TPS	73	55	0	18	363	337	461	428	7	8
47	27=	Bond Bryan Architects	86	55	9	31	40	55	91	110	2	2
28	29=	EPR Architects	84	54	3	30	57	54	111	91	1	1
–	29=	Rolfe Judd	62	54	8	8	47	54	74	83	1	2
–	31	tp bennett	84	52	3	32	48	52	150	155	1	4
33	32	Arup Group	105	48	0	57	1,373	1,334	4,358	3,986	17	85
–	33=	Pick Everard	96	46	11	50	136	150	366	377	8	8
49=	33=	HTA	84	46	0	38	37	50	80	105	2	2
38=	35=	S&P Architects	59	45	17	14	50	52	71	72	4	4
32	35=	Holder Mathias Architects	57	45	18	12	51	45	72	70	2	3
38=	35=	Jestico + Whiles	69	45	0	24	42	45	74	89	1	2
38=	38	Make	78	43	0	35	42	43	101	100	2	4
–	39=	Kohn Pedersen Fox Associates	111	42	0	69	44	42	210	151	1	6
–	39=	Levitt Bernstein Associates	59	42	0	17	28	42	55	76	1	1
–	39=	Penoyre & Prasad	55	42	0	13	33	42	60	66	1	1
–	39=	RH Partnership Architects	59	42	0	17	39	42	63	63	3	3
–	43=	BFLS	72	41	0	31	50	41	108	90	1	
34	43=	P+HS Architects	50	41	23	9	45	41	60	59	3	3
–	45	Hawkins\Brown	68	40	0	28	38	40	79	83	1	1
–	46	Scott Wilson Group	58	39	0	19	1,658	1,473	3,476	3,109	39	79
42=	47=	Hadfield Cawkwell Davidson	65	38	10	27	47	44	84	90	1	1
41	47=	Sidell Gibson Architects	55	38	10	17	46	48	71	75	2	2
42=	47=	Watkins Gray International	48	38	4	10	40	38	60	57	2	2
35=	50=	Halcrow Group	37	37	0	0	1,517	1,225	4,223	3,842	24	97

