

**BIM-BASED SOFTWARE FOR CONSTRUCTION  
WASTE ANALYTICS USING ARTIFICIAL  
INTELLIGENCE HYBRID MODELS**

**By**

**OLUGBENGA OLAWALE AKINADE**



*A thesis submitted in partial fulfilment of the requirements of the  
University of the West of England, Bristol  
for the degree of Doctor of Philosophy*

## DECLARATION

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

Signed: OLUGBENGA OLAWALE AKINADE

Signature .....

Date .....

## ABSTRACT

The Construction industry generates about 30% of the total waste in the UK. Current high landfill cost and severe environmental impact of waste reveal the need to reduce waste generated from construction activities. Although literature shows that the best approach to Construction Waste (CW) management is minimization at the design stage, current tools are not robust enough to support architects and design engineers. Review of extant literature reveals that the key limitations of existing CW management tools are that they are not integrated with the design process and that they lack Building Information Modelling (BIM) compliance. This is because the tools are external to design BIM tools used by architects and design engineers. This study, therefore, investigates BIM-based strategies for CW management and develops Artificial Intelligence (AI) hybrid models to predict CW at the design stage. The model was then integrated into Autodesk Revit as an add-in (BIMWaste) to provide CW analytics.

Based on a critical realism paradigm, the study adopts exploratory sequential mixed methods, which combines both qualitative and quantitative methods into a single study. The study starts with the review of extant literature and Focus Group Interviews (FGIs) with industry practitioners. The transcripts of the FGIs were subjected to thematic analysis to identify prevalent themes from the quotations. The factors from the literature review and FGIs were then combined and put together in a questionnaire survey and distributed to industry practitioners. The questionnaire responses were subjected to a rigorous statistical process to identify key strategies for BIM-based approach to waste efficient design coordination.

Results of factor analysis revealed five groups of BIM strategies for CW management, which are: (i) BIM-based collaboration for waste management, (ii) waste-driven design process and solutions, (iii) lifecycle waste analytics, (iv) innovative technologies for waste intelligence and analytics, and (v) improved documentation for waste management. The results improve the understanding of BIM functionalities and how they could improve the effectiveness of existing CW management tools. After that, the key strategies were developed into a holistic BIM framework for CW management. This was done to incorporate industrial and technological requirements for BIM enabled waste management into an integrated system.

The framework guided the development of AI hybrid models and BIM-based tool for CW management. Adaptive Neuro-Fuzzy Inference System (ANFIS) model was developed for CW prediction and mathematical models were developed for CW minimisation. Based on historical Construction Waste Record (CWR) from 117 building projects, the model development reveals that two key predictors of CW are “*Gross Floor Area (GFA)*” and “*Construction Type*”. The models were then incorporated into Autodesk Revit as an add-in to enable the prediction of CW from building designs. The performance of the add-in was tested using a test plan and two test cases. The results show that the tool performs well and that it predicts CW according to waste types, element types, and building levels. The study generated several implications that would be of interest to stakeholders in the construction industry. Particularly, the study provides a clear direction on how CW management strategies could be integrated into a BIM platform to streamline CW analytics.

## **DEDICATION**

To my heartbeat,

Omolola Oluwatoyosi

and

to my little princess,

Jemima Oluwatoyosi

## ACKNOWLEDGEMENT

My profound gratitude to God Almighty, the giver of life for the grace to complete this research.

My sincere appreciation goes to my mentor and director of studies, Professor Lukumon Oyedele for his tremendous supervision, exemplary leadership, guidance, and encouragement throughout the PhD research journey. Your incredible patience and support were invaluable to the success of the study. I will also like to appreciate the contributions and support of my second supervisor, Dr. Kamran Munir.

I am grateful for the financial support provided by Innovate UK and Balfour Beatty Construction Services (CSUK). I would like to thank Jonathan Law (Technical Manager at CSUK) and Peter Trebilcock (Director of BIM at CSUK) for facilitating part of the data collection process.

I acknowledge the supports from other staff members at the University of the West of England, Bristol. I am indeed grateful to Dr Svetlana Cicmil, Dr. Ximing Ruan, Dr Vikas Kumar, Dr. Charles Booth, Prof. Lamine Mahdjoubi, Dr Ismail Adelopo, Dr Akin Ojolo, Dr Bolanle Karimu, Dr Anu Ajayi, Dr Lukman Akanbi, and Dr Juan Manuel Davila Delgado. I must express my sincere gratitude to FBL Graduate School, particularly Dr Helen Frisby, Samantha Watts, and Dr Paul Spencer who diligently provided the required support and for stimulating a vibrant research environment.

Many thanks to Pastor and Deaconess Olujimmy Apata for their spiritual support. A big thank you to my friends and colleagues, Saheed Ajayi, Muhammad Bilal, Hafiz Alaka Hakeem Owolabi, and Udonna Okeke.

I am deeply and forever indebted to my family: my parents (Mr. Emmanuel Akinade and Mrs. Margaret Akinade), my parents-in-law (Prof. Gabriel Arawomo and Mrs. Francesca Arawomo), my brothers and brothers-in-law (Akintunde, Akindeji, Olatunji, Omosola, Omotola, Olabade and Adeyinka) and my sisters and sisters-in-law (Foluso, Omowumi, Olayemi, Tolulope, Omobola - Pepper, Oreoluwa, Adenike, and Ese). Words are not enough to describe my gratitude for your constant support.

I am eternally grateful to my wife and heartbeat, Omolola for her sincere love, prayers, and encouragement. To my little princess, Jemima for the smile that brightens me up after a long day.

God bless you all.

## LIST OF PUBLICATIONS

- 1) **Olugbenga O. Akinade**, Lukumon O. Oyedele, Kamil Omoteso, Saheed O. Ajayi, Muhammad Bilal, Hakeem A. Owolabi, Hafiz A. Alaka, Lara Ayriss, John Henry Looney, BIM-based deconstruction tool: Towards essential functionalities, *International Journal of Sustainable Built Environment*, Available online 29 January 2017
- 2) **Akinade, O.O.**, Oyedele, L.O., Ajayi, S.O., Bilal, M., Alaka, H.A., Owolabi, H.A., Bello, S.A., Jaiyeoba, B.E. and Kadiri, K.O., 2016. Design for Deconstruction (DfD): Critical success factors for diverting end-of-life waste from landfills. *Waste Management*.
- 3) **Akinade, O.O.**, Oyedele, L.O., Munir, K., Bilal, M., Ajayi, S.O., Owolabi, H.A., Alaka, H.A. and Bello, S.A., 2016. Evaluation criteria for construction waste management tools: towards a holistic BIM framework. *International Journal of Sustainable Building Technology and Urban Development*, pp. 1-19.
- 4) **Akinade, O.O.**, Oyedele, L.O., Bilal, M., Ajayi, S.O., Owolabi, H.A., Alaka, H.A. and Bello, S.A., 2015. Waste minimisation through deconstruction: A BIM based Deconstructability Assessment Score (BIM-DAS). *Resources, Conservation and Recycling*, 105, pp. 167-176.
- 5) Bilal, M., Oyedele, L.O., Munir, K., Ajayi, S.O., **Akinade, O.O.**, Owolabi, H.A. and Alaka, H.A., 2017. The application of web of data technologies in building materials information modelling for construction waste analytics. *Sustainable Materials and Technologies*.
- 6) Bilal, M., Oyedele, L.O., Qadir, J., Munir, K., Ajayi, S.O., **Akinade, O.O.**, Owolabi, H.A., Alaka, H.A. and Pasha, M., 2016. Big Data in the construction industry: A review of present status, opportunities, and future trends. *Advanced Engineering Informatics*, 30(3), pp. 500-521.
- 7) Bilal, M., Oyedele, L.O., **Akinade, O.O.**, Ajayi, S.O., Alaka, H.A., Owolabi, H.A., Qadir, J., Pasha, M. and Bello, S.A., 2016. Big data architecture for construction waste analytics (CWA): A conceptual framework. *Journal of Building Engineering*, 6, pp. 144-156.
- 8) Bilal, M., Oyedele, L.O., Qadir, J., Munir, K., **Akinade, O.O.**, Ajayi, S.O., Alaka, H.A. and Owolabi, H.A., 2015. Analysis of critical features and evaluation of BIM software: towards a plug-in for construction waste minimization using big data. *International*

*Journal of Sustainable Building Technology and Urban Development*, 6(4), pp. 211-228.

- 9) Ajayi, S.O., Oyedele, L.O., **Akinade, O.O.**, Bilal, M., Alaka, H.A. and Owolabi, H.A., 2017. Optimising material procurement for construction waste minimization: An exploration of success factors. *Sustainable Materials and Technologies*.
- 10) Ajayi, S.O., Oyedele, L.O., Bilal, M., Akinade, O.O., Alaka, H.A. and Owolabi, H.A., 2017. Critical management practices influencing on-site waste minimization in construction projects. *Waste management*, 59, pp.330-339.
- 11) Ajayi, S.O., Oyedele, L.O., Akinade, O.O., Bilal, M., Alaka, H.A., Owolabi, H.A. and Kadiri, K.O., 2017. Attributes of design for construction waste minimization: A case study of waste-to-energy project. *Renewable and Sustainable Energy Reviews*, 73, pp.1333-1341.
- 12) Ajayi, S.O., Oyedele, L.O., **Akinade, O.O.**, Bilal, M., Owolabi, H.A., Alaka, H.A. and Kadiri, K.O., 2016. Reducing waste to landfill: A need for cultural change in the UK construction industry. *Journal of Building Engineering*, 5, pp. 185-193.
- 13) Ajayi, S.O., Oyedele, L.O., Kadiri, K.O., **Akinade, O.O.**, Bilal, M., Owolabi, H.A. and Alaka, H.A., 2016. Competency-based measures for designing out construction waste: task and contextual attributes. *Engineering, Construction and Architectural Management*, 23(4).
- 14) Ajayi, S.O., Oyedele, L.O., Bilal, M., **Akinade, O.O.**, Alaka, H.A., Owolabi, H.A. and Kadiri, K.O., 2015. Waste effectiveness of the construction industry: Understanding the impediments and requisites for improvements. *Resources, Conservation and Recycling*, 102, pp.101-112.



## TABLE OF CONTENTS

DECLARATION .....	ii
ABSTRACT .....	iii
DEDICATION .....	iv
ACKNOWLEDGEMENT .....	v
LIST OF PUBLICATIONS .....	vii
LIST OF FIGURES .....	xv
LIST OF TABLES .....	xviii
LIST OF ACRONYMS .....	xx
1 INTRODUCTION .....	1
1.1 Background of study .....	1
1.2 BIM for Construction Waste Management .....	2
1.3 Hybrid Models for Construction Waste Analytics .....	4
1.4 Problem statement .....	5
1.5 Gap in Knowledge and Research Justification .....	6
1.6 Research Questions .....	7
1.7 Aim and Objectives .....	7
1.8 Research methodology .....	8
1.8.1 Methodology for Objective 1 .....	8
1.8.2 Methodology for Objective 2 .....	10
1.8.3 Methodology for Objective 3 .....	11
1.8.4 Methodology for Objective 4 .....	12
1.9 Unit of Analysis .....	12
1.10 Thesis contribution .....	13
1.11 Scope of Research .....	14
1.12 Layout of thesis .....	15
2 CONSTRUCTION WASTE MANAGEMENT STRATEGIES AND TOOLS .....	18
2.1 Overview .....	18
2.2 Definition and Sources of Construction Waste .....	18
2.3 Design for Construction Waste Prediction .....	20
2.4 Design for Construction Waste Minimisation .....	21
2.4.1 Design for Material Optimisation .....	22
2.4.2 Design for Waste Efficient Procurement .....	23

2.4.3	Design for Material Recovery and Reuse .....	24
2.4.4	Design for Offsite Construction.....	26
2.4.5	Design for Deconstruction and Flexibility.....	26
2.5	Construction Waste Management Tools .....	27
2.5.1	Waste Management Plan Templates and Guides.....	28
2.5.2	Waste Data Collection and Audit Tools .....	30
2.5.3	Waste Prediction Tools.....	30
2.5.4	Waste Quantification Models .....	31
2.5.5	GIS Tools.....	31
2.6	Limitations of existing construction waste management tools .....	32
2.6.1	Existing CW management Tools are Completely Detached from the Design Process	34
2.6.2	Existing CW Management Tools Lack Interoperability Capabilities.....	35
2.6.3	Construction Waste Data are not Sufficient.....	36
2.6.4	Waste management responsibilities are not clear .....	37
2.6.5	Lifecycle Analysis (LCA) of CW Performance is not available .....	37
2.7	Summary .....	38
3	BUILDING INFORMATION MODELLING (BIM) AND ARTIFICIAL INTELLIGENCE (AI) SYSTEMS.....	40
3.1	Overview .....	40
3.2	Building Information Modelling: Concepts and Benefits.....	41
3.3	BIM in the Changing UK Construction Industry .....	43
3.3.1	UK BIM Level 2 Programme .....	44
3.4	Building Information Modelling Platforms.....	47
3.5	BIM for Designing out Construction Waste .....	48
3.5.1	Team Communication and Integration .....	50
3.5.2	Parametric Modelling and Visualisation.....	50
3.5.3	Building Performance Analysis and Simulation.....	51
3.5.4	Automatic Documentation Generation .....	52
3.5.5	Improved Building Lifecycle Management.....	53
3.5.6	Interoperability with Other Applications.....	53
3.6	BIM Development Tools.....	54
3.6.1	IFC Development Tools.....	55

3.6.2	BIM Application Programming Interfaces .....	56
3.7	Artificial Intelligence System Development .....	58
3.7.1	Review of Relevant Theories in Artificial Intelligence and Associated Areas .....	59
3.7.2	Implications of the Theories for the Study .....	65
3.7.3	Types of Artificial Intelligence Systems.....	66
3.8	Summary .....	77
4	RESEARCH METHODOLOGY.....	79
4.1	Overview .....	79
4.2	Research Paradigms .....	81
4.2.1	Ontological and Epistemological Requirements of the Study .....	81
4.2.2	Available Research Paradigms .....	82
4.2.3	Adopted Research Paradigm for the Study .....	87
4.3	Research Strategy and Methods .....	89
4.3.1	Qualitative Research .....	90
4.3.2	Quantitative Research .....	91
4.3.3	Mixed Methods Research .....	92
4.4	Exploratory Sequential Mixed Methods Design .....	93
4.5	Ethical Considerations.....	96
4.6	Software Development Methodologies.....	96
4.6.1	Waterfall Model .....	97
4.6.2	Incremental Development.....	97
4.6.3	Spiral Development .....	98
4.6.4	Agile Programming.....	98
4.6.5	Rapid Application Development.....	99
4.7	Summary .....	100
5	HOLISTIC BIM FRAMEWORK FOR CONSTRUCTION WASTE MANAGEMENT	
	102	
5.1	Overview .....	102
5.2	Sampling Techniques .....	102
5.3	Qualitative Data Collection.....	104
5.4	Qualitative Data Analysis.....	105
5.5	Evaluative Criteria for Construction Waste Tools .....	108
5.6	Quantitative data collection.....	108

5.6.1	Questionnaire Design.....	108
5.7	Quantitative Data Analyses.....	112
5.7.1	Reliability analysis and Descriptive Statistics.....	113
5.7.2	Exploratory Factor Analysis.....	115
5.8	Data Validity and Reliability.....	116
5.9	BIM Framework for Construction Waste Management.....	117
5.10	Summary.....	119
6	AI HYBRID MODEL DEVELOPMENT FOR CONSTRUCTION WASTE PREDICTION.....	122
6.1	Overview.....	122
6.2	Model Development Process and Experimental Setup.....	122
6.3	Construction Waste Data Collection and Exploration.....	123
6.4	Data Preparation for ANFIS Model Development.....	134
6.5	Adaptive Neuro-Fuzzy Inference System (ANFIS).....	135
6.6	ANFIS Model Development and Training.....	139
6.6.1	Input selection for ANFIS Models.....	139
6.6.2	ANFIS Structure and Training.....	142
6.6.3	ANFIS Model Evaluation.....	146
6.6.4	Computing Waste by Material Types and Management Routes.....	149
6.7	Mathematical Model for Dimensional Coordination.....	151
6.7.1	Computing Required Bricks.....	152
6.8	Summary.....	159
7	BIM-BASED SYSTEM FOR CONSTRUCTION WASTE PREDICTION AND MINIMISATION (BIMWASTE).....	160
7.1	Overview.....	160
7.2	Software Development Environment.....	160
7.2.1	C# Programming Environment.....	160
7.2.2	Revit 2017 Application Programming Interface (API).....	162
7.2.3	User Interface (UI) and Presentation Frameworks.....	166
7.3	System Design for BIMWASTE.....	167
7.4	BIM-based software for Construction Waste Prediction.....	167
7.4.1	User Interface Module.....	168
7.4.2	Custom Parameters Module.....	174