Key to all tables on page 48

08.10.2010 **BUILDING MAGAZINE**



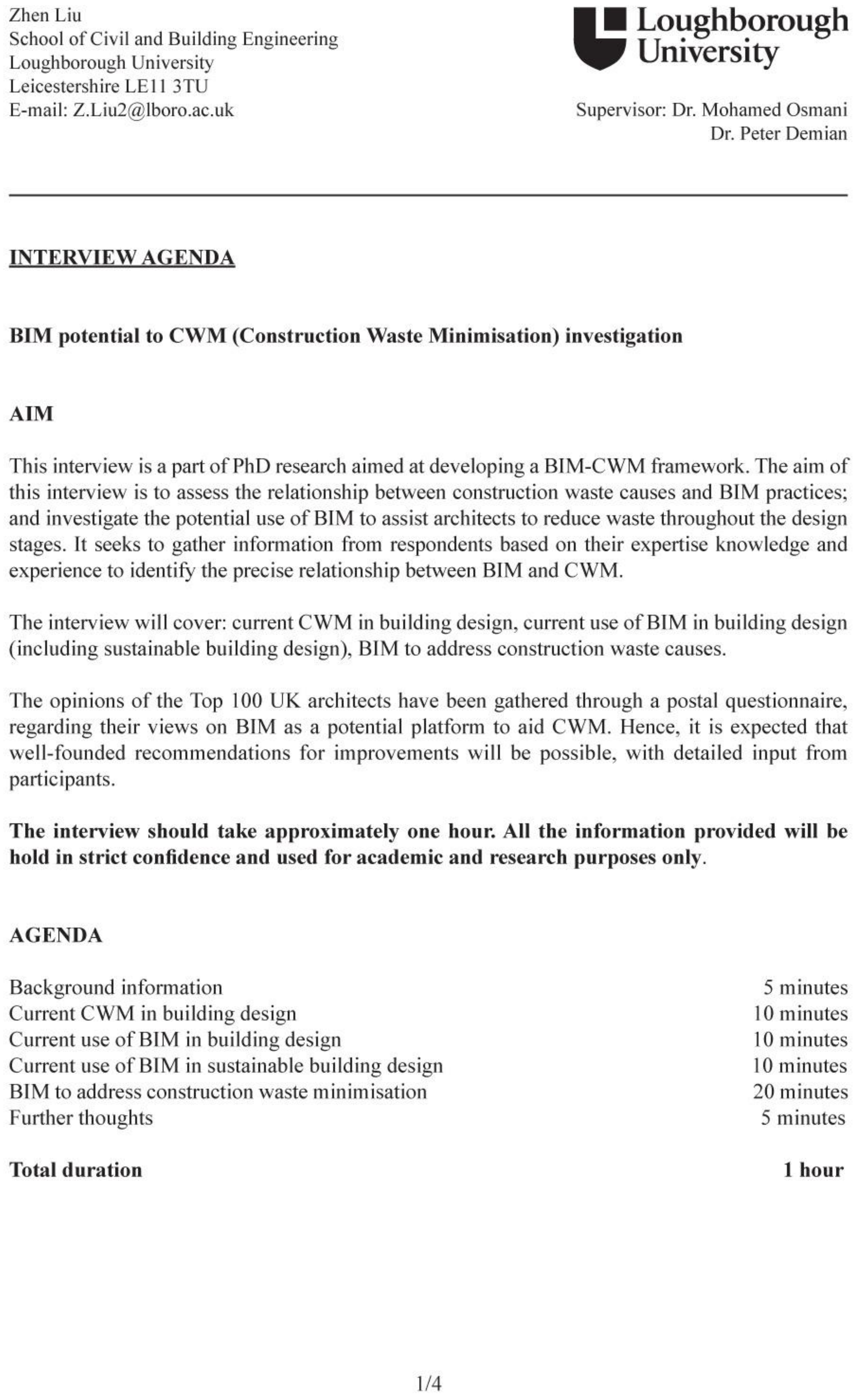
40toparchitectsdr 5/10/10 15:58 Page 55

top 250 / 55

Rank		Practice	Architectural staff				Total UK chartered staff		Total UK staff		Offices	
2009	2010		Total	Chartered architects	Technologists	Technicians	2009	2010	2009	2010	UK	Worldwide
35=	50=	Stephen George & Partners	60	37	5	23	45	38	90	78	4	4
71=	52=	UKBS	61	35	0	26	238	257	537	549	34	34
-	52=	Barton Willmore	63	35	12	28	183	141	361	259	9	9
-	54=	Atkins Walters Websters	34	32	13	2	32	32	45	44	3	3
61=	54=	Pozzoni	42	32	8	10	29	32	52	56	2	2
53	56=	Boyes Rees Architects	51	31	12	20	32	32	62	62	1	1
54=	56=	Pollard Thomas Edwards Architects	72	31	0	41	31	32	84	85	2	2
54=	58=	The GHM Consultancy Group	46	30	0	16	40	41	65	66	3	3
52	58=	Anshen & Allen	52	30	1	22	34	31	84	67	1	4
-	58=	Alway Group	30	30	0	0	24	31	41	55	8	10
63=	58=	Architecture plb	30	30	0	0	24	30	45	66	2	2
58=	58=	KSS	54	30	1	24	29	30	81	76	2	2
54=	58=	RTKL UK	47	30		17	30	30	64	59	1	10
46	64	Swanke Hayden Connell Architects	47	29	0	18	38	29	102	79	2	9
-	65	Adam Architecture	52	28	7	24	32	28	68	67	5	5
68=	66=	Quattro Design Architects	30	27	10	3	27	27	38	35	2	2
-	66=	Stanton Williams	36	27	0	9	27	27	47	47	1	2
75=	68	YRM UK	43	26	2	17	24	26	45	51	1	3
-	69=	Lacey Hickie & Caley	42	25	9	17	28	27	57	55	3	3
-	69=	Associated Architects	38	25	3	13	26	25	57	45	1	1
61=	71=	Mace	22	22	9		821	939	2,054	2,178	11	25
66=	71=	Acanthus LW Architects	31	22	0	9	24	23	39	38	1	1
-	73=	Urban Vision	40	20	5	20	48	64	493	492	2	2
-	73=	Cooper Cromar	28	20	3	8	26	20	42	33	1	1
71=	75=	Calfordseaden	39	19	2	20	88	75	256	213	4	4
75=	75=	Frankham Consultancy Group	29	19	3	10	99	102	237	246	4	4
66=	77=	Parsons Brinckerhoff	35	18	0	17	769	872	1,871	2,138	16	19
75=	77=	McBains Cooper	30	18	0	12	140	134	214	204	8	13
-	77=	Baily Garner	33	18	0	15	79	76	175	148	2	2
-	80=	Hunters	40	17	0	23	57	49	101	88	2	4
79=	80=	The Harris Partnership	51	17	0	34	41	39	95	92	4	4
86=	80=	John Robertson Architects	32	17	0	15	18	17	43	37	1	2
79=	80=	Shepheard Epstein Hunter	26	17	0	9	18	17	24	30	1	1
86=	84=	Kendall Kingscott	29	16	5	13	36	37	82	79	4	4
82=	84=	Lee Evans Partnership	25	16	2	9	24	21	51	37	1	1
-	84=	The Miller Partnership	17	16	5	1	15	16	22	20	1	1
71=	87=	Mott MacDonald	30	15	0	15	2,800	2,555	6,100	5,950	34	137
81	87=	Race Cottam Associates	28	15	1	13	18	15	50	35	2	2
82=	89=	Ingleton Wood	36	14	3	22	67	66	128	127	5	5
92	89=	Pellings	18	14	3	4	68	71	102	103	2	2
89=	89=	The Tooley and Foster Partnership	23	14	0	9	14	14	31	31	1	1
68=	92=	Darling Associates	29	13	0	16	17	13	31	32	1	3
93=	92=	Househam Henderson Architects	24	13	1	11	12	13	29	29	2	5
86=	92=	Miller Bourne	20	13	0	7	15	13	26	24	1	1
96	95	Bidwells Building Consultancy	14	11	3	3	42	48	61	68	12	12
-	96=	AD Architects	17	10	1	7	9	10	16	19	1	1
-	96=	ttsp	31	10	3	21	12	10	46	43	1	2
-	98=	Bovis Lend Lease Consulting	14	9	4	5	226	212	334	302	10	11
-	99=	JCMT Architects	17	9	0	8	7	9	16	19	1	1
97=	100	Brodie Plant Goddard	11	8	5	3	15	18	31	34	2	2

Key to all tables on page 48

Appendix 2.2 Interviews schedule



Zhen Liu
School of Civil and Building Engineering
Loughborough University
Leicestershire LE11 3TU
E-mail: Z.Liu2@lboro.ac.uk

Loughborough University

Supervisor: Dr. Mohamed Osmani
Dr. Peter Demian

INTERVIEW AGENDA

BIM potential to CWM (Construction Waste Minimisation) investigation

AIM

This interview is a part of PhD research aimed at developing a BIM-CWM framework. The aim of this interview is to assess the relationship between construction waste causes and BIM practices; and investigate the potential use of BIM to assist architects to reduce waste throughout the design stages. It seeks to gather information from respondents based on their expertise knowledge and experience to identify the precise relationship between BIM and CWM.

The interview will cover: current CWM in building design, current use of BIM in building design (including sustainable building design), BIM to address construction waste causes.

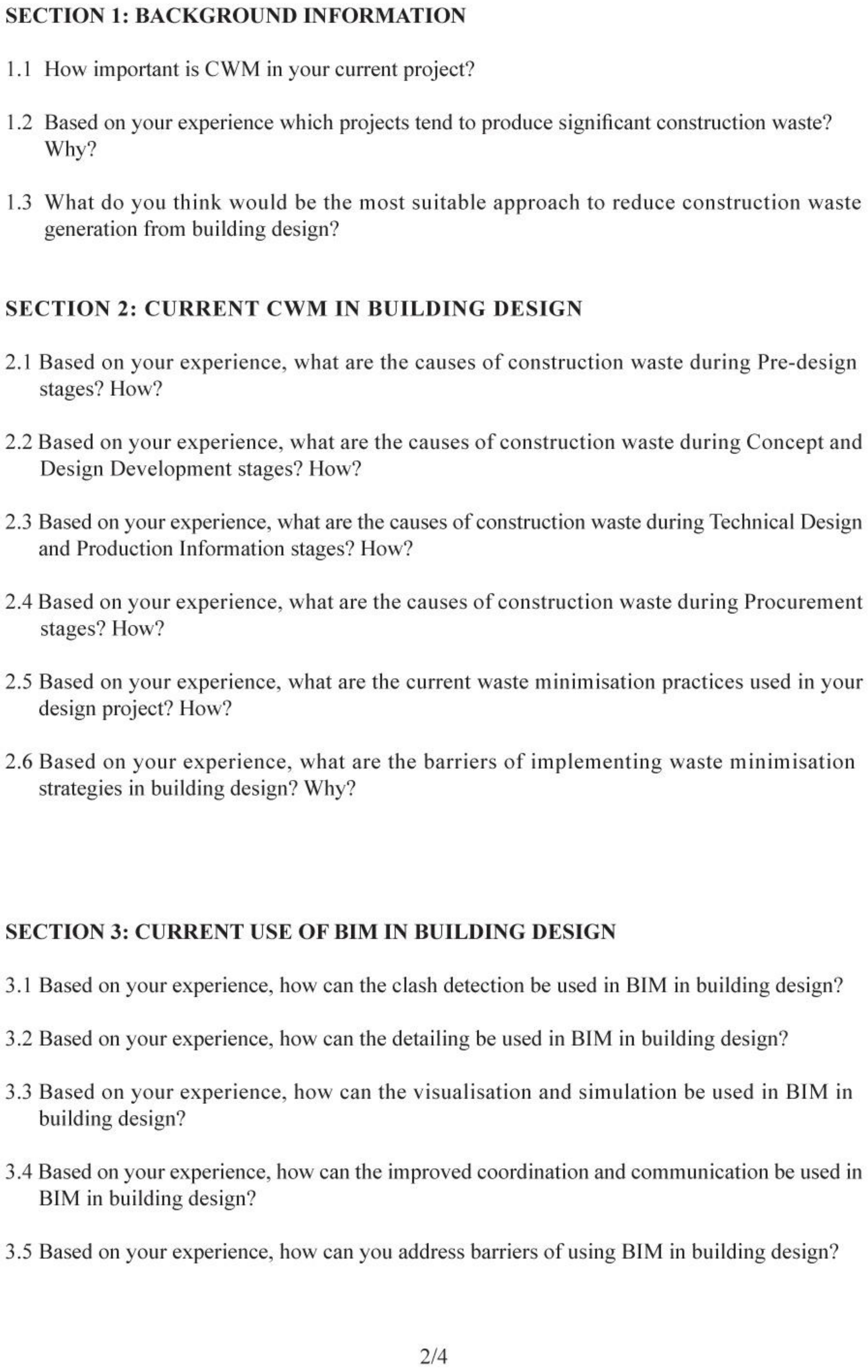
The opinions of the Top 100 UK architects have been gathered through a postal questionnaire, regarding their views on BIM as a potential platform to aid CWM. Hence, it is expected that well-founded recommendations for improvements will be possible, with detailed input from participants.

The interview should take approximately one hour. All the information provided will be hold in strict confidence and used for academic and research purposes only.

AGENDA

Background information	5 minutes
Current CWM in building design	10 minutes
Current use of BIM in building design	10 minutes
Current use of BIM in sustainable building design	10 minutes
BIM to address construction waste minimisation	20 minutes
Further thoughts	5 minutes
Total duration	**1 hour**

1/4



SECTION 1: BACKGROUND INFORMATION

1.1 How important is CWM in your current project?

1.2 Based on your experience which projects tend to produce significant construction waste? Why?

1.3 What do you think would be the most suitable approach to reduce construction waste generation from building design?

SECTION 2: CURRENT CWM IN BUILDING DESIGN

2.1 Based on your experience, what are the causes of construction waste during Pre-design stages? How?

2.2 Based on your experience, what are the causes of construction waste during Concept and Design Development stages? How?

2.3 Based on your experience, what are the causes of construction waste during Technical Design and Production Information stages? How?

2.4 Based on your experience, what are the causes of construction waste during Procurement stages? How?

2.5 Based on your experience, what are the current waste minimisation practices used in your design project? How?

2.6 Based on your experience, what are the barriers of implementing waste minimisation strategies in building design? Why?

SECTION 3: CURRENT USE OF BIM IN BUILDING DESIGN

3.1 Based on your experience, how can the clash detection be used in BIM in building design?

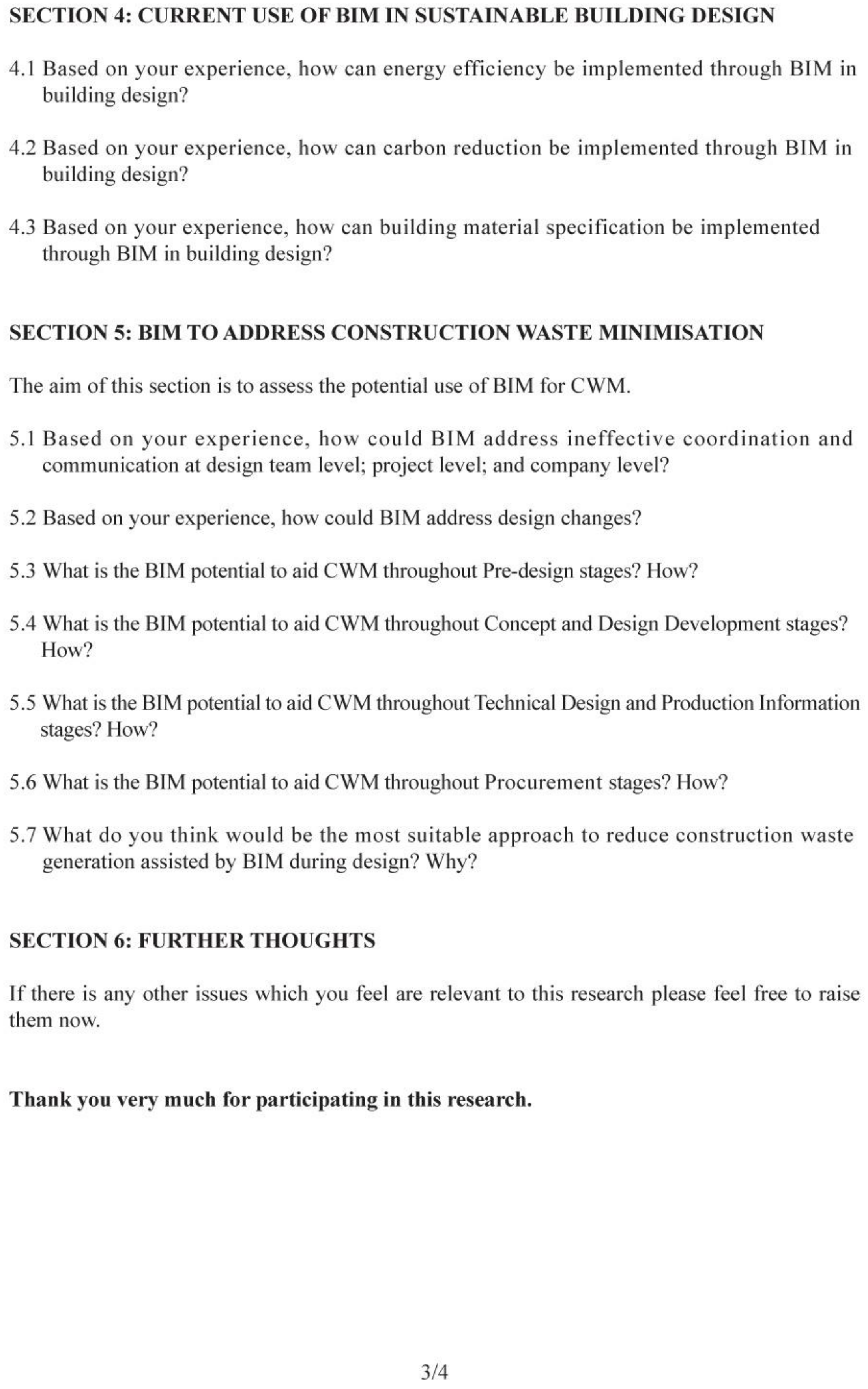
3.2 Based on your experience, how can the detailing be used in BIM in building design?

3.3 Based on your experience, how can the visualisation and simulation be used in BIM in building design?

3.4 Based on your experience, how can the improved coordination and communication be used in BIM in building design?

3.5 Based on your experience, how can you address barriers of using BIM in building design?

2/4



SECTION 4: CURRENT USE OF BIM IN SUSTAINABLE BUILDING DESIGN

4.1 Based on your experience, how can energy efficiency be implemented through BIM in building design?

4.2 Based on your experience, how can carbon reduction be implemented through BIM in building design?

4.3 Based on your experience, how can building material specification be implemented through BIM in building design?

SECTION 5: BIM TO ADDRESS CONSTRUCTION WASTE MINIMISATION

The aim of this section is to assess the potential use of BIM for CWM.

5.1 Based on your experience, how could BIM address ineffective coordination and communication at design team level; project level; and company level?

5.2 Based on your experience, how could BIM address design changes?

5.3 What is the BIM potential to aid CWM throughout Pre-design stages? How?

5.4 What is the BIM potential to aid CWM throughout Concept and Design Development stages? How?

5.5 What is the BIM potential to aid CWM throughout Technical Design and Production Information stages? How?

5.6 What is the BIM potential to aid CWM throughout Procurement stages? How?

5.7 What do you think would be the most suitable approach to reduce construction waste generation assisted by BIM during design? Why?

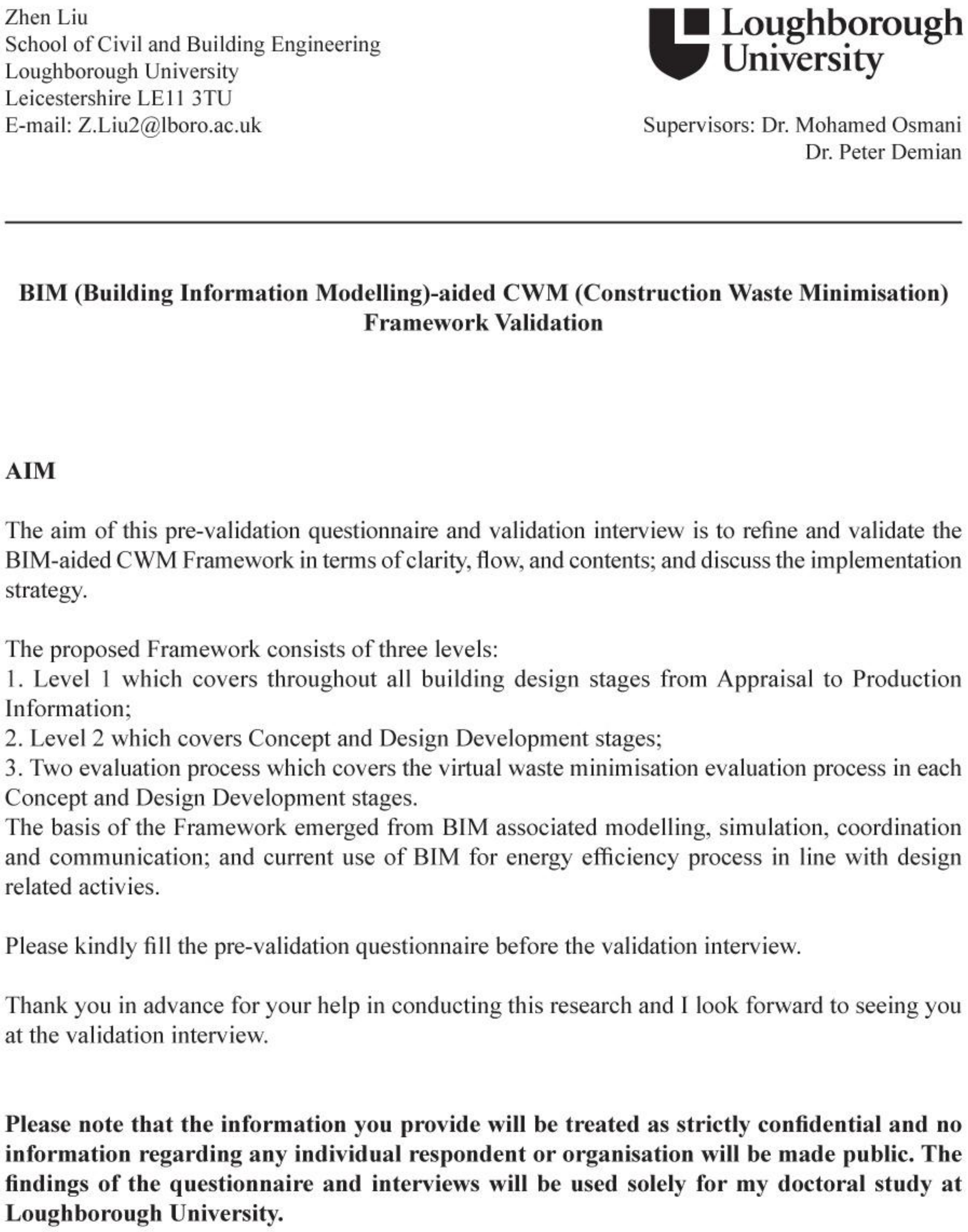
SECTION 6: FURTHER THOUGHTS

If there is any other issues which you feel are relevant to this research please feel free to raise them now.