7.4.3	Material Database for BIMWaste .....	178
7.4.4	Material Take-Off Calculation Module .....	179
7.4.5	Report Generation Module .....	180
7.5	BIM-Based Design Advisor for Material Optimisation.....	185
7.6	System Testing for BIMWaste.....	192
7.6.1	Results for Test Case 1 .....	195
7.6.2	Results for Test Case 2 .....	197
7.7	Summary .....	198
8	DISCUSSION OF RESULTS .....	200
8.1	Overview .....	200
8.2	Evaluative Criteria for Construction Waste Tools .....	200
8.2.1	Waste Prediction Criteria.....	200
8.2.2	Waste Data Criteria.....	202
8.2.3	BIM Criteria.....	203
8.2.4	Commercial and Procurement Criteria .....	204
8.2.5	Design Criteria.....	206
8.2.6	Technological Criteria .....	207
8.3	BIM Strategies for Design-based Construction Waste Management.....	208
8.3.1	BIM-based Collaboration for Waste Management.....	208
8.3.2	Waste-Driven Design Process and Solutions.....	210
8.3.3	Lifecycle Waste Analytics .....	212
8.3.4	Innovative Technologies for Waste Intelligence and Analytics .....	213
8.3.5	Improved Documentation for Waste Management.....	215
8.4	Holistic BIM Framework for Construction Waste Management.....	216
8.4.1	Infrastructure Layer .....	216
8.4.2	Data Layer.....	217
8.4.3	Presentation Layer .....	218
8.4.4	BIM Business Domain Layer.....	218
8.4.5	Service Domain Layer .....	219
8.4.6	Application Layer .....	220
8.5	BIM-Based Construction Waste Prediction using Hybrid Models .....	220
8.6	Summary .....	223
9	CONCLUSION, RECOMMENDATIONS, AND FUTURE WORKS .....	225

9.1	Overview .....	225
9.2	Summary of the Study .....	225
9.3	Main Findings of the Study .....	227
9.3.1	Strategies for BIM-Based Construction Waste Management .....	228
9.3.2	Development of AI Hybrid Models for CW Prediction .....	231
9.3.3	Development and Testing of BIM-Based Tool for CW Management .....	232
9.4	Implications of the Study .....	233
9.4.1	Implications for practice .....	233
9.4.2	Theoretical Implications .....	236
9.5	Limitations of the Study .....	237
9.6	Areas of Future Research .....	238
REFERENCES .....		240
APPENDIX A: FOCUS GROUP INTERVIEW SCHEDULE .....		277
APPENDIX B: SURVEY COVER LETTER AND QUESTIONNAIRE SAMPLE .....		279

## LIST OF FIGURES

Figure 1.1: Layout of Thesis .....	16
Figure 2.1: Strategies for Construction Material Recovery .....	25
Figure 2.2: Current Waste Management Tools .....	29
Figure 3.1: Concepts of Building Information Modelling .....	42
Figure 3.2: BIM Collaborative Platform .....	43
Figure 3.3: Reform Movements and Important Milestones within the UK Construction Industry .....	45
Figure 3.4: BIM Maturity Model by Bew and Richards (2008) .....	46
Figure 3.5: BIM Functionalities Framework for Construction Waste Management .....	51
Figure 3.6: Theoretical Underpinning of Study .....	60
Figure 3.7: Balance Theory for Recycling of Construction and Demolition Wastes .....	63
Figure 3.8: Architecture of a Knowledge Based System .....	71
Figure 3.9: Processes in Knowledge Based System Development .....	72
Figure 4.1: Paradigms Framework Proposed by Burrell and Morgan (1979) .....	83
Figure 4.2: An Overview of the Sequential Exploratory Mixed Method Design Process .....	93
Figure 5.1: Methodological flowchart .....	103
Figure 5.2: A Framework of Criteria for Evaluating the Performances of Waste Management Tools .....	109
Figure 5.3: Framework for a BIM-Based Construction Waste Management System .....	120
Figure 6.1: Process of Model Development .....	123
Figure 6.2: Distribution of Waste Data Record by Waste Type .....	127
Figure 6.3: Distribution of Total Waste Output by Construction Type .....	128
Figure 6.4: Waste Management Routes of Waste Types .....	131
Figure 6.5: Waste Management Routes of Construction Type .....	132
Figure 6.6: Distribution of GFA according to Construction Type .....	132
Figure 6.7 Distribution of Cost according to Construction Type .....	133
Figure 6.8: Distribution of Total Waste Output according to Construction Type .....	133
Figure 6.9: Block Diagram of Proposed ANFIS Model .....	134
Figure 6.10: ANFIS Model Development Flowchart .....	135
Figure 6.11: A Two Inputs and one Output ANFIS System .....	137
Figure 6.12: RMSE for two-input ANFIS Model for CW Prediction .....	142
Figure 6.13: Block Diagram of the Final ANFIS Model .....	143

Figure 6.14: Network Structure of ANFIS Model with Grid Partitioning.....	144
Figure 6.15: Fuzzy Rules for the ANFIS Model.....	146
Figure 6.16: Rule Viewer for the ANFIS Model.....	147
Figure 6.17: Gaussian Membership Function for Variable “Gross Floor Area” .....	148
Figure 6.18: Gaussian Membership Function for Variable “Gross Floor Area” .....	148
Figure 6.19: Comparison of Actual and Predicted Values .....	149
Figure 6.20: Standard Cavity Wall Fully Filled with Insulation .....	152
Figure 6.21: Stretcher Bond using 215x102.5x65 Brick .....	154
Figure 6.22: Graph of Wall Length against br+.....	156
Figure 7.1: Visual Studio Community Integrated Development Environment .....	161
Figure 7.2: Debugging Revit Plugin in Visual Studio .....	162
Figure 7.3: Enabling Managed Compatibility Mode in Visual Studio .....	162
Figure 7.4: The Two DLL References (RevitAPI.dll and RevitAPIUI.dll) Needed for Add-in Development.....	163
Figure 7.5: Autodesk Revit API Framework.....	163
Figure 7.6: Code Structure for External Command Class .....	164
Figure 7.7: Code Structure for External Application Class.....	165
Figure 7.8: Structure of a .addin manifest file for External Application.....	165
Figure 7.9: Process flow for BIMWaste .....	169
Figure 7.10: Class Implementation for BIMWaste Ribbon Panel.....	170
Figure 7.11: BIMWaste Ribbon Panel.....	170
Figure 7.12: Welcome Page for BIMWaste.....	171
Figure 7.13: BIMWaste About Dialog.....	171
Figure 7.14: BIMWaste Preferences Dialog.....	172
Figure 7.15: BIMWaste Application Settings Page.....	172
Figure 7.16: Create CWA Model Dialog.....	173
Figure 7.17: BIMWaste Reports Window .....	175
Figure 7.18: Sample Dashboard of a CWA Report .....	175
Figure 7.19: Sample Waste Distribution by Levels Stacked Chart .....	176
Figure 7.20: Sample Waste Distribution by Element and Material Types .....	176
Figure 7.21: Sample of Exported Bill of Quantity in Excel Format.....	177
Figure 7.22: Project Parameters for CWA.....	177
Figure 7.23: Create Project Parameters Function .....	178



Figure 7.24: Material Database Class .....	179
Figure 7.25: Functions for Collecting All Element and Materials.....	181
Figure 7.26: Functions for Getting all Level and Their Elevation.....	181
Figure 7.27: Function for Getting Elements According to Level .....	182
Figure 7.28: Function for Calculating Gross Floor Area.....	182
Figure 7.29: HTML Code for Report Head Tag.....	182
Figure 7.30: HTML Code for Element-Material Waste Distribution Panel .....	183
Figure 7.31: JavaScript Code for Stacked Bar Chart.....	183
Figure 7.32: Sample Element-Material Waste Distribution Stacked Chart.....	184
Figure 7.33: Menu Bar to Access Panels of the Reports .....	184
Figure 7.34: Design Advisor Button on BIMWaste Ribbon.....	185
Figure 7.35: Material Optimisation Design Advisor Dialog .....	187
Figure 7.36: Selecting Single and All Elements in Document Preview .....	188
Figure 7.37: Updating Element Details Table and Chart. The selected element is shown in the preview panel .....	189
Figure 7.38: Selecting all Elements of Type CL_W1 .....	190
Figure 7.39: Possible Replacement Elements for Basic Wall CL_W1.....	191
Figure 7.40: Save Chart as PNG image .....	192
Figure 7.41: CWA Dashboard for Test Case 1 .....	195
Figure 7.42:Waste Output by Element Type for Test Case 1 .....	196
Figure 7.43: Waste Distribution by Building Levels for Test Case 1.....	196
Figure 7.44: CWA Dashboard for Test Case 2.....	197
Figure 7.45: Waste Output by Element Type for Test Case 2.....	198
Figure 7.46: Waste Distribution by Building Levels for Test Case 2.....	199

## LIST OF TABLES

Table 1.1: Research Road Map, Methodologies, and Outputs .....	9
Table 2.1: Design-based Causes of Construction Waste .....	19
Table 2.2: Existing Tools for Construction Waste Management and their Limitation.....	33
Table 3.1: A Comparison of API of top BIM Software.....	49
Table 3.2: IFC Development Tools .....	57
Table 3.3: Comparison of Artificial Intelligence Techniques .....	67
Table 3.4: Artificial Intelligence Techniques in Construction Studies.....	68
Table 3.5: Comparison of Different AI Techniques .....	75
Table 3.6: Classification of Hybrid Systems .....	76
Table 4.1: Critical Choice of Methodology .....	80
Table 4.2: Comparison of Alternative Inquiry Paradigms.....	84
Table 4.3 Comparison of Qualitative and Quantitative Research.....	89
Table 5.1: Overview of the focus group discussions and the participants.....	105
Table 5.2: Descriptive interpretive analysis process.....	106
Table 5.3: Example of classification based on the coding scheme.....	107
Table 5.4: Evaluative Criteria for Existing Waste Management Tools (a).....	110
Table 5.5: Evaluative Criteria for Existing Waste Management Tools (b) .....	111
Table 5.6: Demographics of survey respondents.....	113
Table 5.7: Reliability analysis and ranking of critical factors for designing out waste.....	114
Table 5.8: Component labelling and corresponding criteria from exploratory factor analysis .....	116
Table 6.1: Cost Classification Range.....	124
Table 6.2: Gross Floor Classification Range .....	124
Table 6.3: Sample Construction Waste Data Record.....	125
Table 6.4: Total Waste Output by Waste Type.....	126
Table 6.5: Total Waste Output by Construction Type.....	127
Table 6.6: Total Waste Output by Project Usage .....	128
Table 6.7: GFA Classification of Waste Data Record.....	129
Table 6.8: Cost Classification of Waste Data Record.....	129
Table 6.9: Waste Data Distribution with respect to Construction Type, Project Use Type and Waste Type .....	130
Table 6.10: Construction Waste Management Routes.....	131

Table 6.11: Input and Output Variables for ANFIS .....	139
Table 6.12: Sample of Waste Data .....	140
Table 6.13: Details of Hybrid Learning Algorithm .....	140
Table 6.14: Results of Input Selection for ANFIS Model .....	141
Table 6.15: Input Membership Functions for ANFIS.....	145
Table 6.16: Performance of ANFIS Using Different Membership Functions.....	147
Table 6.17: Construction Waste Output Distribution by Construction Types and Waste Types .....	150
Table 6.18: Distribution of Waste Management Route .....	151
Table 6.19: Composition of Standard Cavity Wall.....	152
Table 6.20: Metrics for Dimensional Coordination of Cavity Wall .....	153
Table 6.21: Bricks Requirement and Potential Waste (height, $l_h = 3000\text{mm}$ ).....	157
Table 7.1: Test Plan for BIMWaste .....	193
Table 7.2: Test Cases for BIMWaste.....	194
Table 7.3: Overview of Test Results.....	195

## LIST OF ACRONYMS

<b>3D</b>	Three Dimensional
<b>ACO</b>	Ant Colony Optimisation
<b>AEC</b>	Architectural, Engineering and Construction
<b>AI</b>	Artificial Intelligence
<b>ANFIS</b>	Adaptive Neuro-Fuzzy Inference System
<b>ANN</b>	Artificial Neural Network
<b>API</b>	Application Programming Interface
<b>BIM</b>	Building Information Modelling
<b>BQ</b>	Bill of Quantity
<b>BRE</b>	Building Research Establishment
<b>BREEAM</b>	Building Research Establishment Environmental Assessment Method
<b>BWAS</b>	Building Waste Assessment Score
<b>CAD</b>	Computer Aided Design
<b>CW</b>	Construction Waste
<b>CDW</b>	Construction and demolition waste
<b>CO<sub>2</sub></b>	Carbon dioxide
<b>COBie</b>	Construction Operations Building Information Exchange
<b>CW</b>	Construction Waste
<b>DEFRA</b>	Department for Environment, Food, and Rural Affairs
<b>DfD</b>	Design for Deconstruction
<b>DoW</b>	Design out Waste
<b>DoWT-B</b>	Designing Out Waste Tool for Buildings
<b>DRWE</b>	Demolition and Renovation Waste Estimator
<b>FGI</b>	Focus Group Interview
<b>FS</b>	Fuzzy System
<b>FST</b>	Fuzzy Set Theory
<b>gbXML</b>	Green Building Extensible Markup Language
<b>GFA</b>	Gross Floor Area
<b>GIS</b>	Geographic Information System
<b>GPS</b>	Global Positioning System
<b>ICE</b>	Institution of Civil Engineers
<b>ICT</b>	Information and Communication Technology
<b>IDE</b>	Integrated Development Environment

<b>IES</b>	Integrated Environmental Solutions
<b>IFC</b>	Industry Foundation Classes
<b>IPD</b>	Integrated Product Delivery
<b>KBS</b>	Knowledge Based System
<b>n-D</b>	N-Dimensional
<b>NBS</b>	National Building Specification
<b>NRM 2</b>	New Rules of Measurement for detailed measurement of building works
<b>NWT</b>	Net Waste Tool
<b>RAD</b>	Rapid Application Development
<b>RIBA</b>	Royal Institute of British Architects
<b>RMSE</b>	Root Mean Square Error
<b>SDK</b>	Software Development Kit
<b>SMARTWaste</b>	Site Methodology to Audit, Reduce and Target Waste
<b>SMM</b>	Standard Method of Measurement for building works
<b>SPSS</b>	Statistical Package for the Social Sciences
<b>SWMP</b>	Site Waste Management Plan
<b>UI</b>	User Interface
<b>UK</b>	United Kingdom
<b>UML</b>	Unified Modelling Language
<b>USA</b>	United States of America
<b>USEPA</b>	United States Environmental Protection Agency
<b>WDR</b>	Waste Data Records
<b>WPM</b>	Waste Prediction Models
<b>WRAP</b>	Waste and Resources Action Programme

# 1 INTRODUCTION

## 1.1 Background of study

The rapid urbanisation across the globe has led to the inevitably large volume of Construction Waste (CW). From 2004 to 2012, CW contributed the largest percentage (about 30%) of the total waste sent to landfill in the UK (DEFRA, 2011, 2012). According to Osmani (2012b), this percentage of waste requires a payment close to £200 million as annual landfill tax. Apart from the high landfill cost, the disposal of waste has resulted into severe ecological damage (Lu *et al.*, 2011; Nagapan *et al.*, 2012b; Oyedele *et al.*, 2013), shortage of land (Gavilan and Bernold, 1994), and increased transportation and project costs (Yuan, 2012). The constant increase in landfill charges instituted by most countries to discourage waste disposal to landfills has not reduced the amount of CW sent to landfills (Matsueda and Nagase, 2012). Still, the volume of waste sent to landfill sites is a major concern owing to the cost of waste disposal and its adverse environmental impacts. To avoid the undesirable impacts of waste disposal, there is need for an overall change in strategy towards preservation of the finite natural resources, reduction in demand for landfill, and reduction in the total project cost (Oyedele *et al.* 2013). According to Ajayi *et al.* (2016), a number of construction waste management strategies have been encouraged to ensure a tighter loop of material and building components.

With so many building construction taking place annually, the environmental and economic impacts of CW cannot be ignored. Tackling the challenges of CW requires a strategic approach to planning for CW reduction and recovery of building materials for reuse or recycling. This requires dealing with the problem at source, which is usually at the design stage by designing out waste. Despite the consensus in the literature that CW could be reduced through design (Faniran and Caban, 1998; Mcdonald and Smithers, 1998; Poon, Yu and Jaillon, 2004; Liu *et al.*, 2011; Osmani, 2012b, 2013), waste minimisation is still not given priority during the design process (Poon, Yu and Jaillon, 2004; Osmani, Glass and Price, 2008).

The opportunities in designing out waste have motivated various stakeholders to develop initiatives such as “designing out waste” by Waste and Resources Action Programme (WRAP) and SMARTWaste by Building Research Establishment (BRE) (BRE, 2008b; Langdon, 2011). The UK government also commissioned waste minimisation and sustainability initiatives, which include “halving waste to landfill by 2012 relative to 2008” (Oyedele *et al.*, 2013), “Zero waste to landfill by 2020” (Phillips *et al.*, 2011), and Site Waste Management Plan (SWMP) Regulation (WRAP, 2008). Likewise, the United States Environmental Protection Agency (USEPA) has also set targets to characterise and understand CW material stream as well as promoting research on best practices for CW reduction and recovery (USEPA, 2003). All of these suggest an operational shift from on-site CW management to design based CW management (Osmani, 2013). However, a review of existing CW management tools reveals key underlying problems to design-based CW management. This is because the tools either are too late at the design stage or are not embedded within the design process (Akinade *et al.*, 2016). This makes the tools difficult to be used by architects and design engineers. To overcome these problems, evidence shows that techniques in Building Information Modelling (BIM) could be adopted by design teams for the purpose of waste minimisation (Liu *et al.*, 2011). The BIM-based approach allows CW process to be tightly integrated into the design process and into existing software used by architects and design engineers.