Thank you very much for participating in this research.

Appendix 2.3 BaW Framework validation documents

Appendix 2.3.1 Functional specification letter for the BaW Framework validation



Zhen Liu
School of Civil and Building Engineering
Loughborough University
Leicestershire LE11 3TU
E-mail: Z.Liu2@lboro.ac.uk

Loughborough University

Supervisors: Dr. Mohamed Osmani
Dr. Peter Demian

BIM (Building Information Modelling)-aided CWM (Construction Waste Minimisation) Framework Validation

AIM

The aim of this pre-validation questionnaire and validation interview is to refine and validate the BIM-aided CWM Framework in terms of clarity, flow, and contents; and discuss the implementation strategy.

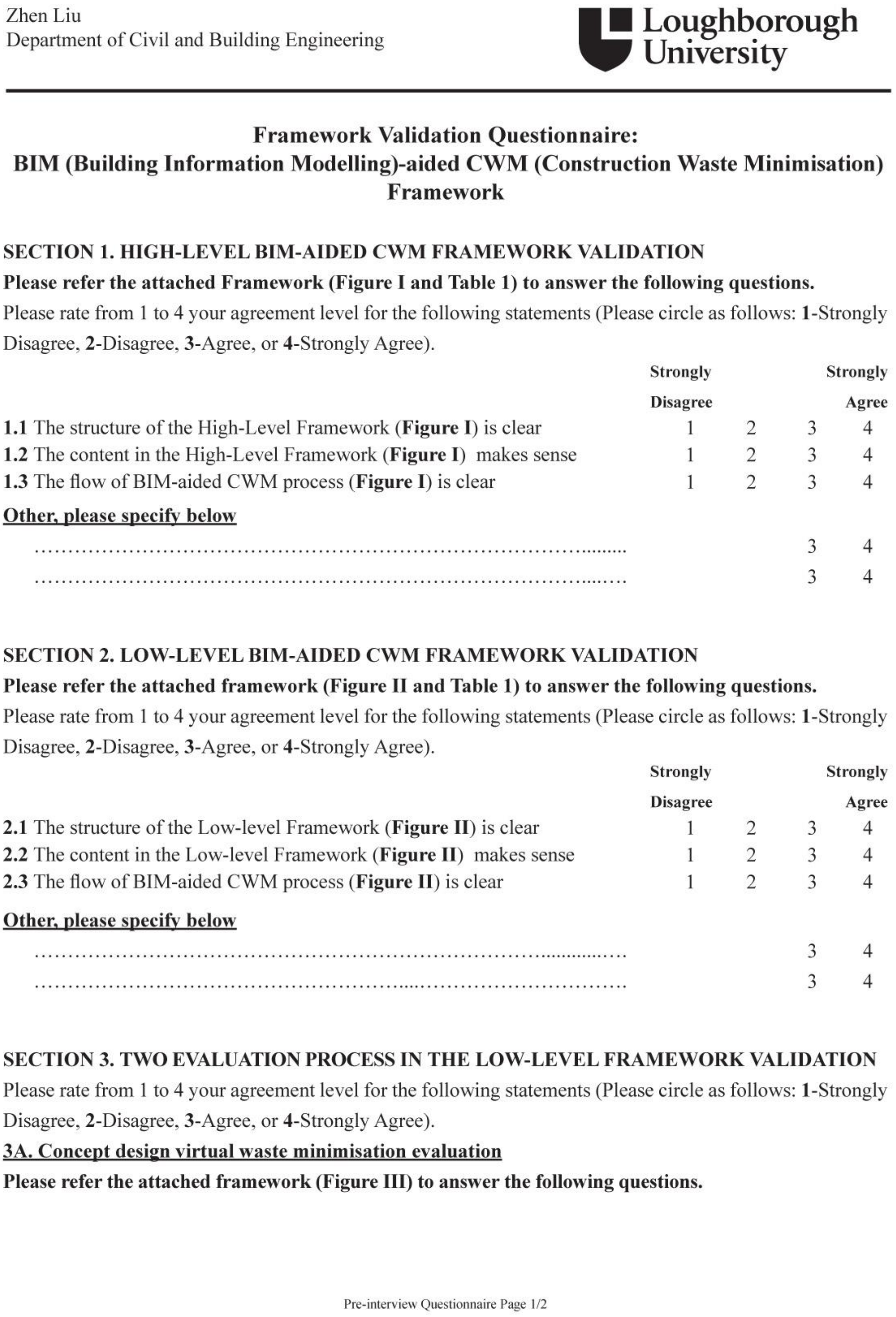
The proposed Framework consists of three levels:
1. Level 1 which covers throughout all building design stages from Appraisal to Production Information;
2. Level 2 which covers Concept and Design Development stages;
3. Two evaluation process which covers the virtual waste minimisation evaluation process in each Concept and Design Development stages.
The basis of the Framework emerged from BIM associated modelling, simulation, coordination and communication; and current use of BIM for energy efficiency process in line with design related activies.

Please kindly fill the pre-validation questionnaire before the validation interview.

Thank you in advance for your help in conducting this research and I look forward to seeing you at the validation interview.

Please note that the information you provide will be treated as strictly confidential and no information regarding any individual respondent or organisation will be made public. The findings of the questionnaire and interviews will be used solely for my doctoral study at Loughborough University.

Appendix 2.3.2 BaW Framework validation questionnaire



Zhen Liu
Department of Civil and Building Engineering

Loughborough University

Framework Validation Questionnaire:
BIM (Building Information Modelling)-aided CWM (Construction Waste Minimisation) Framework

SECTION 1. HIGH-LEVEL BIM-AIDED CWM FRAMEWORK VALIDATION

Please refer the attached Framework (Figure I and Table 1) to answer the following questions.

Please rate from 1 to 4 your agreement level for the following statements (Please circle as follows: **1**-Strongly Disagree, **2**-Disagree, **3**-Agree, or **4**-Strongly Agree).

	Strongly Disagree			Strongly Agree
1.1 The structure of the High-Level Framework (**Figure I**) is clear	1	2	3	4
1.2 The content in the High-Level Framework (**Figure I**) makes sense	1	2	3	4
1.3 The flow of BIM-aided CWM process (**Figure I**) is clear	1	2	3	4
<u>Other, please specify below</u>				
……………………………………………………………………………........			3	4
……………………………………………………………………………...….			3	4

SECTION 2. LOW-LEVEL BIM-AIDED CWM FRAMEWORK VALIDATION

Please refer the attached framework (Figure II and Table 1) to answer the following questions.

Please rate from 1 to 4 your agreement level for the following statements (Please circle as follows: **1**-Strongly Disagree, **2**-Disagree, **3**-Agree, or **4**-Strongly Agree).

	Strongly Disagree			Strongly Agree
2.1 The structure of the Low-level Framework (**Figure II**) is clear	1	2	3	4
2.2 The content in the Low-level Framework (**Figure II**) makes sense	1	2	3	4
2.3 The flow of BIM-aided CWM process (**Figure II**) is clear	1	2	3	4
<u>Other, please specify below</u>				
………………………………………………………………………...........….			3	4
……………………………………………….....………………………….			3	4

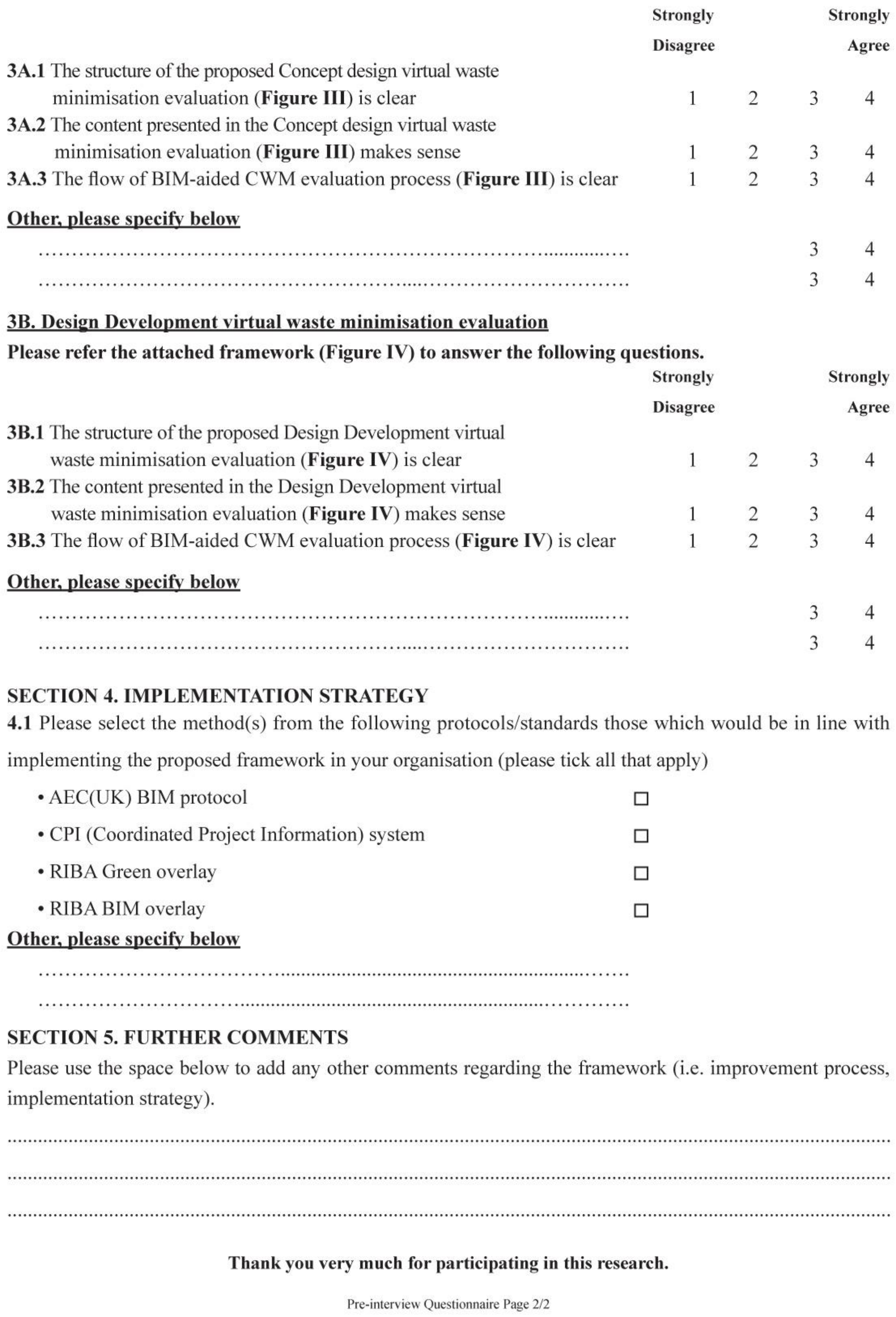
SECTION 3. TWO EVALUATION PROCESS IN THE LOW-LEVEL FRAMEWORK VALIDATION

Please rate from 1 to 4 your agreement level for the following statements (Please circle as follows: **1**-Strongly Disagree, **2**-Disagree, **3**-Agree, or **4**-Strongly Agree).

<u>3A. Concept design virtual waste minimisation evaluation</u>

Please refer the attached framework (Figure III) to answer the following questions.

Pre-interview Questionnaire Page 1/2



	Strongly Disagree			Strongly Agree
3A.1 The structure of the proposed Concept design virtual waste minimisation evaluation (**Figure III**) is clear	1	2	3	4
3A.2 The content presented in the Concept design virtual waste minimisation evaluation (**Figure III**) makes sense	1	2	3	4
3A.3 The flow of BIM-aided CWM evaluation process (**Figure III**) is clear	1	2	3	4

Other, please specify below

……………………………………………………………………………….............…			3	4
………………………………………………….....…………………………….			3	4

3B. Design Development virtual waste minimisation evaluation

Please refer the attached framework (Figure IV) to answer the following questions.

	Strongly Disagree			Strongly Agree
3B.1 The structure of the proposed Design Development virtual waste minimisation evaluation (**Figure IV**) is clear	1	2	3	4
3B.2 The content presented in the Design Development virtual waste minimisation evaluation (**Figure IV**) makes sense	1	2	3	4
3B.3 The flow of BIM-aided CWM evaluation process (**Figure IV**) is clear	1	2	3	4

Other, please specify below

……………………………………………………………………………….............…			3	4
………………………………………………….....…………………………….			3	4

SECTION 4. IMPLEMENTATION STRATEGY

4.1 Please select the method(s) from the following protocols/standards those which would be in line with implementing the proposed framework in your organisation (please tick all that apply)

- AEC(UK) BIM protocol ☐
- CPI (Coordinated Project Information) system ☐
- RIBA Green overlay ☐
- RIBA BIM overlay ☐

Other, please specify below

…………………………………...……

……………………………..…………

SECTION 5. FURTHER COMMENTS

Please use the space below to add any other comments regarding the framework (i.e. improvement process, implementation strategy).

....

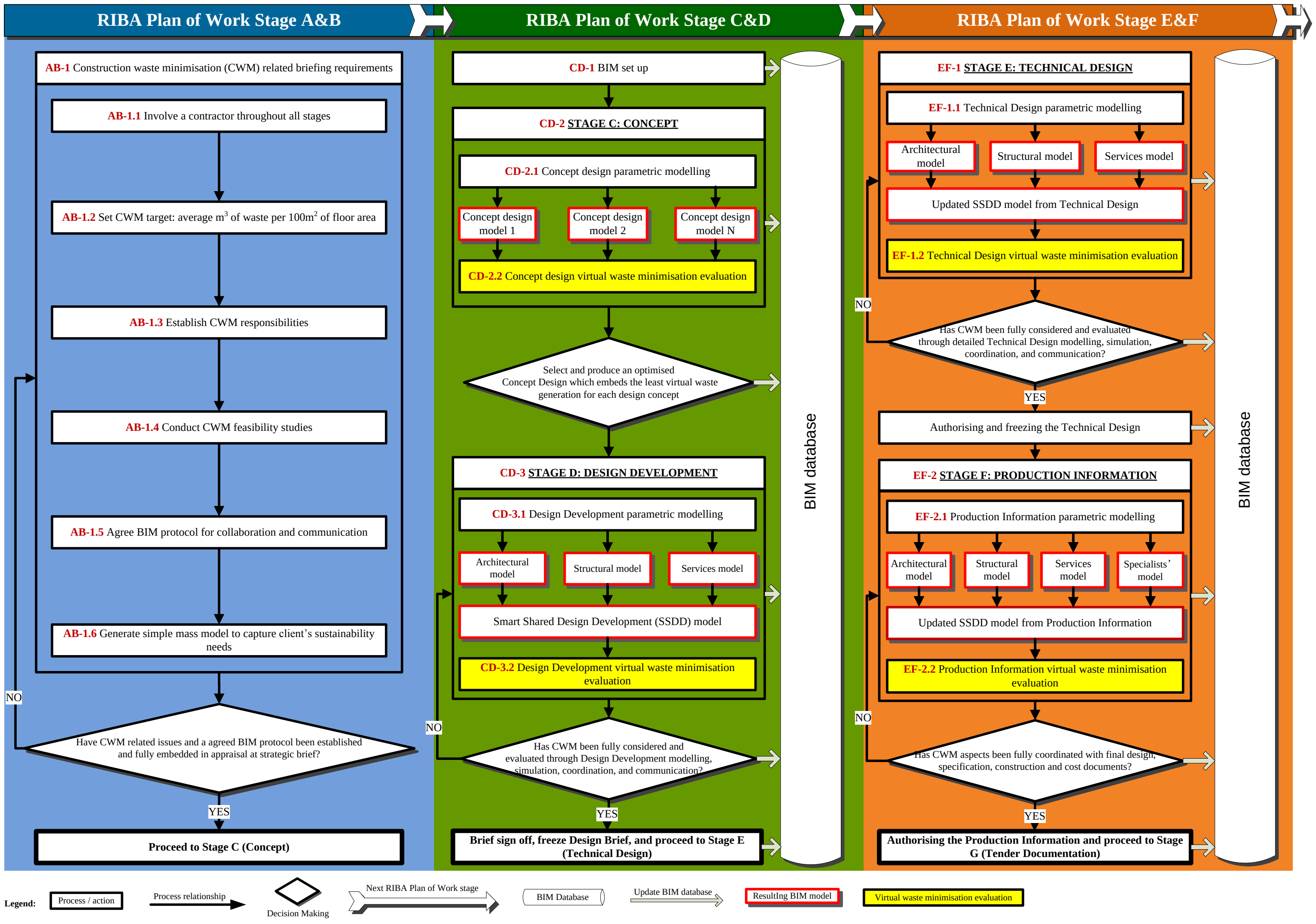
....