This study therefore assists in accomplishing set targets for the adoption of BIM and the implementation of favourable design strategies for CW minimisation. Thus, the study contributes significant economic, social, and environmental gains by reducing demand for landfills, reducing  $CO_2$  emission, conserving embodied energy, preserving natural environment, and reducing project cost.

## **1.2 BIM for Construction Waste Management**

The recent wide adoption of BIM has revolutionised the approach to timely project delivery across the world (Eastman *et al.*, 2011). The benefits accruable from BIM have stimulated several nations to set a deadline for its adoption. For example, the UK government has stipulated that from April 2016, all procurement in public sector work must adopt BIM approach. This deadline has forced most companies in the UK to integrate BIM into their

activities to sustain their competitive advantage. A recent survey of about 1,000 UK construction professionals by National BIM Survey (RIBA, 2016) reveals an uptake in the adoption of BIM from 48% in 2015 to 54% in 2016. The survey also reveals that 95% of people expect to adopt BIM on their project within three years. This means that the UK now ranks alongside USA, Finland, Singapore, New Zealand, Hong Kong. with regards to BIM adoption. The increasing adoption of BIM in the construction industry (Azhar, 2011) has improved system interoperability (Steel, Drogemuller and Toth, 2012), information sharing, visualisation of n-D models and decision making processes (Eastman *et al.*, 2011). BIM also provides a platform for seamless collaboration among stakeholders from different disciplines (Grilo and Jardim-Goncalves, 2010). Accordingly, BIM knowledge taps into various fields, which include project management, construction, engineering, information technology, policy and regulation. Accordingly, the expectations of BIM cut across these fields (Singh, Gu and Wang, 2011). Considering the numerous benefits of BIM, there is a need to systematically structure such diverse knowledge in an efficient way to enhance the understanding and efficient development of BIM for CW management. However, none of the existing BIM software offers CW management functionality.

The foregoing reveals the need for a system to organise the different modules and components of BIM-enabled CW management tool into an integrated system. Chief among the functionalities of such BIM-enabled CW management are: (i) CW prediction at the design stage and (ii) CW minimisation through designing out waste. This means that an efficient CW management strategy must incorporate a means of predicting the waste potentials of building right from the design stage. In addition, the tool must provide a mechanism that could be used to reduce the waste potentials of building at the design stage. This is based on dealing with the problem of CW at source before waste is generated rather than “end-of-pipe” treatment when waste has been generated. These tasks therefore necessitate the need to understand the complexity of intertwined processes of building design practice, CW management techniques, sources of CW, and Design-out-Waste (DoW) process. As such, this study takes a holistic approach to assess perspectives on BIM-based building design principles and how interplay among them could ensure successful CW prediction and minimisation.



### 1.3 Hybrid Models for Construction Waste Analytics

Advancement in Information and Communication Technologies (ICT) and BIM technologies reveals that any promising innovation within the Architectural, Engineering, and Construction (AEC) industry requires BIM compliance (Liu *et al.*, 2011) and that computer support is indispensable in construction related tasks to achieve the required flexibility, reliability, and efficiency (Eastman *et al.*, 2009). It is based on the foregoing that this study explores an intersection of research frontier in Artificial Intelligence (AI), BIM, sustainability and building construction studies to understand how CW management could be integrated into existing BIM platforms. This study therefore lays on this premise to formalise CW prediction and minimisation strategies into a hybrid AI computational system. This is with the aim of integrating the computational system with existing BIM framework to support architects during the early design stages.

Hybrid systems is a promising research field that integrate multiple AI techniques to find synergetic solution to specific problems. As such, hybrid systems overcome specific limitations of individual techniques and they combine their strengths (Son, Kim and Kim, 2012; Kim, 2013). For example, Fuzzy Inference System (FIS) may be suited to domain knowledge representation and uncertainty handling but it lacks good learning ability (Munakata, Jani and Engineering, 1994). However, machine learning techniques such as NN that possess good learning capability are not uncertainty nor imprecision tolerant. Therefore, the hybridization of complementary AI techniques could produce powerful intelligent systems that could solve practical computing problems (Mohanty, Ravi and Patra, 2013).

The motivation to the development of hybrid systems is the awareness that combined approaches could be necessary to tackle complex AI problems. This means that hybridization of AI techniques focuses on the integration of AI techniques than the creation of new techniques (Abraham, 2005; Melin *et al.*, 2007; Heemels *et al.*, 2009). As such, well-understood techniques should be integrated to address weaknesses of complementary methods and leverage their strengths. According to Abraham (2003), the hybridization of AI techniques has resulted into outstanding results in different areas of study, which include decision support, image recognition, process control, and other areas.

To achieve CW prediction and minimisation capabilities for the proposed BIM system, AI hybrid models were adopted. The study uses Adaptive Neuro-Fuzzy Inference System (ANFIS) method that integrates the strengths of Artificial Neural Networks (ANN) and Fuzzy Systems (FS) into a single hybrid system (Jang, 1993). The proposed hybrid systems provide exceptional capability by synergising human-like reasoning of FS with connectionist learning based structure of ANN. Adequate CW record data were therefore collected for the purpose of model development, training and testing.

#### **1.4 Problem statement**

Evidence from literature suggests that an operational shift from on-site waste management to design based waste management is needed for effective CW management (Faniran and Caban, 1998; Mcdonald and Smithers, 1998; Poon, Yu and Jaillon, 2004; Liu *et al.*, 2011; Osmani, 2012b, 2013). This requires dealing with the problem at source, which is usually at the design stage by designing out CW before it occurs. Tackling this problem calls for a strategic approach to planning for CW reduction using appropriate design tools. However, a review of existing CW management tools reveals key underlying problems to design-based CW management. First, despite the general knowledge that taking the right decisions during design could minimise CW, none of the existing tools has been fully integrated into building design process. This makes the tools too late at the design stage and therefore makes their usage by architects and design engineers difficult. Second, none of the existing waste management tools is BIM compliant (Cheng and Ma, 2011). This is because the tools are external to BIM software used by designers, thereby limiting their usability. Third, despite the current effort to achieve full software interoperability in the AEC industry, existing CW management tools lack interoperability capabilities with other software. Overcoming these problems require tight integration of BIM-based approach to CW management into design process and software used by architects and design engineers.

Achieving this offers huge opportunities for an effective and economical waste quantification, waste minimisation, collaboration amongst stakeholders and supply-chain integration. This means that bringing together design, procurement, and commercial processes into BIM software provides a means of economical CW management. BIM capability for CW

management tools would favour automatic capture of design parameters for CW analytics. It would also help to mitigate errors from manual entry of parameters as done in existing CW management tools. Pointedly, integrating CW management with BIM increases the usability of CW management tools to make appropriate waste minimisation decisions within BIM software. Such system would leverage BIM modelling platforms and their material database to understand and visualise the effects of design decisions on CW generation. The integration also offers a powerful synergy for simulating performances of buildings with respect to CW. In addition, BIM would provide a powerful collaboration platform for all stakeholders towards an effective CW management, seamless information sharing, and software interoperability. This would enable all stakeholders to participate actively in CW decision-making.

## **1.5 Gap in Knowledge and Research Justification**

Despite the benefits accruable from the use of BIM and the steep rise its adoption, the use of BIM for CW management is often neglected (Akinade *et al.*, 2015). Although there are several studies that have stimulated the consciousness of BIM for CW management (Liu *et al.*, 2011; Won, Cheng and Lee, 2016), none of the studies has provided clear instructions on how BIM could be used for this purpose. Besides, this lack of provision for clear instructions raises serious concerns on how CW management could be incorporated into BIM. The set of studies only provides conceptual frameworks by identifying factors that must be considered during design (Liu *et al.*, 2011; Osmani, Glass and Price, 2008; Won, Cheng and Lee, 2016). Thus, the studies fail to provide a methodological mechanism needed to understand how to implement the design principles for CW management. Another challenge is that none of the studies provides an objective measure of performance for DoW principles. These limitations therefore reveal the need to take a holistic approach to investigating CW management principles empirically and to develop a framework for integrating the principles into BIM.

Design out Waste Tool for Buildings (DoWT-B) (WRAP, 2011a) seems to be the most practical of all the existing tools in the sense that it could forecast the impact of design changes on waste output. However, it does not engage all stakeholders, and it is external to BIM software, thereby limiting its usability. The only BIM enabled waste management tool is the Demolition and Renovation Waste Estimation (DRWE) tool (Cheng and Ma, 2013), which

leveraged on the BIM technology through the Autodesk Revit API. However, the system only estimates waste generation from demolition and renovation of existing buildings. This clearly shows that the development of a BIM-enabled tool for simulating the different aspects of waste reduction is timely. Considering the foregoing reveals that the use of BIM for CW management would be an effort channelled in the right direction. This is because literature reveals that design decisions have high impact on CW generation (Faniran and Caban, 1998; Osmani et al., 2008). Based on the identified gap in knowledge, this study seeks to identify key BIM functionalities that could provide effective decision-making mechanisms for CW prediction and minimisation at the design stages. At the end, this study develops a BIM-based CW management tool that is code named BIMWaste.

## **1.6 Research Questions**

Based on the research aim and objectives, this study would answer the following research questions:

- a) What are the underlying strategies for BIM-based CW prediction and minimisation at the design stage?
- b) What are the critical features of BIM for CW prediction and minimisation?
- c) How can the strategies for CW prediction and minimisation be formalised into a computational system?
- d) How can the computational system for CW prediction and minimisation be integrated into existing BIM platforms?

## **1.7 Aim and Objectives**

The overall aim of this study is to investigate how design-based CW management capabilities could be incorporated into existing BIM platforms. The study is targeted towards the development of a BIM-based tool for CW management, which could be used by architects and design engineers to quantify CW output of buildings at the design stage. To achieve the overall aim of the study, the following specific objectives were proposed:

- a) To investigate strategies for enabling BIM-based CW management at the design stage
- b) To formalise strategies for CW prediction and minimisation into computational systems using Artificial Intelligence (AI) hybrid models
- c) To integrate the computational systems for CW management into existing BIM platform
- d) To test the performance of the BIM-based CW management tool

## 1.8 Research methodology

This mixed methods study adopts several techniques to achieve the specific objectives. The techniques include systematic literature review, focus group discussions, questionnaire survey, thematic analysis of qualitative data, statistical analysis of quantitative data, hybrid AI techniques, Rapid Application Development (RAD) framework, and software testing techniques. Table 1.1 presents the tasks required to accomplish the research objectives and the corresponding expected outputs. The following subsections briefly describe the methodological approaches adopted for the each of the research objectives.

### 1.8.1 Methodology for Objective 1

---

*Objective: To investigate strategies for enabling BIM-based construction waste management at the design stage.*

---

To achieve this objective, strategies for enabling BIM-based CW management were identified using a mixed methods strategy. Second, a holistic BIM framework for CW management was then developed.

- a) Review of extant literature on concept of waste management, types and causes of construction waste, construction waste management techniques, and CW management tools was carried out.

Table 1.1: Research Road Map, Methodologies, and Outputs

<b>PROJECT AIM:</b> “To investigate how design-based CW management capabilities could be incorporated into existing BIM platforms.”			
<b>OBJECTIVES</b>	<b>TASKS</b>	<b>MTD</b>	<b>OUTPUTS</b>
1) <i>To investigate strategies for enabling CW prediction and minimisation at the design stage.</i>	1) Review of existing CW management tools and identify their limitations.	LR FGI	<ul style="list-style-type: none"> <li>▪ Evaluation criteria for existing CW tools</li> <li>▪ BIM features for CW management</li> <li>▪ Expectations of stakeholders on BIM for CW management.</li> <li>▪ Holistic BIM framework for CW management</li> </ul>
	2) Conduct FGI to identify BIM strategies for CW management.	TA QS	
	3) Conduct a detailed survey research to undertake a wider verification of factors identified during FGIs.	SA	
	4) Develop a holistic BIM framework for CW management.		
2) <i>To formalise strategies for CW prediction and minimisation into computational systems.</i>	5) Collect Waste Record Data. Carry out CW data preparation and set-up database.	GA ANFIS	<ul style="list-style-type: none"> <li>▪ CW database</li> <li>▪ AI Hybrid models for CW prediction and minimisation</li> </ul>
	6) Select features that best predict CW	MM	
	7) Develop Hybrid AI models for CW prediction		
3) <i>To integrate the computational systems for CW management into BIM platforms</i>	8) Setup software development environment	RAD	<ul style="list-style-type: none"> <li>▪ Full BIMWaste software</li> <li>▪ Autodesk Revit Plugin for BIMWaste</li> </ul>
	9) Design and implement prototypes for BIMWaste	C#	
	10) Integrate BIMWaste into existing BIM software	Revit	
	11) Prepare operation guide for BIMWaste		
4) <i>To test the BIM-based CW management tool in terms of its CW prediction and minimisation capabilities.</i>	12) Develop BIM designs as test cases	FT	<ul style="list-style-type: none"> <li>▪ Fully tested BIMWaste software</li> <li>▪ Test results</li> </ul>
	13) Test BIMWaste in terms of their performance and acceptance	NFT AT	

**KEY:** MTD – Methods; LR - Literature Review; FGI – Focus Group Interview; QS – Questionnaire Survey; RAD – Rapid Application Development; TA – Thematic Analysis; SA – Statistical Analysis; ANFIS – Adaptive Neuro-Fuzzy Inference System; FT - Functional Testing; NFT - Non-Functional Testing; AT - Acceptance Testing; MM – Mathematical Modelling.

The limitations of existing CW management tools were also identified. A comprehensive review of the concept of BIM, BIM development tools, BIM features for designing out waste, and Artificial Intelligence Hybrid models was carried out.

- b) Focus Group Interviews (FGIs) were conducted with architects, design managers, M&E engineers, construction project managers, civil engineers, structural engineers, and BIM specialists. The FGI was conducted to establish a baseline for the expectations of UK construction stakeholders in terms of BIM for CW management. The transcripts of the FGIs were then subjected to thematic analysis to identify the themes across the discussions. The results were used to identify a list of evaluative criteria for CW tools and strategies for BIM-based CW management.
- c) The factors identified from the qualitative data analysis were developed into a questionnaire survey to verify the factors using a larger population sample. Respondents for the questionnaire survey were chosen from the UK construction industry. The questionnaire survey was adequately pilot-tested and administered. The completed questionnaires were then subjected to exploratory factor analysis to identify the underlying structure of the factors.
- d) Based on the foregoing, a holistic BIM framework for CW management was developed using an architecture-based layered approach. This approach allows related components to be grouped into layers and to ensure hierarchical categorisation of components.

## **1.8.2 Methodology for Objective 2**

---

*To formalise strategies for construction waste prediction and minimisation into computational systems.*

---

To achieve this objective, appropriate CW data was compiled from waste contractors. The data was cleaned and prepared into a database to aid analysis and model development. Accordingly, the following methods were employed:

- a) Historical Waste Data Records (WDR) was collected from reputable waste contractors and put in a database.
- b) The data was subjected to exploratory data analysis to understand the distribution and structure of the data.
- c) A hybrid model based on Adaptive Neuro-Fuzzy Inference System (ANFIS) was developed to predict CW from a set of features.
- d) A Dimensional Coordination Model (DCM) was then developed for CW minimisation using mathematical modelling.

### **1.8.3 Methodology for Objective 3**

---

*To integrate the computational systems for construction waste management  
with BIM platforms*

---

First, requirement gathering for the proposed BIM plugin was carried out. Autodesk Revit was chosen as the BIM platform for the plugin development because it is widely used and it provides a rich Application Programme Interface (API) and Software Development Toolkit (SDK). In addition, Revit provides a powerful BIM parametric modelling platform and a robust material database. The following methods were used to achieve the development and integration of the Revit plugin:

- a) The development of the full system is based on Rapid Application Development (RAD) framework. RAD employs a sequence of activities that encourages rapid response to users' needs.
- b) Software development environment was setup and configured. The environment is made up of C# programming Integrated Development Environment (IDE) using Visual Studio Community 2015, Revit 2017 Software Development Kit (SDK), and User Interface (UI) frameworks such as JQuery, Bootstrap, and ChartJS.



- c) System design was done using Unified Modelling Language (UML) in StarUML environment.
- d) The modules of the full BIM-based software for CW prediction and minimisation (BIMWaste) were developed in C# and integrated into Autodesk Revit as a Plugin.

#### **1.8.4 Methodology for Objective 4**

---

*To test the performance of the BIM-based CW management tool*

---

The full system was eventually tested for CW prediction accuracy, usability, and acceptability. Accordingly, the following activities were carried out to achieve the objective:

- a) A plan for functional and non-functional testing of BIMWaste was developed. The test plan contains a list of activities that was carried out during the test and the objectives.
- b) Test cases of BIM designs were then developed in Autodesk Revit.
- c) The full software was then tested based on the plan and test cases.