....

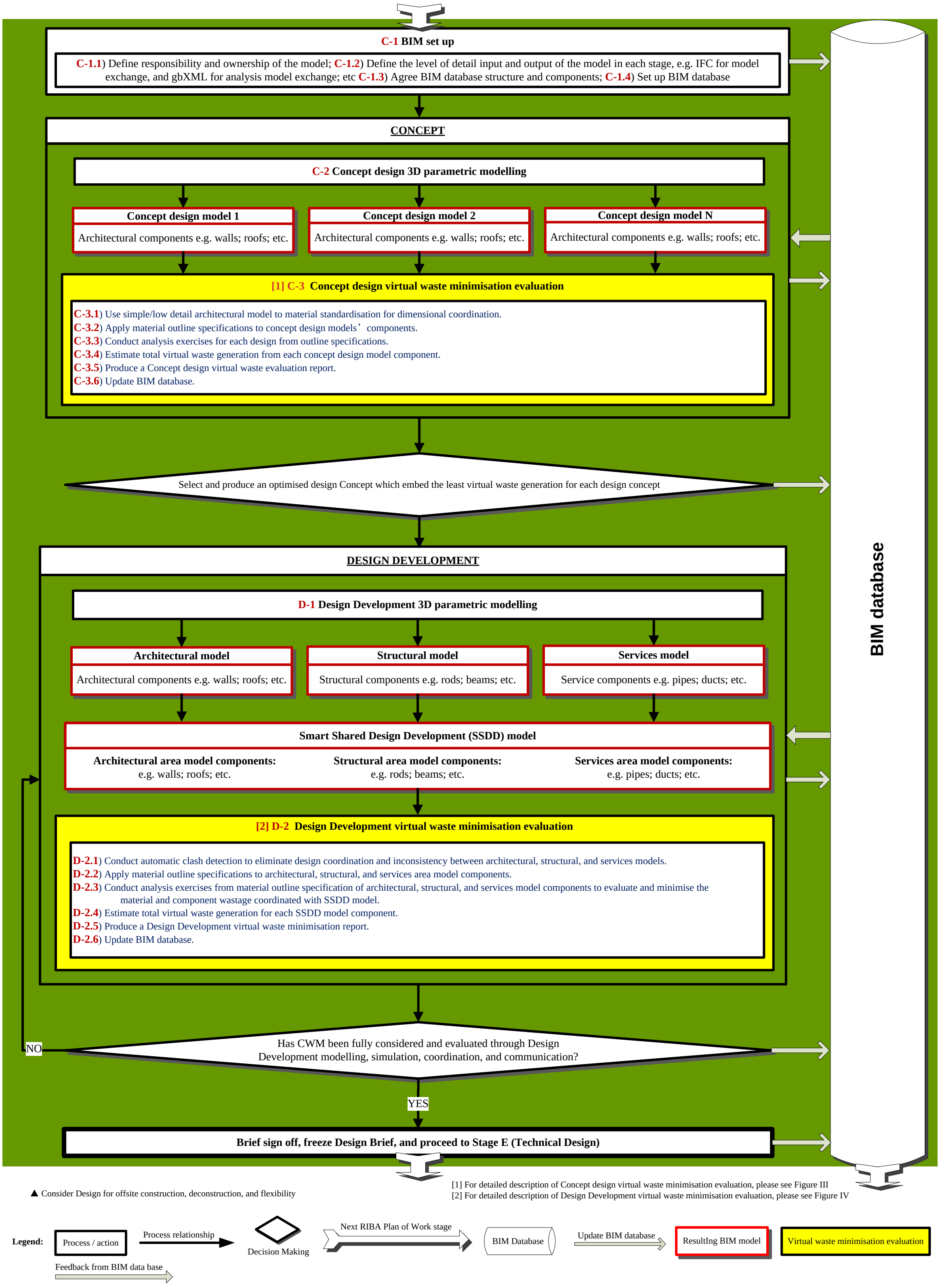
Thank you very much for participating in this research.

Pre-interview Questionnaire Page 2/2

Appendix 2.3.2.1 High-level BaW Framework



Appendix 2.3.2.2 Low-level BaW Framework



C-1.1) Define responsibility and ownership of the model; **C-1.2**) Define the level of detail input and output of the model in each stage, e.g. IFC for model exchange, and gbXML for analysis model exchange; etc **C-1.3**) Agree BIM database structure and components; **C-1.4**) Set up BIM database

C-3.1) Use simple/low detail architectural model to material standardisation for dimensional coordination.
C-3.2) Apply material outline specifications to concept design models' components.
C-3.3) Conduct analysis exercises for each design from outline specifications.
C-3.4) Estimate total virtual waste generation from each concept design model component.
C-3.5) Produce a Concept design virtual waste evaluation report.
C-3.6) Update BIM database.

Select and produce an optimised design Concept which embed the least virtual waste generation for each design concept