### **1.9 Unit of Analysis**

According to Trochim (2006), it is important to identify the unit of analysis for a study to ensure that results are correctly interpreted. Unit of analysis is the major entity that would be studied and analysed in a research. This entails the identification of “who” or “what” is analysed to draw conclusions. The unit of analysis of a study could be individuals, groups, organisations, partnership, communities, projects, artefacts, or geographical units. The choice among these options is dependent on the problem a study tries to address.

Drawing upon the focus of this study to investigate how design-based CW prediction and minimisation could be incorporated into BIM platforms, the most concrete unit of analysis is building designs. Building design of 117 projects were analysed using the developed computational tools to predict their material waste generation potential. Considering that this

study also seeks to understand stakeholders' expectations on the use of BIM for CW management, this study also includes individuals as less significant unit of analysis. However, the focus of identifying stakeholders' expectations is to develop a holistic BIM framework for CW management, which guides the development of the full BIM system for CW prediction and minimisation. Based on the foregoing, the results, conclusions, and recommendations from this study must be interpreted and used within the context of building designs.

### **1.10 Thesis contribution**

It is generally accepted in the literature that the best approach to CW management is minimisation through design (Faniran and Caban, 1998; Osmani, Glass and Price, 2008; Zhang, Wu and Shen, 2012). This is because design based philosophy offers flexible and cost-effective approach to CW management before it occurs. This places huge responsibilities on architects and design engineers to ensure that waste is given high priority in addition to project time and cost during design. Despite the willingness of architects and design engineers to carry out these duties, existing waste management tools cannot support them effectively. Besides, none of the existing CW management tools is BIM compatible despite the benefits of BIM in improving building process performances. Therefore, this study contributes to knowledge in two major ways: Academic knowledge and industrial practices.

This research made significant academic contribution to CW management at the design stages in several ways. The study identified the limitations of existing CW management tools. The two key limitations are: (i) the tools are completely detached from the design process, and (ii) existing tools lack interoperability capability. Accordingly, the study employed BIM to address the key limitations identified. This study therefore improves the understanding of how CW prediction and minimisation strategies could be captured and represented using AI artefacts. Particularly, the study contributed significantly to BIM studies by developing a system to streamline the estimation and minimisation of CW in BIM environment. The study also helps to understand expectations of industry stakeholders on the use of BIM for CW management.

In terms of industrial practices, the study creates awareness on the roles of design in CW minimisation and it broadens the understanding of how design-related factors influence CW generation. The software (code named BIMWaste) developed as part of this study is useful to architects and design engineers by providing them with insights into identifying sources of CW

during design. BIMWaste predicts the potential CW output of a building design and it provides suggestion on how CW could be minimised through dimensional coordination and material optimisation. BIMWaste also provides a basis for comparative analysis of building designs and for selecting the one with the least CW potential among options without affecting building forms or function. In addition, BIMWaste could provide a guideline or benchmark for monitoring building CW in the AEC industry.

### **1.11 Scope of Research**

This study explores a multi-disciplinary intersection of research frontier in AI, BIM, and construction sustainability, which are all individually vast areas of study. As such, it is important to define the scope of the study with respect to definition of waste, types of projects considered, building lifecycle stages, and implementation scope. Although, LEAN include non-material waste such as waste associated with transportation, time loss, under-utilisation, inadequate training, and waiting (Koskela, 2004), material waste has the highest environmental impact (Faniran and Caban, 1998; Osmani *et al.* 2008; Oyedele *et al.* 2013). As such, waste considered in this study is limited to building material waste and the definition of waste used in the study does not cover non-material waste. Material waste could be explored in three sustainability dimensions depending on the scope of assessment (BS EN 15643-1, 2010), which are economic, environmental, and social. However, this study only considers environmental dimension of sustainability.

Projects in the construction industry fall under three broad sectors, which are building, infrastructure, and industrial. Projects that are classified under building includes residential and non-residential, such as retail, commercial and institutional buildings. Infrastructure includes projects such as highway, bridges, dams, and utility distribution. Projects that are classified under industrial include refineries, manufacturing plants, process plants, and related projects. However, this study has only considered building construction projects and the software produced from this study should be used within this scope. In terms of the scope of the building lifecycle stage, this study focused on the prediction of CW at the design stages, which include Stage 2 (Concept Design) to Stage 4 (Technical Design). Software developed in this study is useful to architects and design engineers at these stages to predict and minimise CW.

## 1.12 Layout of thesis

This thesis consists of ten chapters as shown in Figure 1.1. The summaries of other chapters and their place in the research process are summarised as follows:

**Chapter 2** contains a review of extant literature on CW management. The chapter defines the concept of CW and it identifies key causes of waste. The chapter discusses CW prediction and the role of design in CW minimisation. The chapter also contains a discussion of existing strategies and tools for CW management. The chapter ends with the discussion of the limitations of existing CW management tools.

**Chapter 3** details the significance of BIM in the changing construction ecosystem and how BIM could be leveraged for CW management. The chapter discusses the current BIM implementation strategy and presents a review of existing BIM software. The state of the art in BIM development is also discussed to identify how BIM capacities could be employed for CW management. The chapter ends with the review of Artificial Intelligence techniques and the theoretical underpinnings of the thesis. The chapter reviews relevant theories and it discusses their place in the study. The theories are tragedy of the commons, graph theory, theories of evidential reasoning, and theory of building layers.

**Chapter 4** contains the methodological approach of the study. The chapter covers the research philosophy, strategies, and approaches that were adopted for this study. Details of the data collection and analyses techniques adopted for the study are presented. After the discussion of software development frameworks, the chapter ends with the presentation of the adopted framework for software development.

**Chapter 5** discusses the expectations of stakeholders on the use of BIM for CW management. Sequential exploratory mixed methods strategy was employed using focus group interviews and questionnaire survey. The exploratory factor analysis of the responses reveals five major groups of BIM expectations for CW management, which are important considerations for the deployment of BIM-based practices for CW management. The chapter ends with the development of a holistic BIM framework for CW management.



*Figure 1.1: Layout of Thesis*

**Chapter 6** presents the development of AI hybrid models for CW prediction and minimisation. An ANFIS model was developed for CW prediction and a mathematical model was developed for dimensional coordination. The chapter ends with the evaluation and testing of the models.

**Chapter 7** contains the integration of the developed models for CW prediction and minimisation into BIM software. As such, a BIM system for CW prediction and minimisation (BIMWaste) was developed. The chapter discusses the development environment needed for BIM development, system design for BIMWaste, and the development process for BIMWaste. At the end, BIMWaste was tested with some test cases to verify its operations and accuracy.

**Chapter 8** contains the discussion of the findings of the study. It presents a set of evaluative criteria for CW tools and it discusses the features of BIM that are relevant to CW management. After this, the chapter discusses a holistic BIM framework for CW management, which presents functional systems of a robust CW management tool. The chapter ends with the discussion of findings from CW data record exploratory analysis and software testing.

**Chapter 9** concludes the thesis with a summary of the study and its key results. The contribution of the study to both academic and industry practices are discussed in details. The chapter also highlights limitations of the study and areas of future research.

## **2 CONSTRUCTION WASTE MANAGEMENT STRATEGIES AND TOOLS**

### **2.1 Overview**

This chapter contains the discussion on the concept, definition, and causes of Construction Waste (CW). The chapter presents a thorough review of extant literature on CW management to understand existing research stream in design for CW prediction and minimisation. Five design principles for CW minimisation are discussed, which are design for material optimisation, design for waste efficient procurement, design for material recovery and reuse, design for off-site construction, and design for deconstruction and flexibility. Thereafter, existing CW management tools are reviewed to identify their limitations. A list of 32 tools was identified in five categories, which include waste data collection and audit, waste prediction, waste quantification models, waste management plan templates and guide, and location-enabled services. The limitations of these tools were identified after a thorough review. Key limitations of existing CW tools are: (i) existing CW tools are completely detached from the design process, (ii) existing CW management tools lack interoperability capabilities, (iii) CW data are not sufficient, (iv) CW management responsibilities are not clear, and (v) lifecycle analysis of CW performance is not available.

### **2.2 Definition and Sources of Construction Waste**

Construction material waste could be defined as by-product of the building construction process or building materials and components that could not fulfil the purpose for which they were procured (Osmani, 2011). CW covers a wide range of categories such as: (a) waste from the construction of buildings; (b) waste from demolition of buildings; (c) soil, rock and vegetation from clearing, earth moving, and excavation; and (d) waste from road planning and maintenance (Symonds and Associates, 1999). These categories of CW are basically composed of ten groups of materials as identified by the UK Environmental Agency (2014). The ten groups of construction material waste are: (i) insulation and asbestos materials; (ii) concrete, bricks, tiles and ceramics; (iii) wood, glass and plastic; (iv) bituminous mixtures, coal

tar and tar; (v) metallic waste including cable; (vi) soil, contaminated soil, stones and dredging soil; (vii) gypsum (viii) cement; (ix) paint and vanishes; and (x) adhesives and sealants.

Studies on sources of CW waste (Skoyles, 1976; Craven, Okraglik and Eilenberg, 1994; Gavilan and Bernold, 1994; Faniran and Caban, 1998; Ekanayake and Ofori, 2000; Serpell and Labra, 2003) classified the key contributors into six groups, which are design, materials procurement, materials handling, operations, residual related and others. However, there is consensus that the planning and design (pre-construction) stages are responsible for the largest percentage of CW. Some causes of design waste as identified in the literature are shown in Table 2.1.

*Table 2.1: Design-based Causes of Construction Waste*

No	Design Causes of Waste	Reference
1	Design changes during the construction stages	(Faniran and Caban, 1998; Osmani, Glass and Price, 2008; Poon, 2007; Yuan and Shen, 2011)
2	Lack of knowledge about standard size of available materials and dimensional coordination	(Treloar <i>et al.</i> , 2003; Ekanayake and Ofori, 2004)
3	Unfamiliarity with materials alternatives	(Ekanayake and Ofori, 2000)
4	Complex detailing or lack of detailing information in drawings	(Ekanayake and Ofori, 2000; Oyedele <i>et al.</i> , 2013)
5	Building Complexity	(Keys, Baldwin and Austin, 2000; Baldwin <i>et al.</i> , 2009)
6	Lack of Coordination and communication among teams	(Baldwin <i>et al.</i> , 2009)
7	Errors in contract documents and drawings	(Bossink and Brouwers, 1996)

In a comparative study of causes of design waste, Ekanayake & Ofori (2004) found out that design changes during construction, designers' inexperience and lack of dimensional coordination are the key causes of design waste. Osmani (2013) also identified the key design waste causes in relation to their sources and origin, with respect to RIBA plan of work stages (RIBA, 2009), during the building's lifecycle and found out that CW originates from all work stages particularly in the design stages. These findings have stimulated a number of studies to mitigate the generation of CW during design (Faniran and Caban, 1998; Keys, Baldwin and Austin, 2000; Poon, 2007; Khoramshahi, 2007; Chen, Li and Wong, 2002; Osmani, 2012b; Nagapan *et al.*, 2012b)



Despite the literature that abounds for causes and management of CW, few studies have been carried out to develop tools for design-based waste management. Besides, most of these few studies focus on CW management frameworks (Jun, Qiuzhen and Qingguo, 2011; Liu *et al.*, 2011; Osmani, 2012b), disposal cost estimation (Chen *et al.*, 2006; Yuan *et al.*, 2011; Cheng and Ma, 2011) and demolition waste quantification (Cochran *et al.*, 2007a; Wu *et al.*, 2014; Rosmani and Hassan, 2012). This therefore reveals a huge gap in knowledge because no design tool exists to assist architects and design engineers to estimate the CW output potential of a building design and to proffer ways of reducing the CW. Laying on a solid premise of the importance of reducing the amount of CW to landfills, this study therefore seeks to integrate favourable design strategies for construction waste prediction and management into BIM. This is to ensure that the tool is practicable for use at the design stages.

### **2.3 Design for Construction Waste Prediction**

In achieving effective CW management, robust Waste Prediction Models (WPMs) are needed to estimate the waste potentials of building models accurately before construction. This is because an increase in CW disposal costs will affect the project cost considerably. The review of extant literature reveals four broad categories of WPMs, which are: (i) waste generation rate based models (Poon, Yu and Jaillon, 2004; Masudi *et al.*, 2011; Li *et al.*, 2013); (ii) construction activities based models (Fatta *et al.*, 2003; Ekanayake and Ofori, 2004; Wang *et al.*, 2004); (iii) building elements and materials based models (Shen *et al.*, 2005; Jalali, 2007; Bergsdal, Bohne and Brattebø, 2007; Cochran *et al.*, 2007b; Solís-Guzmán *et al.*, 2009); and (iv) simulation based models (Wu, Fan and Liu, 2013; Salem *et al.*, 2008; Zaman and Lehmann, 2013). These models have set the foundation for CW quantification, however, their reliability is not guaranteed. This is because the peculiarity of building properties and activities affecting CW generation are quite diverse. As such, treating every building the same way could be misleading.

For example, similar building designs in different locations cannot be treated the same way despite their similar GFA and material specification because there are numerous factors such as soil type, construction type, and project use class, which could influence CW generation. This means that results of WPM may have been implicitly over-generalised to all buildings. This therefore reveals the need to examine the critical factors that have direct impacts on CW generation at a granular level. This is because there are wide varieties of unique factors, which

can be used to predict CW during design stages. The expectation of a robust WPM therefore taps into the perceived degree of accuracy from relationship among specific variables, which goes beyond waste generation rates, construction activities, building materials, and historical waste data. There are certain factors, such as soil type, construction methodology, design quality, and competency of site workers that are associated with waste output potentials of building models. This calls for a rethink of the development of a robust and holistic quantification model for an accurate estimation of CW at the design stage. This thus sets the stage for the full integration of WPMs into existing design tools.

## **2.4 Design for Construction Waste Minimisation**

Over the decades, building construction activities have generated the largest volume of waste across the globe (Faniran and Caban, 1998; USEPA, 2003; Osmani, 2013). This waste is attributed to the constant uptake of construction, demolition and renovation activities during which villages are built into towns, towns into cities and cities into mega cities (Jaillon and Poon, 2014a). In fact, this uptake of building activities results in about 30% of the total annual waste generation worldwide (Jun, Qiuzhen and Qingguo, 2011). This thus puts immense pressure on the depleting landfill sites and affects the environment adversely. To ensure the conservation of natural resources and to reduce the cost and impacts of waste disposal, effective waste management practices must be put in place. This will ensure that flow of construction materials in a closed loop to minimise waste generation, preserve natural resources and reduce demand for landfills. To achieve this, effective management strategies such as waste reduction, component reuse, and material recycling are needed to divert CW from landfills (Oyedele *et al.*, 2013).

Ekanayake & Ofori (2004) classified waste minimisation strategies into two groups: planning and control. Waste minimisation strategies based on planning is preferable because it focuses on preventive measures rather than remedial measures. It was suggested that quality design, efficient construction scheduling, and site layout are planning strategies that embrace waste minimisation. Amongst strategies identified, quality design stands as the most preferred strategy because the largest percentage of CW is caused by activities at pre-construction stages and that design decisions have high impact on CW generation (Faniran and Caban, 1998; Ekanayake and Ofori, 2004; Osmani, 2012a). Accordingly, effective decision-making mechanisms are needed during the design stages to minimise waste. In line with this, WRAP,

(2009) produced a design guideline to assist the design team with opportunities for designing out waste based on five principles, which are:

- i) Design for materials optimisation,
- ii) Design for waste efficient procurement,
- iii) Design for material recovery and reuse,
- iv) Design for off-site construction, and
- v) Design for deconstruction and flexibility.

#### **2.4.1 Design for Material Optimisation**

Material optimisation approach to CW minimisation focuses on lean design towards material resources efficiency without compromising the design functions and aesthetics. Lean design applies lean production principles to eliminate waste and to improve engineering processes. The lean design principle considers design process in five areas of improvement (Freire and Alarcón, 2002). The five areas are client, administration, project, resource, and information. However, in terms of CW, material optimisation is key to waste elimination. This is because evidence across extant literature reveals that the construction industry consumes about 50% of the natural resources and contributes a large proportion of waste (about 30%) to landfills. These percentages have raised concerns among stakeholders about the environmental sustainability of the construction industry because material depletion is inevitable if the current rate of natural resources extraction and waste generation continues. Likewise, this will affect the environment negatively by increasing the likelihood of greenhouse effect and CO<sub>2</sub> emission.

As such, design for material optimisation as a lean design process considers design process as a value generation activity (Freire and Alarcón, 2002). This approach is helpful to determine how resources are efficiently utilised and to ensure that the needs of the clients are met (Koskela, 2007). Huovila (1997) highlights that the value generation model therefore emphasises reduction in loss of value, optimal performance of design functions, and lack of defect. Based on this concept, areas of potential waste reduction for material optimisation include standardisation of available building elements, efficient material substitution, and dimensional coordination of the entire design. Achieving all these will minimise excessive cutting and it will help to reduce the number of variables for operational refinement. In

addition, dimensional coordination of design will potentially encourage reuse of offcuts and formworks.