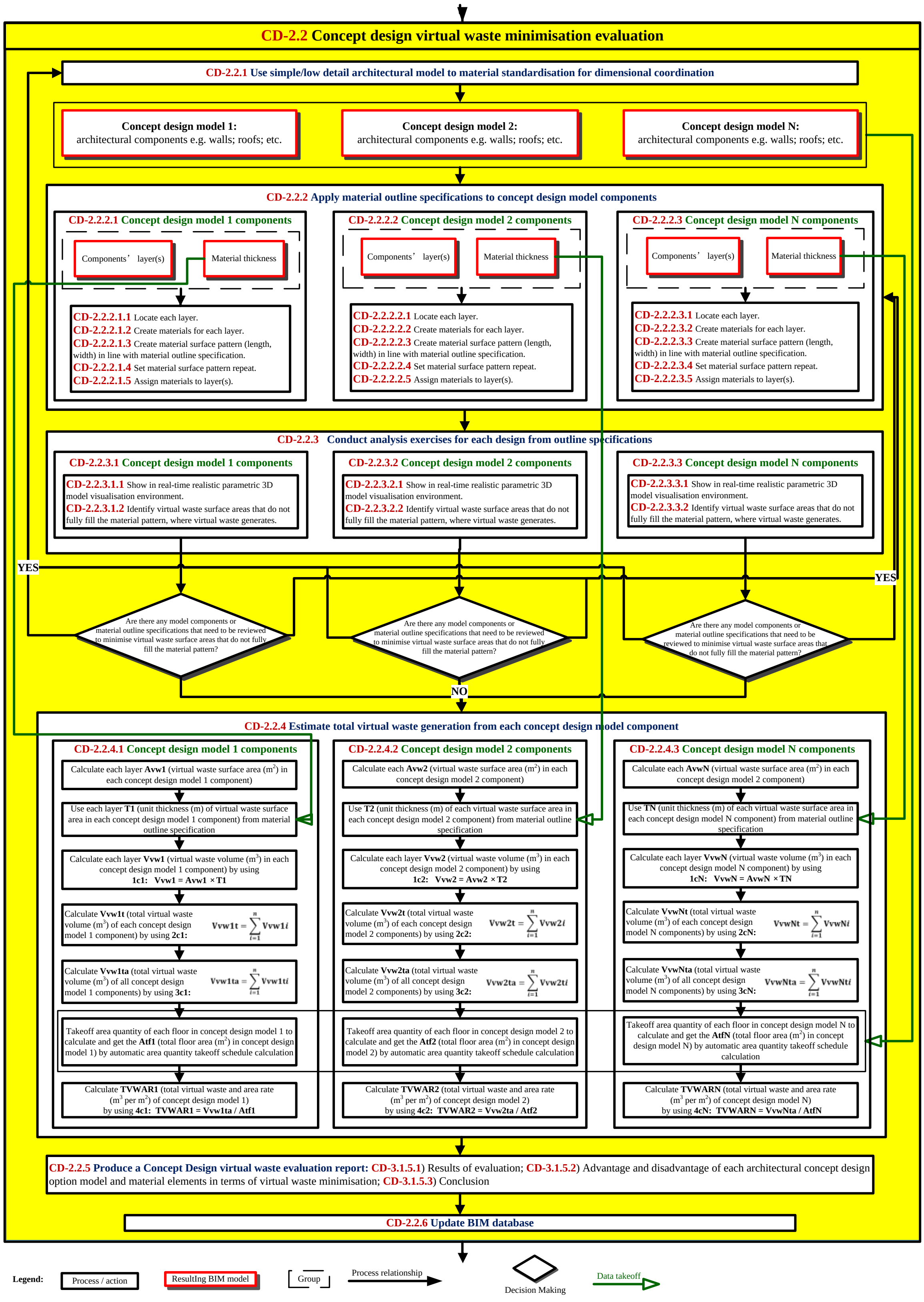
D-2.1) Conduct automatic clash detection to eliminate design coordination and inconsistency between architectural, structural, and services models.
D-2.2) Apply material outline specifications to architectural, structural, and services area model components.
D-2.3) Conduct analysis exercises from material outline specification of architectural, structural, and services model components to evaluate and minimise the material and component wastage coordinated with SSDD model.
D-2.4) Estimate total virtual waste generation for each SSDD model component.
D-2.5) Produce a Design Development virtual waste minimisation report.
D-2.6) Update BIM database.

Has CWM been fully considered and evaluated through Design Development modelling, simulation, coordination, and communication?

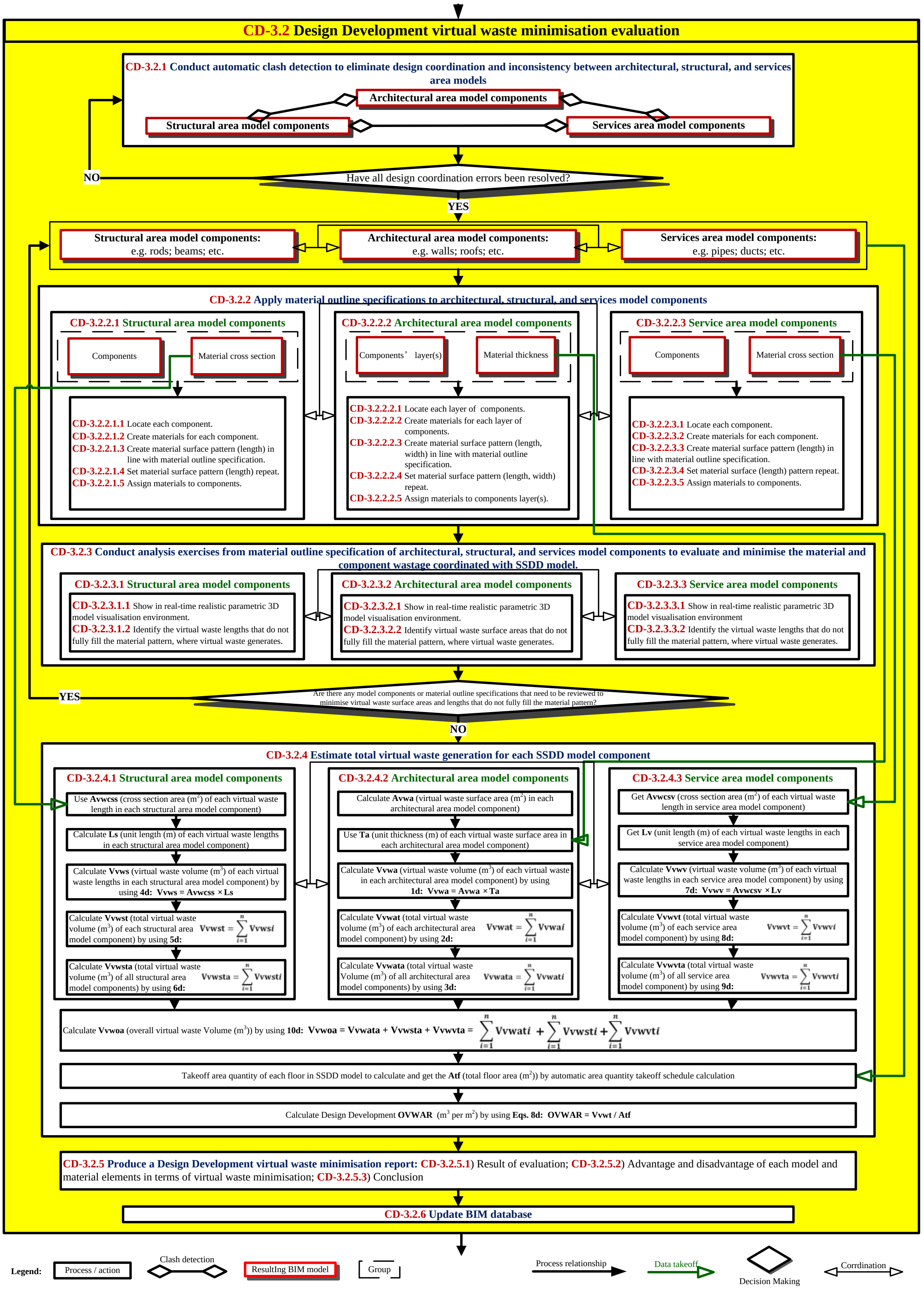
▲ Consider Design for offsite construction, deconstruction, and flexibility

[1] For detailed description of Concept design virtual waste minimisation evaluation, please see Figure III
[2] For detailed description of Design Development virtual waste minimisation evaluation, please see Figure IV