Therefore, architects and design engineers must be equipped with the knowledge of material specifications and standards to understand the constituent of materials, their performance, design code of practice, and materials that favour the design intentions. In this regard, the materials' fitness for use and quality could be assessed by a list of parameters, which include function, composition, waste potential, strength, reliability, durability among others. Green Guide (Anderson and Shiers, 2009), which is a specification guide for the relative environmental performance of over 250 materials and components, could be employed to achieve effective building material substitution at the design stage. The Green guide was developed to provide material standardisation and to provide a wide range of alternatives for different material and components types. The foregoing reveals that it is important to tackle the challenge of material specification optimisation from three perspectives: (a) material fit for purpose, (b) material composition of components, and (c) material performance for assurance of quality control.

#### **2.4.2 Design for Waste Efficient Procurement**

Evidence shows that inefficiencies in the coordination of procurement activities could lead to CW (Greenwood, 2003; Dainty and Brooke, 2004; Wang, Kang and Tam, 2008; Khanh and Kim, 2014). Considering that cost of building materials could take up to 50% of the project cost, appropriate strategies must be employed to ensure that accurate materials are purchased and that materials are delivered efficiently (Faniran and Caban, 1998; Oyedele *et al.*, 2013). Waste efficient procurement could be achieved through just-in-time delivery (Dainty and Brooke, 2004; Al-Hajj and Hamani, 2011), efficient delivery schedule (Khanh and Kim, 2014), procurement of preassembled components (Formoso *et al.*, 2002), and provision for take back scheme for unused materials (Al-Hajj and Hamani, 2011; Nagapan *et al.*, 2012a).

According to Daniel and Koskela (2008), a mutual relationship exists between building design and material procurement. This means that design methodology could influence the procurement process (Burguet, Ganuza and Hauk, 2012). As such, design for waste efficient procurement is concerned with how building design process and methodologies could achieve low waste supply chains. According to Osmani *et al.* (2008), a key task in this regard is

freezing design process before starting procurement process. This is to avoid possible reworks and variation of orders. In additions, architects and design engineers needs to ensure the use of preassembled components (Formoso *et al.*, 2002), modular building design, use of standardised materials to reduce off-cuts (McKechnie and Brown, 2007), specification of materials with less packaging (Yuan, 2013). During material specification, accurate material take-off must be ensured to avoid excessive order. Appropriate communication must also be ensured between the project team and suppliers in terms of preferred methods of waste reduction.

### **2.4.3 Design for Material Recovery and Reuse**

To accomplish design for material recovery, it is desired to employ commonly observed design rules, which satisfies both offsite construction and deconstruction needs (Warszawski, 1999). These rules would help to maximise the flexibility of design and to minimise CW generation. According to Crowther (2005), material recovery could be for four main purposes, which are: (i) relocation of buildings, (ii) component reuse in other buildings, (iii) material reprocessing, and (iv) material recycling. This is in line with the viewpoint of Kibert (2003) who suggests that realisation of material recovery for multiple purposes will significantly reduce Construction and Demolition Waste (CDW) and helps to divert waste from landfills. Material recovery for building relocation involves the salvage of all the building materials and components without waste generation. This is only possible if all the building materials and components are separable and reusable (Crowther, 2005). Although it is impracticable to achieve 100% material recovery, McDonough and Braungart (2002) argued that recovery of building components for relocation and reuse remains the most preferred recovery purpose because they require the least energy and new resources (Oyedele, Ajayi and Kadiri, 2014). According to Jaillon and Poon (2014a), other purposes of material recovery require additional energy and materials to reprocess or recycle the materials. Although it is becoming common practice to recycle an entire building, a more significant challenge is designing a building whose materials could be recovered with minimal reprocessing.

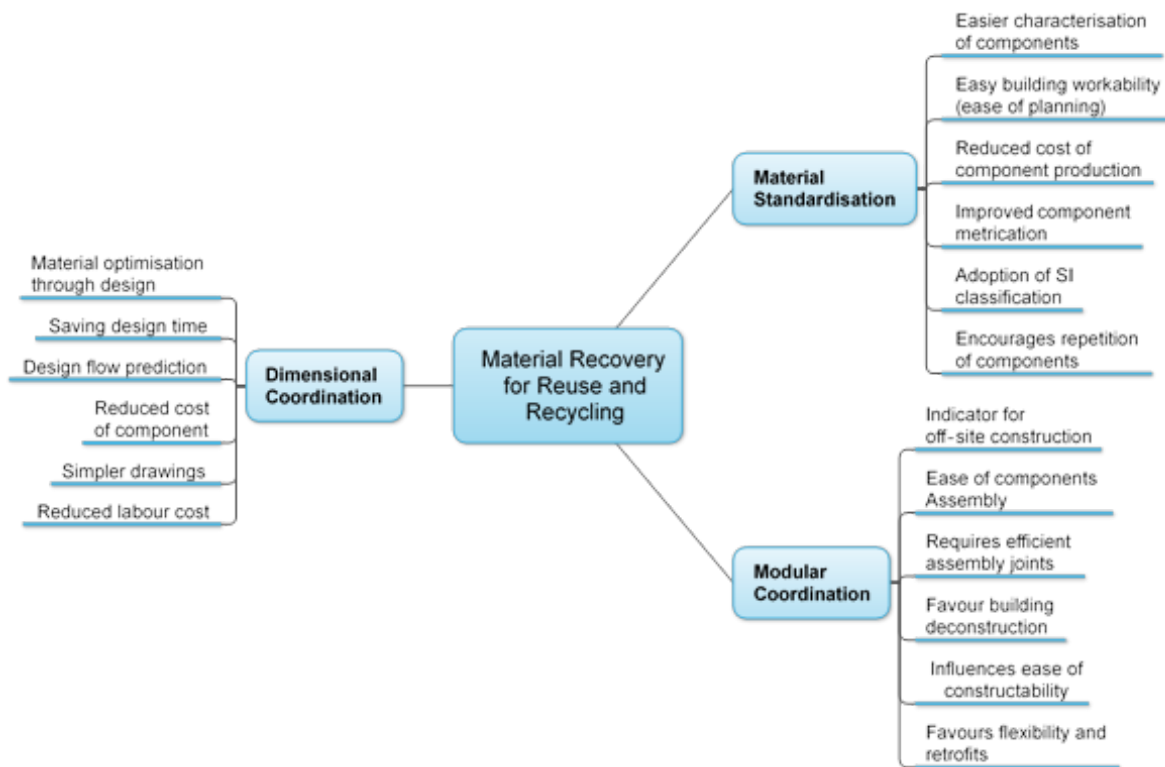


Figure 2.1: Strategies for Construction Material Recovery

Three design methods that favour construction material recovery are dimensional coordination, modular coordination, and standardisation of materials as shown in Figure 2.1. Dimensional coordination is a systematic system for planning spaces, component placement and fittings such that all the components fits together without the need to cut or extend (Triakha, 1999). The aim of dimensional coordination is to provide a platform for optimising material usage. Modular coordination encourages repetition of building components through an efficient metrication to reduce variability of dimensions of building components. In all, standardisation of materials stands out as the most important of these methods (Vernikos *et al.*, 2012). In particular, material standardisation encourages mass production of components during offsite construction and enables easier identification of components during deconstruction. The purpose of these design methods is to allow easy adaptation of prefabrication and interchangeability of building components (Warszawski, 1999).

#### **2.4.4 Design for Offsite Construction**

Offsite construction is a process where components are prefabricated and preassembled offsite within a controlled environment and transported to site (Jaillon and Poon, 2014b). The most common offsite construction practices include formworks, scaffolding, rebar works, concrete placements, welding, masonry works, façade, bathroom pods, stairs, roof structures, windows and doors. (Jaillon, Poon and Chiang, 2009; Baldwin *et al.*, 2009; Kozlovská and Spišáková, 2013). A key indicator for offsite construction is modular coordination (Addis, 2008; Tam *et al.*, 2007). Advantages of adopting offsite construction practices include improved environmental performance through waste reduction, reduced construction cost and shortened construction time, and early standardisation and freezing of design layout. Even, Tam *et al.* (2007) argues that offsite construction could reduce waste generation by 100% and cost of waste management by 84.7%.

Despite the well documented benefits of offsite construction, it has not been fully adopted by contractors (Tam *et al.*, 2007; Jaillon and Poon, 2014b; Begum, Satari and Pereira, 2010; Jaillon, Poon and Chiang, 2009). Major constraints to the adoption of offsite construction include lack of research information and expert advice at early design stage, transportation and vertical movement of components, time required for the initial design development, lack of offsite construction experience, limited space for holding offsite components, and lack of hoist equipment capacity. Besides, the decision to employ off-site construction is mostly based on familiarity and personal preferences but not on rigorous data analysis and research information (Pasquire and Gibb, 2002).

#### **2.4.5 Design for Deconstruction and Flexibility**

Deconstruction is “*the whole or partial disassembly of buildings to facilitate component reuse and material recycling*” (Kibert, 2008) to eliminate demolition through the recovery of reusable materials (Gorgolewski, 2006). This is with the aim of rapid relocation of building, reduced demolition waste, improved flexibility and retrofitting. (Addis, 2008). Despite a growing discrepancy of opinion on whether CDW could be completely eradicated (Yuan and Shen, 2011; Zaman and Lehmann, 2013), existing studies show that effective deconstruction could drive effective CDW eradication initiatives (Guy, Shell and Esherick, 2006; Tingley, 2012; Akbarnezhad, Ong and Chandra, 2014). Apart from helping to divert waste from landfills, deconstruction also enables other benefits, which include: (a) *environmental benefits*: by

reducing site disturbance (Lassandro, 2003), minimising harmful emission, reducing health hazard (Chini and Acquaye, 2001) and preserving embodied energy (Thormark, 2001) through material reuse; (b) *social and economic benefits*: by providing business opportunities through material recovery, reuse and recycling; and providing employment to support deconstruction infrastructure.

To enable a well-planned deconstruction, conscious efforts must be taken by architects and engineers right from the design stages (Kibert, 2008). As such, the eventual purpose of deconstruction must be identified to guarantee the success of Design for Deconstruction (DfD). This will enhance understanding of relevant design strategies and tools required for deconstruction. Several studies have discussed existing perspectives on DfD principles and how interplay among them could ensure successful building deconstruction. These studies provide a solid foundation for contemporary DfD process and are majorly driven by efficient building elements selection to facilitate easy disassembly (Addis, 2008). The highlight of building elements selection process include: (i) the specification of durable materials (Tingley, 2012); (ii) using materials with no secondary finishes (Guy and Ciarimboli, 2008); (iii) using bolt/nuts joints instead of gluing (Chini and Balachandran, 2002; Webster and Costello, 2005); (iv) avoiding toxic materials (Guy, Shell and Esherick, 2006); and (v) using prefabricated assemblies (Jaillon, Poon and Chiang, 2009).

In addition, Guy *et al.* (2006) noted that the types and numbers of building materials, components, and connectors must be minimised to simplify disassembly and sorting process. The use of recycled and reused materials is also encouraged (Hobbs and Hurley, 2001; Crowther, 2005) during design specification to broaden existing supply-demand chain for future deconstructed products. Evidence shows that reusing concrete components could reduce material cost by 56% (Charlson, 2008). These requirements place huge responsibilities on architects and engineers at ensuring that design has the least impact on the ecosystem throughout the building's lifecycle (Yeang, 1995).

## **2.5 Construction Waste Management Tools**

The increasing attention received by CW from the industry and academia and the recent advancement in Information and Communication Technologies (ICT) and Computer Aided Design (CAD) technologies have favoured the development of various tools to assist



practitioners in the implementation of waste management strategies. In fact, computer support is indispensable in construction related tasks to achieve the required flexibility, reliability, and efficiency (Eastman *et al.*, 2009). It is on this basis that this section reviews existing CW management tools to assess their functionalities and limitations.

After compiling the relevant papers from peer-reviewed journals, a filtering process was carried out to ensure that the papers match the research scope. This was accomplished by scanning the titles and abstracts and imposing certain exclusion criteria to remove papers outside the scope of this study. As such, publications on nuclear/radioactive waste, municipal solid waste and waste from electronic and electrical equipment were excluded. The scope of the literature review is to include publications that have a direct impact on construction waste management. After the filtering process, 22 tools were identified from the collected papers. Thereafter, a cross-examination of the identified papers was undertaken by manually scanning through the references cited. As a result, 10 additional tools were identified, thus bringing the total number of tools to 32. After a careful assessment of the primary functions of these tools identified from the literature review, five broad classifications of tools emerged, which are:

- i) Waste management plan templates and guides,
- ii) Waste data collection and audit tools,
- iii) Waste quantification models,
- iv) Waste prediction tools, and
- v) Geographic Information System (GIS)-enabled waste tools.

The five classifications along with their associated tools are illustrated in Figure 2.2 and their corresponding descriptions are given in the following sections.

### **2.5.1 Waste Management Plan Templates and Guides**

A typical Waste Management Plan (WMP) captures information such as quantities and specification of materials, procurement details, volume of waste generated, and costs (transportation, labour, and disposal) to determine the economic and environmental feasibility of waste management. As such, WMPs provide automated spreadsheet templates to facilitate the computation of variables of interest such as waste output and costs. Examples of WMPs include cost-effective waste management plans (Mills, Showalter and Jarman, 1999), Site

Waste Management Plans (SWMPs) (WRAP, 2008), and material logistic plans (WRAP, 2007b). A major drawback of the development process used for WMPs is the reliability of the data and the accuracy of the computations on which the economic and environmental comparisons of alternative strategies are based (Mills, Showalter and Jarman, 1999).

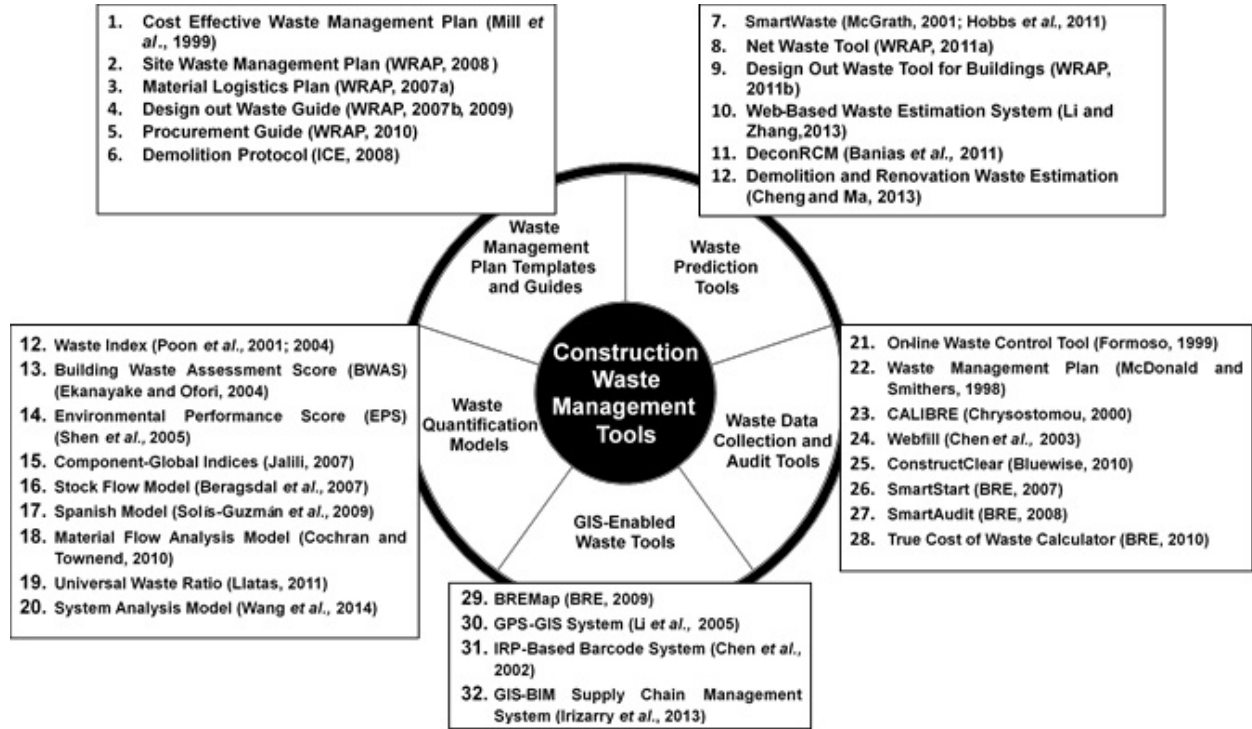


Figure 2.2: Current Waste Management Tools

On the other hand, Waste Management Guide (WMG) provides a list of steps to assist waste practitioners in identifying potential areas for waste minimization. Examples of WMGs include Designing out Waste guide (WRAP, 2007a, 2009), Procurement Guidance (WRAP, 2010), and Demolition Protocol (ICE, 2008). Despite the relevance of these guides, they fail to identify direct and indirect design waste origins, causes and sources, which could inform the implementation of waste reduction design principles (Osmani, 2013). The guides also lack the appropriate design parameters required for the coordination of processes and communication among stakeholders, making it difficult to incorporate design principles for waste minimization into software systems.