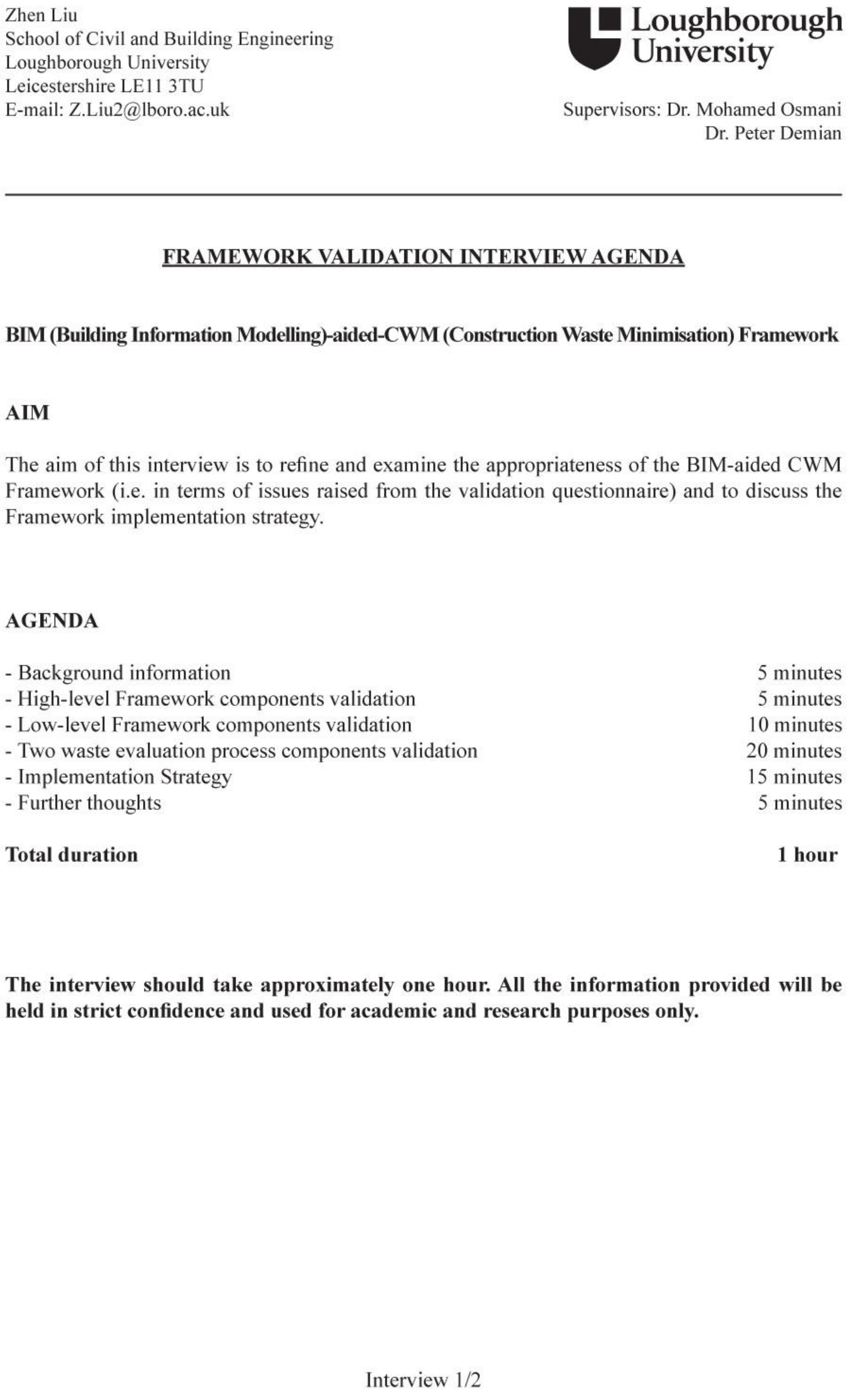
Appendix 2.3.2.3 The Low-level BaW Framework Concept stage waste evaluation process



Appendix 2.3.2.4 The Low-level BaW Framework Design Development stage waste evaluation process



Appendix 2.3.3 BaW Framework validation interview schedule



Zhen Liu
School of Civil and Building Engineering
Loughborough University
Leicestershire LE11 3TU
E-mail: Z.Liu2@lboro.ac.uk

Loughborough University

Supervisors: Dr. Mohamed Osmani
Dr. Peter Demian

FRAMEWORK VALIDATION INTERVIEW AGENDA

BIM (Building Information Modelling)-aided-CWM (Construction Waste Minimisation) Framework

AIM

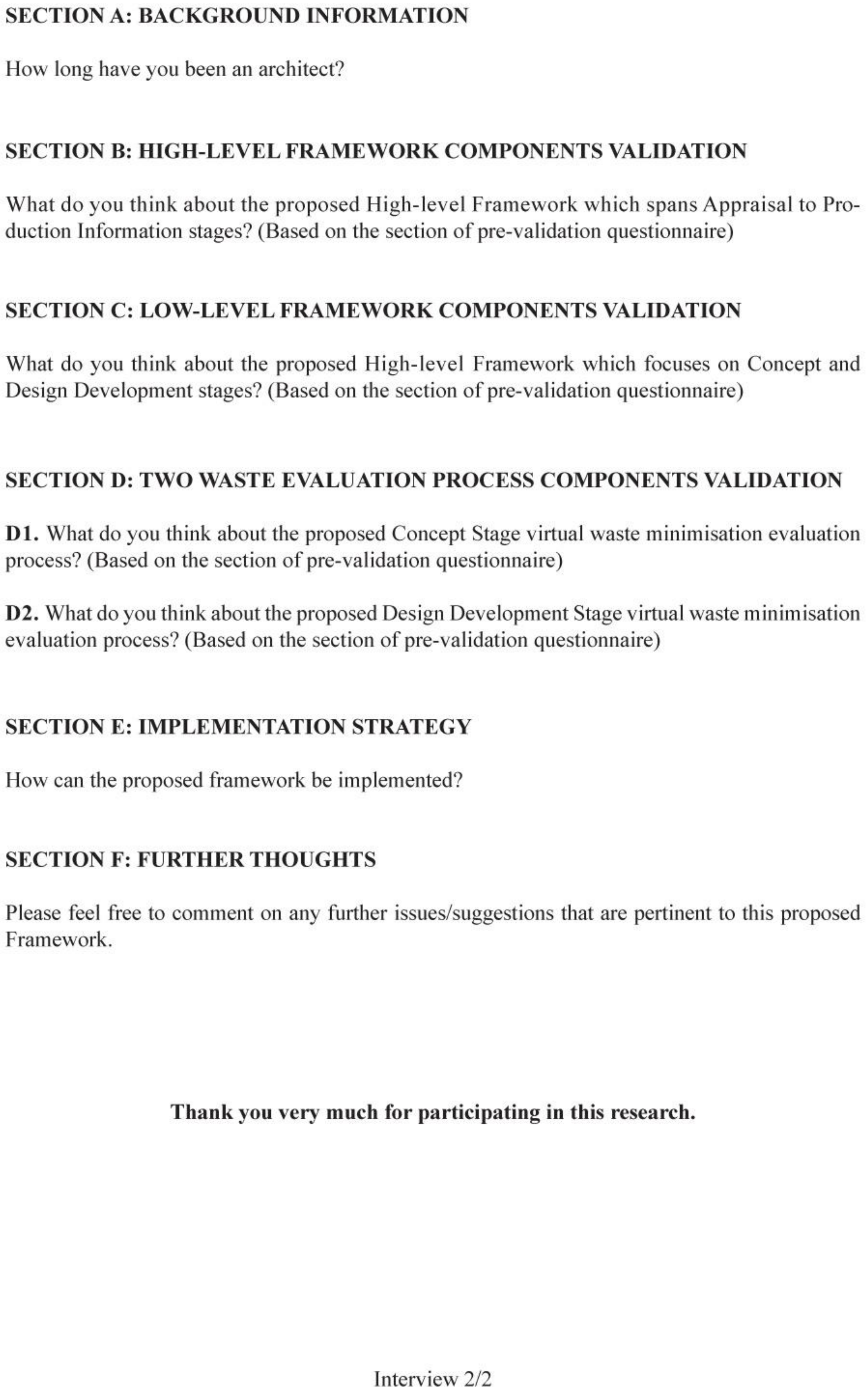
The aim of this interview is to refine and examine the appropriateness of the BIM-aided CWM Framework (i.e. in terms of issues raised from the validation questionnaire) and to discuss the Framework implementation strategy.

AGENDA

- Background information	5 minutes
- High-level Framework components validation	5 minutes
- Low-level Framework components validation	10 minutes
- Two waste evaluation process components validation	20 minutes
- Implementation Strategy	15 minutes
- Further thoughts	5 minutes
Total duration	**1 hour**

The interview should take approximately one hour. All the information provided will be held in strict confidence and used for academic and research purposes only.

Interview 1/2



SECTION A: BACKGROUND INFORMATION

How long have you been an architect?

SECTION B: HIGH-LEVEL FRAMEWORK COMPONENTS VALIDATION

What do you think about the proposed High-level Framework which spans Appraisal to Production Information stages? (Based on the section of pre-validation questionnaire)

SECTION C: LOW-LEVEL FRAMEWORK COMPONENTS VALIDATION

What do you think about the proposed High-level Framework which focuses on Concept and Design Development stages? (Based on the section of pre-validation questionnaire)

SECTION D: TWO WASTE EVALUATION PROCESS COMPONENTS VALIDATION

D1. What do you think about the proposed Concept Stage virtual waste minimisation evaluation process? (Based on the section of pre-validation questionnaire)

D2. What do you think about the proposed Design Development Stage virtual waste minimisation evaluation process? (Based on the section of pre-validation questionnaire)

SECTION E: IMPLEMENTATION STRATEGY

How can the proposed framework be implemented?

SECTION F: FURTHER THOUGHTS

Please feel free to comment on any further issues/suggestions that are pertinent to this proposed Framework.

Thank you very much for participating in this research.

Interview 2/2