### **2.5.2 Waste Data Collection and Audit Tools**

A key challenge to the study of construction waste management is deficiency in waste data (Hobbs, Blackwell and Adams, 2011). Therefore, to tackle this challenge, a number of tools have been developed to provide means of logging the amount, type, and sources of waste generated in a building project. In turn, the data could be used to mitigate future waste generation, produce a benchmark for waste generation, forecast waste generation, or properly compute disposal charges. Examples of such tools include online waste control tool (Formoso, Isatto and Hirota, 1999), waste management planning online tool (McDonald and Smithers, 1998), Calibre (Chrysostomou, 2000), Webfill (Chen, Li and Wong, 2003), and ConstructClear (BlueWise, 2010).

In addition, the Building Research Establishment (BRE) developed SMARTStart (BRE, 2007), SMARTAudit (BRE, 2008a), and True Cost of Waste Calculator (BRE, 2010), Site Methodology to Audit, Reduce and Target Waste (SMARTWaste) (Mcgrath, 2001; Hobbs, Blackwell and Adams, 2011). To sum up, waste data collection and audit activities are primarily aimed at improving waste quantification. For this reason, the quality of the waste data must be ensured to guarantee the accuracy of waste quantification (Cochran *et al.*, 2007b). A major setback to this is that most CW is not segregated and it is referred to as general waste.

### **2.5.3 Waste Prediction Tools**

Waste prediction tools were developed to assist practitioners to estimate the expected waste output of building projects. Examples of waste prediction tools include SMARTWaste (Mcgrath, 2001; Hobbs, Blackwell and Adams, 2011), Net Waste Tool (NWT) (WRAP, 2011b), Designing-out Waste Tool for Buildings (DoWT-B) (WRAP, 2011a), Web-based Construction Waste Estimation System (WCWES) (Li and Zhang, 2013), DeconRCM (Baniyas *et al.*, 2011), Demolition and Renovation Waste Estimation (DRWE) tool (Cheng and Ma, 2011).

The main contribution of these tools is the ability to estimate, with varying degrees of accuracy, construction waste before it is generated. They capture and analyse building design specifications to produce waste forecasts and identify the most appropriate construction materials and options. The NWT and the DoWT-B produce a more accurate estimation, but they can only be used after the bill of quantity has been produced and are not compliant with

BIM. Although the DRWE tool is BIM-integrated, it is not actively employed during the design process. Therefore, engaging these tools during the design stages becomes important for real-time waste analysis and reduction.

#### **2.5.4 Waste Quantification Models**

The strength of waste prediction tools largely depends on mathematical and analytical waste quantification models. The waste quantification models provide techniques for computing the quantity of waste generated from building projects. Examples of waste quantification models include Waste Index (Poon, Yu and Jaillon, 2004), Building Waste Assessment Score (BWAS) model (Ekanayake and Ofori, 2004), Environmental Performance Score (Shen *et al.*, 2005), Component-Global Indices (Jalali, 2007), Stock-Flow model (Bergsdal, Bohne and Brattebø, 2007), Spanish model (Solís-Guzmán *et al.*, 2009), and Material Flow Analysis model (Cochran and Townsend, 2010).

However, the majority of these models are based on aggregating waste indices and volumetric data, in spite of the multi-dimensional nature of waste generation factors. As such, a major drawback of these waste quantification models is that most of them were developed without adequate consideration for detailed material information and waste causative factors, thus bringing their reliability into question. The majority of the models were developed using location-specific data as well, therefore rendering them unsuitable for universal application, as the estimation could be influenced by the project type, location, size, and construction methods (Mokhtar *et al.*, 2011).

#### **2.5.5 GIS Tools**

A Geographical Information System (GIS) captures and analyses geographical information to provide visual representation for location-based services (Foote and Lynch, 1996). In fact, GIS integrated technology provides a platform for many location-based services, which can be employed for enterprise decision-making (Maliene *et al.*, 2011). Examples of GIS tools for waste management include BREMap (BRE, 2009), Global Position System (GPS) and GIS technology (Li *et al.*, 2005), and GIS-BIM based supply chain management system (Irizarry, Karan and Jalaei, 2013). A direct application of GIS tools in CW management is urban mining (Brunner, 2011), which is concerned with the preservation of product information for the

purpose of end of life recovery of resources. To achieve this in the most effective way, GIS services could be used to locate the nearest recycling facilities, which will significantly reduce the energy required for the transportation of waste and recyclables.

In spite of the availability of BIM-based GIS tools to capture different aspects of a construction project (Isikdag, Underwood and Aouad, 2008; Choi *et al.*, 2008; Zhang *et al.*, 2009; Elbeltagi and Dawood, 2011), none of them provide waste management functionality. A major drawback to the implementation of such tools is interoperability between architecture, engineering, and construction (AEC) and GIS standards.

From the review of all the construction waste management tools, a key underlying problem is that these tools are designed to be used at the late design stage or not embedded within the design process. This makes the tools difficult to be used by architects and design engineers. The implication of this is that construction waste cannot be minimized by architects and design engineers who are using existing tools.

## **2.6 Limitations of existing construction waste management tools**

To identify inefficiencies of CW management tools, this study carried out in-depth performance assessment of existing CW tools to identify their limitations. Knowing the limitations of existing CW tools is a key mechanism for understanding how the capabilities of BIM could be used to improve them. After an exhaustive review of existing CW management tools, five main limitations that impede their effectiveness and usability were identified. These limitations are summarised thus:

- (i) Existing CW tools are completely detached from the design process,
- (ii) Existing CW management tools lack interoperability capabilities,
- (iii) CW data are not sufficient,
- (iv) CW management responsibilities are not clear, and
- (v) Lifecycle analysis of CW performance is not available.

A summary of existing tools with respect to the year of latest version, locality, BIM compliance, and the five limitations is presented in Table 2.2. Further discussions on these five limitations are presented in the following sub-sections.

Table 2.2: Existing Tools for Construction Waste Management and their Limitation

No.	Category	Tools/ Reference	Locality	A	B	C	D	E
1.	<i>waste management plans templates and guides</i>	Cost effective waste management plan (Mills et al., 1999)	USA	x	x	x	x	x
		Site Waste Management Plan (SWMP) (WRAP, 2008)	UK	x	x	x	x	x
		Material logistic plan (WRAP, 2007)	UK	x	x	x	x	x
		Designing Out Waste Guide (WRAP, 2009)	UK	x	x	x	x	x
		Procurement guidance (WRAP, 2010)	UK	x	x	x	x	x
		Demolition protocol (ICE, 2008)	UK	x	x	x	x	x
2.	<i>Waste data collection and audit tools</i>	CALIBRE (Chrysostomou, 2000)	UK	x	x	x	x	x
		Online Waste Control Tool (Formoso, 1999)	Brazil	x	x	x	x	x
		Waste Management Plan (McDonald and Smither, 1998)	Australia	x	x	x	x	x
		ConstructWise (Bluewise, 2010)	UK	x	x	x	x	x
		True Cost of Waste (BRE, 2010)	UK	x	x	x	x	x
		Webfill (Chen et al., 2003)	Hong Kong	x	x	x	x	x
		SMARTAudit (BRE, 2008)	UK	x	x	x	x	x
		SMARTWaste (Mcgrath, 2001)	UK	x	x	x	x	x
3.	<i>Waste prediction tools</i>	Net Waste Tool (NWT) (WRAP, 2011a)	UK	x	x	x	x	x
		Design-out Waste Tool for Buildings (DoWT-B) (WRAP, 2011b)	UK	✓	x	x	x	x
		Demolition and Renovation Waste Estimation (DRWE) (Cheng and Ma, 2013)	Hong Kong	✓	✓	x	x	x
		DeconRCM (Banias et al., 2011)	Greece	x	x	x	x	x
		Web-based Construction Waste Estimation System (WCWES) (Li and Zhang, 2013)	Hong Kong	x	x	x	x	x
4.	<i>Waste quantification models</i>	Waste index (C. S. Poon et al., 2004)	Hong Kong	x	x	x	x	x
		Building waste assessment score (Ekanayake and Ofori, 2004)	Singapore	x	x	x	x	x
		Stock-Flow model (Bergsdal, H., Bohne, R. A., & Brattebø, 2007)	Norway	x	x	x	x	x
		Spanish model (Solís-Guzmán et al., 2009)	Spain	x	x	x	x	x
		Component-Global Indices (Jalali, 2007)	International	x	x	x	x	x
		Environmental Performance Score (Shen et al., 2005)	China	x	x	x	x	x
		Material Flow Analysis model (Cochran and Townsend, 2010)	USA	x	x	x	x	x
		System Analysis Model (Wang, Li and Tam, 2014)	China	x	x	x	x	x
5.	<i>GIS tools</i>	Universal Waste Ratio (Llatas, 2011)	International	x	x	x	x	x
		BREMap (BRE, 2009)	UK	x	x	x	x	x
		Global Position System (GPS) and GIS technology (Li et al., 2005)	International	x	x	x	x	x
		GIS-BIM based supply chain management system (Irizarry et al., 2013)	International	x	x	x	x	x
		IRP-Based Barcode System (Chen, Li and Wong, 2002)	China	x	x	x	x	x

A - Engaged design process, B – Software interoperability, C - Sufficient CW data, D - Clear CW management responsibility, E – Lifecycle waste analysis

✓ - Functionality available, ✗ - Functionality not available

### **2.6.1 Existing CW management Tools are Completely Detached from the Design Process**

The design process is usually an iterative process that contains a number of stages to meet the client's needs. The design process happens in RIBA work stages 2 - concept design, 3 - developed design, and 4 - technical design (RIBA, 2013). These design process stages help to determine design workflow, tools and software requirements, and to produce building design documents (such as building drawings, materials specification, Computer Aided Design (CAD) models, schedule of work, bill of quantity, and others).

Meanwhile, studies on sources of CW show that the pre-construction (planning and design) stages are responsible for the largest percentage of CW (Faniran and Caban, 1998; Osmani, 2012a; Oyedele *et al.*, 2013; Poon, Yu and Jaillon, 2004). This is primarily due to making inappropriate design decisions, which could lead to design changes (Osmani, Glass and Price, 2008; Poon, 2007). Other sources of CW due to design include unfamiliarity with material alternatives (Ekanayake and Ofori, 2000), lack of knowledge about standard size of materials and dimensional coordination (Treloar *et al.*, 2003), errors in contract documents and drawings (Bossink and Brouwers, 1996), and industry cultural related factors (Ajayi *et al.*, 2016).

Despite the general acceptance that taking the right decisions during design could minimise CW, none of the existing tools has been fully integrated into the design process. Although recent advancements in ICT have culminated in the development of various tools to assist construction industry stakeholders in waste management, these tools are still external to the design process and they can only be used after design is completed. For example, NWT and DoWT-B, which is believed to produce a more accurate waste estimation (Langdon, 2011), could only be used after the bill of quantity has been produced. Thus, this makes it difficult for architects and design engineers to identify possible ways of CW management during design. Besides, advice on CW minimisation at this point is too late and will require significant effort and time to implement.

Despite the increasing adoption of BIM in building design, most of the existing waste management tools are not BIM compliant (Cheng and Ma, 2013). These tools have limited usability because they are external to the BIM software used by designers. This reveals a huge gap in capability since evidence in literature suggest that effective waste minimisation must

start from the design stage (Faniran and Caban, 1998; Wang, Li and Tam, 2014) and this can only be achieved if waste management functionalities are incorporated into design tools.

## **2.6.2 Existing CW Management Tools Lack Interoperability Capabilities**

Due to the emerging importance of BIM in the AEC industry, several companies have adopted BIM to improve multidisciplinary collaboration. Grilo and Jardim-Goncalves (2010) highlights that BIM ensures that all project teams can communicate easily, contribute to decision making and access information about the project. Despite various attempts to encourage communication standards among CAD and BIM tools, software interoperability issues persist. Users essentially focus on interoperability and total cost of ownership as important software selection criteria (Cyon, 2009). Lack of software operability causes problems especially in terms of reduced efficiency and waste (time and cost) (Jackson and Prawel, 2013). According to Brunnermeier and Martin (2002), lack of software interoperability in the USA alone resulted into a yearly loss of at least \$1 billion.

Participating teams therefore expend immense effort to ensure software interoperability because teams have different software needs and varied expertise on the use of software (Cyon, 2009; Hu *et al.*, 2016). This is to ensure that collaborating teams are able to exchange building data without loss of information. This consideration makes the adoption of BIM imperative in the construction industry to satisfy the requirements for software interoperability and effective collaborative practices (Ajayi *et al.*, 2015a; Hu *et al.*, 2016; Grilo and Jardim-Goncalves, 2010). This is to allow collaborating teams to exchange building models among BIM software without loss of information. Despite the current effort to achieve full software interoperability in the AEC industry, most of the existing CW management tools lack interoperability capabilities with other software. Moreover, the process of how CW management can be implemented in BIM environment has not been well documented. This gap has impeded the exploitation of capabilities of BIM software for CW analytics at the design stage.

The support for model exchange among heterogeneous BIM software is engendered by the development of BIM standards such as IFC (Laakso and Kiviniemi, 2012) and gbXML (Dong *et al.*, 2007). The BIM standards provide not only means of cross-platform representation of building materials, but also the representation of building forms and functionalities. While IFC is generally acceptable as the industry standard (Eastman *et al.*, 2011), its current



implementation is not efficient to tackle the always changing demand of the AEC industry (Tibaut, Rebolj and Perc, 2014). This limitation therefore constitutes a great problem to be addressed by BIM and CW practitioners considering the recent rate of BIM adoption and the environmental and economic benefits accruable from effective CW management. Overcoming this challenge of software interoperability among CW management tools and BIM software will engender the exploitation of BIM functionalities within CW analysis tools and vice versa.

### **2.6.3 Construction Waste Data are not Sufficient**

Current efforts in CW management have been focused on understanding how waste output expected from building projects could be estimated at the design stage. Accordingly, existing CW estimation tools calculate waste potentials of buildings using historical regional or national waste generation rates and Gross Floor Areas (GFA) (Poon *et al.*, 2004; Zade and Noori, 2008; Li and Zhang, 2013). However, Mills *et al.* (1999) highlighted that a major limitation of these models is insufficient data about waste. Most waste estimation tools are developed using location specific information thereby making them not universally applicable. Consequently, the reliability of using these tools for CW estimation in other locations could not be guaranteed (Mokhtar *et al.*, 2011). For example, SMARTWaste (Mcgrath, 2001) estimates CW from statistical waste data collected from previous building projects in the UK only. This restriction limits the use of the tool in other countries. Even so, the accuracy of the waste data collected could not be guaranteed because data entry involves a high level of human intervention, which is prone to errors.

A major challenge to developing a robust CW database is that most of the construction waste arising from building projects is not segregated (Langdon, 2011). On further work, Mcgrath (2001) noted that unsegregated waste are mostly collected and transported as general waste. This therefore does not allow data about waste to be properly labelled. In addition, majority of existing CW estimation tools are based on aggregating waste indices and volumetric data despite the multi-dimensional nature of waste generation factors. This raises serious concerns because the tools were developed without adequate consideration for detailed material information and building methodology, among others. Notably, the peculiarities of building activities influencing CW generation are quite diverse and treating them the same way could be misleading.

#### **2.6.4 Waste management responsibilities are not clear**

According to Ajayi *et al.* (2015a), waste generation in building projects is largely dependent on the attitude of stakeholders in taking up waste management responsibilities. Out of these stakeholders, clients make up the core of the building project process (Latham, 1994) and have the greatest influence on waste management issues. Understandably, clients set environmental standards that other stakeholders must meet. Similarly, Teo and Loosemore (2001) highlighted that implementing effective waste management strategies requires cooperation among all participating team, especially in accepting responsibilities towards CW management. Examples of such waste management responsibilities include involvement in analysis of potential waste of project during design, organising and attending waste management meetings, training on waste management tools, setting waste management goals and preparing list of recoverable waste material to be reused or recycled. From these responsibilities, Osmani *et al.* (2008) show that only 2% of building project teams hold waste management meetings and that only 32% of them implemented waste management goals. This is primarily because most people believe that CW is inevitable and can only be managed, reactively mitigated or ignored.

In addition, Osmani *et al.* (2008) highlighted that poorly defined individual responsibilities have contributed to the laxness of individual's commitment to waste management. This gap reveals the need for a clear definition of stakeholders' responsibilities at an early stage of building projects. More importantly, this is imperative to create a synergy of roles on waste management strategies, goals, and choice of tools. To achieve this, contracts and contractual agreements are employed to assign decisive waste management responsibilities. So, contractual clauses are used to communicate waste management responsibilities and penalise poor CW performance (Greenwood, 2003; Dainty and Brooke, 2004). Understandably, Poon *et al.* (2004) suggest that sub-contractors could be assigned additional waste management duties. This is because sub-contractors could be willing to take more responsibilities at the same price due to high competition.

#### **2.6.5 Lifecycle Analysis (LCA) of CW Performance is not available**

Lifecycle Analysis (LCA) evaluates impact of a process or product from its origin to the end of use on the environment (Ortiz, Castells and Sonnemann, 2009). Existing studies on waste management and minimisation show that waste is produced throughout the building lifecycle (Kozlovská and Spišáková, 2013; Osmani, 2013; Yeheyis *et al.*, 2013; Jaillon and Poon,

2014b). This means that CW arises from design stages to the end-of-life of buildings. This has made LCA an important tool in waste management planning and policy-making (Klöpffer, 2006; Ekvall *et al.*, 2007). Accordingly, LCA offers environmental methodology for comparing waste management options in the construction industry. Despite the belief that LCA methodologies could be used for CW management and minimisation (Llatas, 2011), none of the existing CW tools has functionality for LCA for waste. This is because existing tools are useful at specific work stages (Liu *et al.*, 2011) but not throughout the entire building lifecycle. For example, tools such as SMARTWaste, SMARTStart, and Webfill are useful at only the construction stage (RIBA stage K). This however reveals a huge limitation because evidence shows that efficient waste management approach requires a “cradle-to-grave” appraisal of building projects (Morrissey and Browne, 2004; Guy, Shell and Esherick, 2006).

## 2.7 Summary

In this chapter, discussion of the concept, definition, and causes of CW is presented. The chapter starts with a thorough review of extant literature on CW management to understand existing research stream in design for CW prediction and minimisation. Five design principles for CW minimisation were identified and discussed, which are design for material optimisation, design for waste efficient procurement, design for material recovery and reuse, design for off-site construction, and design for deconstruction and flexibility. After which existing CW management tools were reviewed to identify their strengths and limitations. A list of 32 tools was identified in five categories, which include waste data collection and audit, waste prediction, waste quantification models, waste management plan templates and guide, and location-enabled services.

Existing CW management tools provide encouraging results for waste forecast and reduction at the design stage, however, the review of literature revealed that they are not comprehensive enough to tackle the challenges of CW management. It was also revealed that existing CW management suffers from five key limitations, which are: (i) existing CW tools are completely detached from the design process, (ii) existing CW management tools lack interoperability capabilities, (iii) CW data are not sufficient, (iv) CW management responsibilities are not clear, and (v) lifecycle analysis of CW performance is not available. These limitations revealed the need for the development of a holistic CW management tool that

incorporates the strengths and take into consideration the weaknesses of existing CW management tools.

The next chapter contains discussion on the concepts of BIM and AI systems. The discussion is done in two parts: (i) the first part of the chapter focuses three underpinning concepts of BIM, i.e., collaborative practices, technology as digital delivery vehicle, and integrated project data. After this, a critical review of existing BIM software is presented, (ii) the second part of the next chapter focuses on AI systems and associated theories. This part also contains discussion of four main groups of AI models, which are machine-learning techniques, knowledge based systems, evolutionary algorithms, and hybrid systems.

### **3 BUILDING INFORMATION MODELLING (BIM) AND ARTIFICIAL INTELLIGENCE (AI) SYSTEMS**

#### **3.1 Overview**

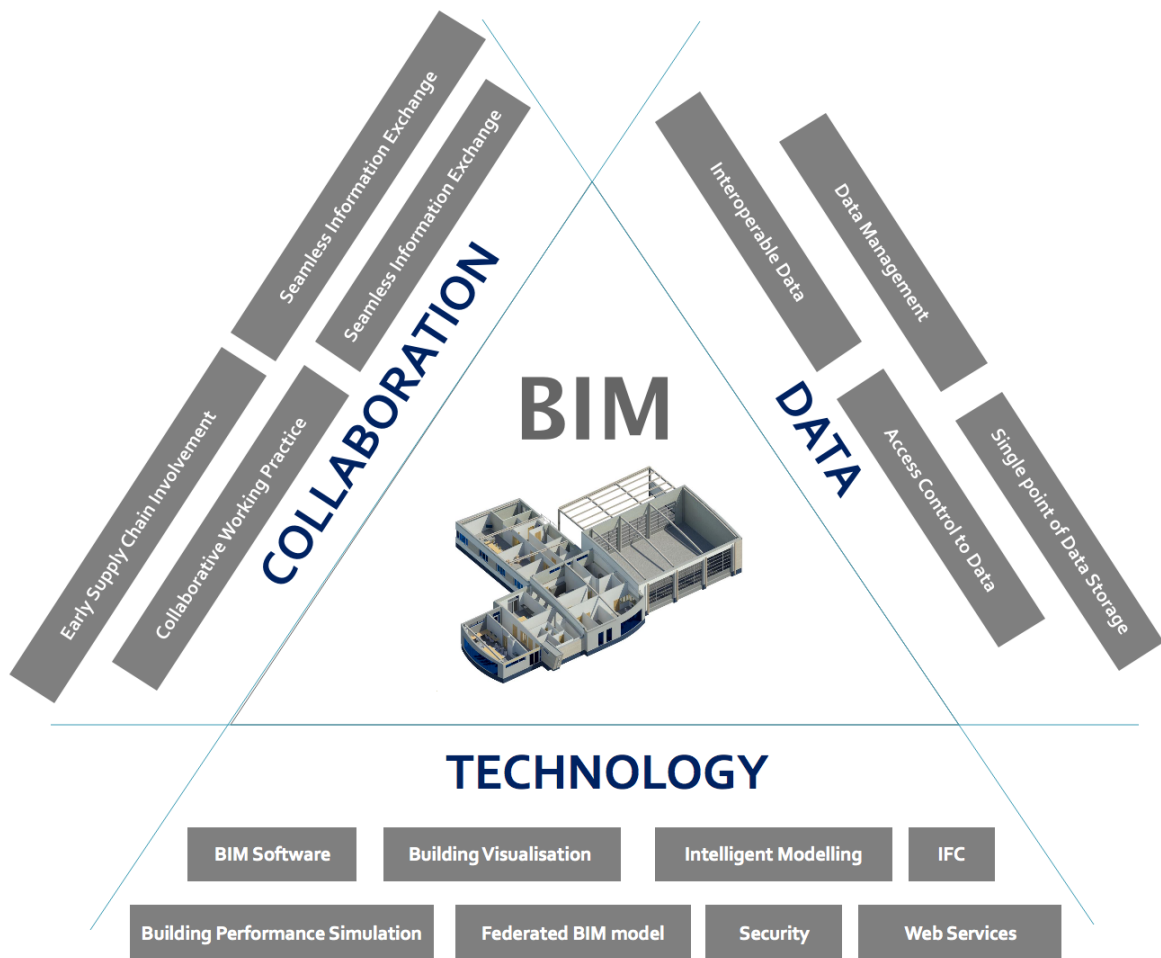
This chapter contains discussion on the concepts of Building Information Modelling (BIM) and Artificial Intelligence (AI) systems in two parts. The first part of the chapter focuses on BIM and its benefits to the construction industry. The three underpinning concepts of BIM, i.e., collaborative practices, technology as digital delivery vehicle, and integrated project data, are discussed. The chapter also presents UK BIM maturity levels and the significance of BIM in the changing UK construction industry. Thereafter, a critical review of existing BIM software is presented with the aim of identifying features of BIM that are needed to overcome the limitations of existing CW management tools. After this, BIM development tools are identified and discussed. The categories of tools discussed are IFC development tools and BIM software Application Programming Interface (API).

The second part of the chapter focuses on AI systems and associated theories. Theories perform significant functions in research by aiding the understanding of observed phenomena and providing direction for future behaviour (Koskela and Howell, 2008). As such, theory provides a common framework for furthering knowledge development and coordinating the process of research. Seymour *et al.* (1997) highlight that existence of well-established theories reveals the maturity of an area of study. Therefore, construction management studies cannot be built using only empirical evidence, but has to be underpinned by a solid theoretical background (Söderlund, 2004). However, construction management as a field of study lacks significant theoretical underpinnings (Shenhar and Dvir, 1996) and particular theories needs to be adopted (Koskela and Howell, 2008). Söderlund (2004) argued that such theoretical perspectives exist in other fields of study and it should be plausible to adopt them in construction management context. This chapter therefore examines the theoretical background of this study. In particular, theories from machine intelligence, evaluation practices, resources management, and decision-making are discussed to determine how they influence the study. The chapter ends with the discussion of four main groups of AI models, which are machine-learning techniques, knowledge based systems, evolutionary algorithms, and hybrid systems.

## 3.2 Building Information Modelling: Concepts and Benefits

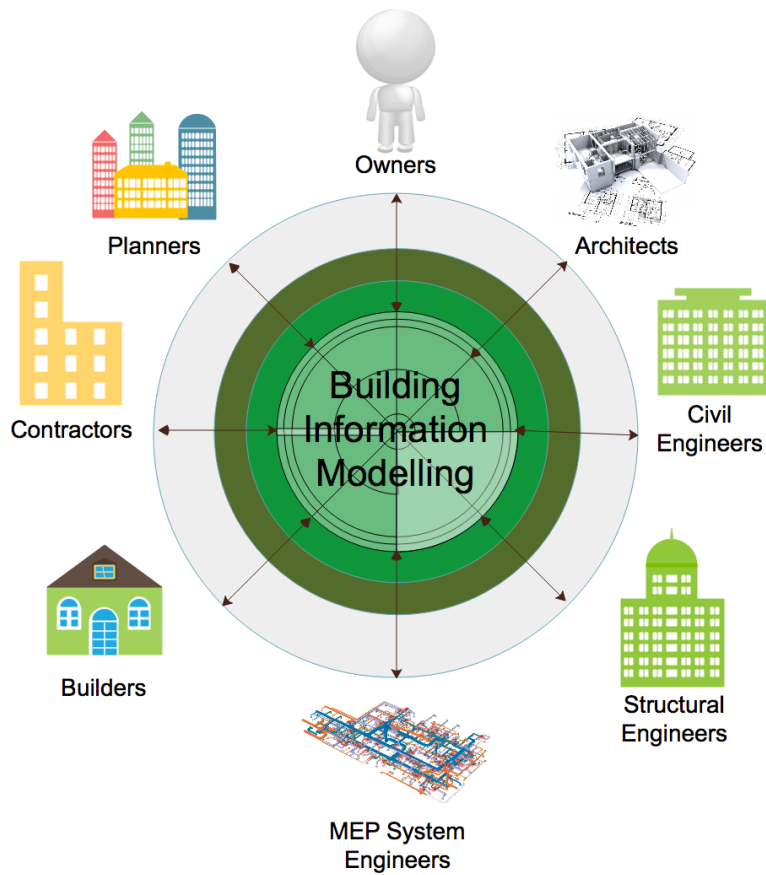
An underlying concept of Building Information Modelling (BIM) is provisioning of an inclusive environment for entire project lifecycle (Grilo and Jardim-Goncalves, 2010). As such, BIM is more of a collaborative process than a piece of software. Although technology provides an implementation delivery vehicle for BIM, resultant effect of BIM on organisations is more from a sociology perspective. This primarily reflects a more collaborative work practice and early involvement of stakeholders (Eastman *et al.*, 2011; Sacks, Radosavljevic and Barak, 2010). In addition, BIM goes beyond the use of an electronic drawing tool or the adoption of technology, but it represents the process of using technology to create, refine, simulate, manage, and communicate virtual representation (form and functions) of buildings to optimise the construction delivery process. This clearly shows that BIM is underpinned by three main concepts: Collaborative practices, Technology as digital delivery vehicle, and integrated project data as shown in Figure 3.1.

Central to the role of Integrated Product Delivery (IPD) in shaping the future of the Architecture, Engineering and Construction (AEC) industry is the adoption of BIM (Ilozor and Kelly, 2012). IPD strives to streamline construction efforts through intensified collaborative planning and clear definition of goals at the early stages of a projects (Mihic, Sertic and Zavrski, 2014). BIM therefore provides the needed technology and framework for successful implementation of IPD. BIM also enables the required platform to engage all the stakeholders throughout the buildings lifecycle. As such, the main purpose of BIM is stakeholders' communication and collaboration to facilitate shared project models, single point of information access, controlled coordination of data, and data transparency (Grilo and Jardim-Goncalves, 2010).



*Figure 3.1: Concepts of Building Information Modelling*

The increasing adoption of BIM has revolutionised the AEC industry (Azhar, 2011) by improving system interoperability information sharing, visualisation of n-D models, speed of delivery, and decision making processes (Steel, Drogemuller and Toth, 2012). Most importantly, BIM also provides a platform for seamless collaboration among stakeholders from different fields of discipline as shown in Figure 3.2. As such, BIM knowledge is accumulated from the various fields and the expectations of BIM cut across these disciplines (Singh, Gu and Wang, 2011).



*Figure 3.2: BIM Collaborative Platform*

### **3.3 BIM in the Changing UK Construction Industry**

Prior to BIM, the UK government and construction industry have attempted to achieve greater efficiency and cost savings across public sector construction projects. Reform movements and important milestones within the UK construction industry are shown in Figure 3.3. The figure details key milestones and discourse of changes in the UK construction industry over 22 years. The trend shows the metamorphosis from a completely fragmented industry to a more collaborative and integrated product delivery based industry. Key landmarks in the delivery of less adversarial and less fragmented construction industry in the UK are Latham Report (Latham, 1994) and Egan Report (Egan, 1998). Much of the thrust of these reports is movement for change within the construction industry towards a “supply chain” system found in manufacturing industry and making the industry more responsive to clients’ needs. Particularly, many organisations were established following Latham and Egan reports. The



organisations include Construction Industry Board (CIB), Strategic Forum for Construction, Construction Task Force, Rethinking Construction, and Construction Excellence.

Apart from Latham and Egan reports, the AVANTI programme in 2002 was instrumental to the use of ICT for improved efficiency and quality of information on construction projects. The AVANTI programme reveals that the use of ICT on construction projects could result into 80% time savings in information search, 50% time savings in tender assessment, and 85% time savings on information processing (Constructing-Excellence, 2006). The results of the programme were instrumental in the development of BS 1192:2007, which sets out common data practices, naming conventions, and file classifications. However, the standard was not widely adopted by the industry; thus, limiting the predicted benefits (RIBA, 2016).

### **3.3.1 UK BIM Level 2 Programme**

Following the global financial crisis and subsequent great recession in 2008/09, some sectors of the UK government and construction industry were subjected to scrutiny to improve efficiency and cost savings - particularly on public sector construction projects. This led to several initiatives, such as sustainable Britain to ensure 80% reduction in carbon emissions by 2050, Zero carbon on new builds by 2018 and 2019 on public and private sector construction projects respectively, and the use of collaborative 3D BIM. The UK Construction Strategy announced the Government's intention in 2011 to require Level-2 BIM (collaborative 3D BIM) on all centrally procured project by 1st April 2016. This is central to the government's objective of achieving 20% savings in procurement cost and carbon burden. The four-year programme to modernise and digitise construction is considered the most ambitious centrally driven BIM implementation programme in the world (HM-Government, 2012). Chief among the objectives of this programme is to transform the construction industry from unmanaged 3D models era (BIM Level 1) to more collaborative and integrated solutions for project delivery (BIM Level 2) as presented in BIM maturity model in Figure 3.4.

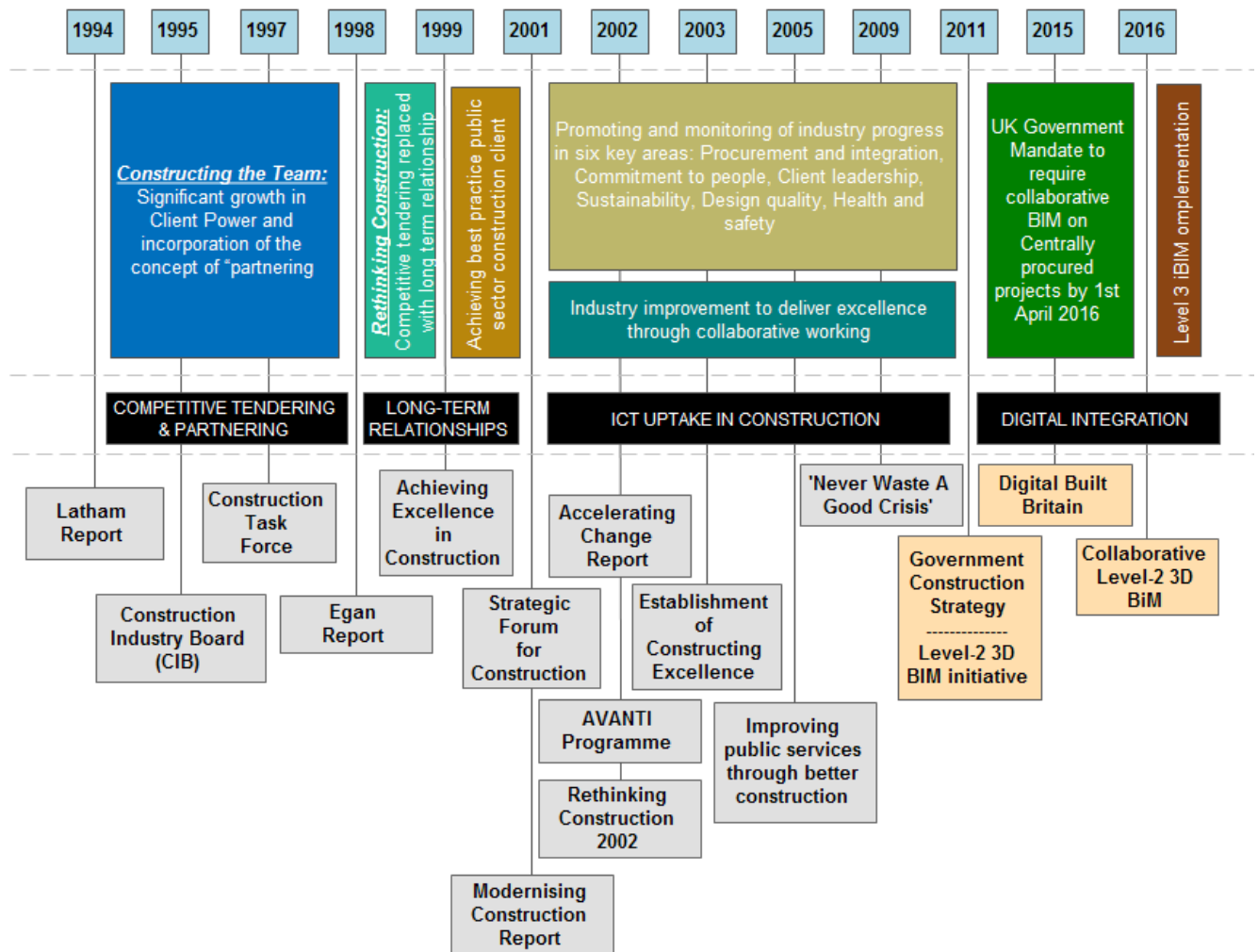


Figure 3.3: Reform Movements and Important Milestones within the UK Construction Industry

The BIM maturity model as stipulated by the UK BIM Industry Working Group is made up of four levels, which are:

**BIM Level 0 – Computer Aided Design (CAD):** Unmanaged Computer Aided Design (CAD) coordination and data exchange through paper and electronic papers such as 2D drawings and PDF files.

**BIM Level 1 – 2D/3D Managed Models:** Managed CAD in 2D or 3D format with common data environment that provides standard data structures and standardisation.

**BIM Level 2 – 3D Collaborative BIM:** Managed 3D collaborative environment held in a federated model. This could include 4D schedule data and 5D cost data.

**BIM Level 3 - Integrated BIM (iBIM):** Fully open process with a single project model and data integration. Integration is enabled by Web services using IFC, IDM, and IFD standards.

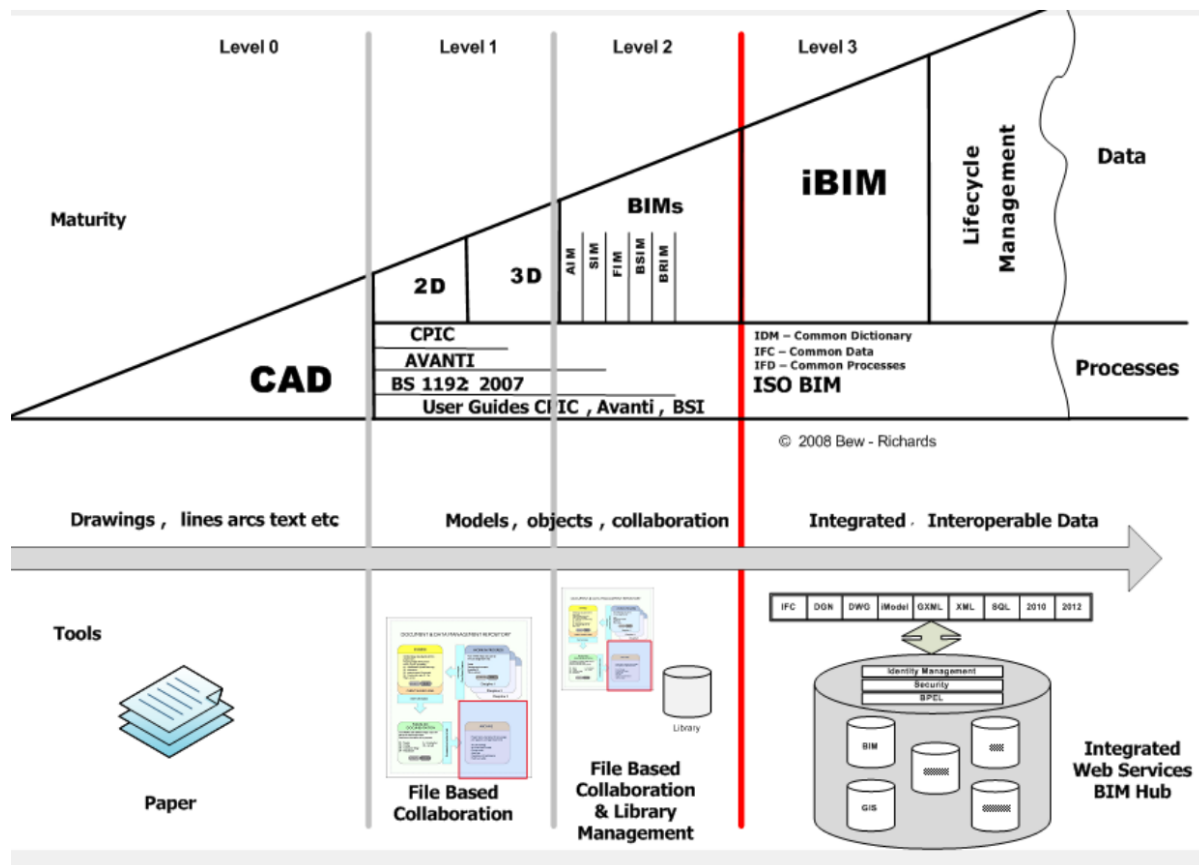


Figure 3.4: BIM Maturity Model by Bew and Richards (2008) (cited in BIM-Industry-Working-Group, 2011) (used with permission of the author)

Critical to reaching UK BIM implementation target was the requirement for contractors to demonstrate Level-2 BIM maturity through digital project and asset information, documentation, and data. This requirement translated to massive uptake of BIM by contractors in the UK. As such, most of the companies were forced from BIM Level 1 to Level 2 to sustain their competitive advantage in the changing construction world. The current trend shows that about 97% of UK construction companies will have adopted BIM by 2020 (RIBA, 2016). UK BIM programme has been instrumental in the delivery process of world-class projects such as

2012 London Olympics, Crossrail, and HS2. Successful delivery of BIM Level-2 in the UK paved the way for “Digital Built Britain” initiative for the adoption of Level 3 BIM. BIM Level 3 employs a fully connected interoperable data chain from start to finish through a robust Web-service based federated model. Level 3 is where the future of Digital construction innovation lies.

### **3.4 Building Information Modelling Platforms**

Recent advances in CAD and ICT has culminated in the development of various BIM software for several purposes. These purposes include architecture, structures, sustainability, MEP, facility management, simulation, and others. The top 10 BIM software used in the industry include Autodesk Revit, Bentley Architecture, Graphisoft ArchiCAD, Nemetschek Vectorworks, Gehry Technology Digital Projects, Nemetschek AllPlan, Trimble SketchUp, 4MSA IDEA Architectural, Tekla Structure, and RhinoBIM (NBS, 2016) as shown in Table 3.2. In addition, several analysis software applications are available to simulate a wide range of building performances. The analysis software include Ecotect (thermal efficiency, lighting, visibility, solar shading and exposure), Green Building Studio (CO<sub>2</sub> emission, energy consumption), and IES (airflow, sound and acoustic quality).

Autodesk Revit is the most popular BIM design software in the AEC industry and it is made up of three integrated products, which are Revit Architecture, Revit Structural, and Revit MEP. The wide adoption of Revit across the industry is motivated by its intuitive user interface, powerful drawing production tools, and large set of product libraries. Revit SEEK library has information from about 850 companies and about 13,750 product lines (Eastman *et al.*, 2011). Revit also supports several building performance simulations, which include energy analysis, environment impact analysis, quantity take-off, construction planning and monitoring. A key limitation of Revit is its in-memory management system. This significantly slows Revit down when memory requirement of projects exceeds 300MB (Eastman *et al.*, 2011).

The level of adoption and the dominant market position of Revit reveals its popular choice for BIM application development (Cheng and Ma, 2013; Kota *et al.*, 2014; Ajayi *et al.*, 2015b). Revit has about 31% of UK CAD software market share (RIBA, 2016). This is because Revit provides an API that could be used to extend the functionalities of Revit. Revit is also popular because of its compatibility with several BIM and CAD platforms (Navisworks, AutoCAD,

SketchUp, form Z, MagiCAD, SismiCAD, and ArchiCAD) and simulation software (Green Building Studio, Eotect, EnergyPlus, TOKMO, Archibus, and Google Earth). This is made possible because of Revit compatibility with popular exchange formats such as IFC, gbXML, DWG, DXF, SAT, ASDK, FBX, ODBC, and others.. Comparison of existing BIM software is shown in Table 3.1.

### **3.5 BIM for Designing out Construction Waste**

In addressing the limitations of existing CW management tools, it is important to adopt solutions available within tools used throughout the entire lifecycle of buildings. This is to ensure effective management of CW right from the planning stages, through subsequent stages, i.e., design, construction, commission, usage and maintenance stages, to the end of life. As such, integrating existing tools with BIM would offer greater flexibility to influence cost and performance of buildings at a stage where design change is cheaper. As such, six BIM functionalities must be adopted for CW management as shown in Figure 3.5. The BIM functionalities are:

- i) Team communication and integration,
- ii) Parametric modelling and visualisation,
- iii) Building performance analysis and simulation,
- iv) Automatic document generation,
- v) Improved building lifecycle management, and
- vi) Software interoperability with other applications.

The features of BIM for designing out CW are discussed as follows:

Table 3.1: A Comparison of API of top BIM Software

Software	Revit	Microstation	ArchiCAD	Vectorworks	Digital Projects	AllPlan	SketchUp Pro	IDEA Architecture	Tekla Structures	RhinoBIM
<b>Developer</b>	Autodesk	Bentley	Graphisoft	Nemetschek	Gehry	Nemetschek	Trimble Navigation	4M	Tekla Corporation	Robert McNeel
<b>File extension</b>	.rvt	.dng	.pln	.wmx	.CATProduct	.ndw	.skp	.dwg	.tsc	.3dm
<b>Operating System</b>	Windows, Mac, Linux	Windows, Mac, Linux	Windows, Mac, Linux	Windows, Mac, Linux	Windows, Mac, Linux	Windows, Linux	Mac, Windows, Mac, Linux	Windows, Mac, Linux	Windows, Mac, Linux	Windows, Mac, Linux
<b>Main Use</b>	Arc, Design, Electrical, and Mech.	Arc, Design, Electrical, and Mech.	Arc, Design, and Mech.	Arc, Design	Arc, Design, Electrical, and Mech.	Arc, Design, Electrical, and Mech.	Arc, Design, Electrical, and Mech.	Arc, Design	Arc, Design, Electrical, and Mech.	Arc, Design, Electrical, and Mech.
<b>API</b>	.NET API	MDL API	GDL API	VectorScript	.NET API	Python API	Ruby & C API	None	Tekla Open API	Rhino Common
<b>Language</b>	C#, VB.NET, VC++, F#	C++	C++	C#	VB.NET	C++	Ruby, C	None	C++	VB.NET, C#, Python
<b>Plug-in</b>	.dll	.dll	.dll	.dll	.dll	.dll	.dll	None	.dll, .exe	.dll
<b>Object Identifier</b>	GUID	tags	GUID	Schema tags	Schema tags	GUID	Schema Tags	GUID	GUID	GUID
<b>Memory Management</b>	Automatic	Automatic	Automatic	Automatic	Automatic	Manual	Manual	Automatic	Automatic	Automatic
<b>IFC</b>	Import/Export	Import/Export	Import/Export	Import/Export	Import/Export	Import/Export	Export	Import/Export	Import/Export	Import/Export
<b>ODBC Support</b>	Yes	Yes	Yes	Yes	No	No	Yes	No	No	No
<b>XML Support</b>	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	Yes
<b>gbXML</b>	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes
<b>License</b>	Proprietary	Proprietary	Proprietary	Proprietary	Proprietary	Proprietary	Proprietary	Proprietary	Proprietary	Proprietary
<b>Academic version</b>	3-Year License	Yes	Free	Free	No	Free	Free	Yes	Yes	Yes

### **3.5.1 Team Communication and Integration**

The extent to which project teams collaborate and communicate is critical to the success of building construction projects (Oyedele and Tham, 2007). CW management is no exception to this because it is important that continued justification should be provided for CW management at all lifecycle stages and all stakeholders must be committed to it. In this regard, BIM can play a major role in ensuring that all stakeholders are actively involved in taking waste management related decisions right from planning through the entire building lifecycle. In keeping with the foregoing fact, evidence suggests that adopting BIM on projects allows every member of the project teams to focus on the success of the project.

Collaborative stakeholders' relationship approach also encourages a 'shared risk and shared reward' philosophy, which engenders process efficiency, harmony among stakeholders and reduced litigation (Eadie *et al.*, 2013a). As such, BIM provides a robust platform for communication and information sharing amongst all stakeholders. BIM also engenders design coordination, task harmonisation, clash detection, and CW management process monitoring. Incorporating collaborative practices into CW management tools would encourage effective participation of all projects teams. Adopting BIM would also facilitate transparent access to shared information, controlled coordination, and monitoring of processes (Eastman *et al.*, 2011).

### **3.5.2 Parametric Modelling and Visualisation**

A common thread runs through all BIM software and it is parametric modelling functionality that enables pre-programmed parameters into digital models to allow automatic manipulation of the model. (Sacks, Eastman and Lee, 2004). Parametric modelling and visualisation are required for intelligent modelling of buildings. According to Tolman (1999), parametric modelling employs an object-oriented approach that enables the reuse of object instances in building models, while sustaining object attributes, behaviour and constraints. This feature aids the adoption of BIM across the AEC industry to improve project delivery and building performance. However, parametric modelling has not been leveraged for providing CW management process at the design stage. This suggests that a BIM platform that allows CW

analytics process parametric modelling and visualisation would assist to optimise the CW management process to benchmark and minimise the environmental impact of design alternatives. In addition, enabling this feature in CW management tools will help to prepare adequately for the actual building construction and to put adequate waste disposal measure in place.



*Figure 3.5: BIM Functionalities Framework for Construction Waste Management*

### **3.5.3 Building Performance Analysis and Simulation**

Another functionality of BIM that aids its wide acceptability is the ability to simulate building performances such as cost estimation, energy consumption, and lighting analysis. According



to Eastman *et al.* (2011), building performance analysis provides a platform for functional evaluation of building models before the commencement of construction. This allows comparison of design options to identify potential design errors and to select the most cost-effective and sustainable solution. The increasing popularity of BIM in the AEC industry has strengthened the development of various tools for design analyses and performance evaluation. Performance evaluation capability of BIM could be employed in CW management tools to identify possible design and operational errors that can lead to waste.

Despite the benefits of building performance analysis and the environmental/economic impacts of CW, none of the existing BIM software has capabilities for CW performance analysis. This gap calls for a rethink of BIM functionalities towards capacity for CW analytics and simulation right from early design stages. This will help to capture and address CW concerns at a stage where design changes are cheaper. The use of BIM for the analysis and simulation of CW management process will help to justify the environmental and economic benefits of CW management. As such, BIM can be used to simulate the cost benefit performance of waste to decide on the appropriate design and CW management options.

#### **3.5.4 Automatic Documentation Generation**

A key benefit of BIM software is automatic capture of design parameters for report generation. Employing BIM during design would eliminate human error during data entry. For example, existing CW management tools require practitioners to manually transfer design parameters from bill of quantity. This approach therefore makes these tools susceptible to errors in waste estimation. Evidence shows that the development of a SWMP and deconstruction plan is an important requirement for a successful CW management (Davison and Tingley, 2011). However, no tool exists with the capability of generating SWMPs and deconstruction plans from building models. As such, BIM features that enable on-demand generation of design documents (such as plan drawings, sections, and schedules) from the model of the buildings could be leveraged for SWMP and deconstruction plan development. This therefore will improve design coordination, time management, and engineering capabilities of CW management activities and documentation.

### **3.5.5 Improved Building Lifecycle Management**

The use of BIM encompasses all project work stages from the planning stage to the end-of-life of buildings. BIM allows information on building requirements, planning, design, construction, and operations to be amassed and used for making management related decisions. This feature allows project teams to embed relevant project information into a federated model. For instance, project information such as bill of quantity, project schedule, cost, and facility management information are incorporated into a single building model. The information thus enables a powerful modelling, visualisation and simulation viewpoint that helps to identify design, construction, and operation related problems before they occur. This distinguishing feature makes BIM applicable to all work stages by accumulating building lifecycle information (Eadie *et al.*, 2013b).

In addition, improved lifecycle management of building offered by BIM encourages data transparency, concurrent viewing and editing of a single federated model, and controlled coordination of information access (Grilo and Jardim-Goncalves, 2010). In this way, BIM helps to address multidisciplinary inefficiency within the fragmented AEC industry (Arayici, Egbu and Coates, 2012). This will certainly improve team effectiveness while reducing project cost and duplication of effort. Although more time is required to create a federated model, its benefits surpass the cost. Since waste is generated at all project work stages, adopting BIM for waste management will allow effective capturing of waste related data from design to the end-of-life of buildings.

### **3.5.6 Interoperability with Other Applications**

Although one could argue that the adoption of BIM is on the rise (Arayici *et al.*, 2011), a major challenge confronted by construction companies is software interoperability (Steel, Drogemuller and Toth, 2012). Various BIM analysis applications are available to simulate a wide range of performance purposes, these include Ecotect (thermal efficiency, lighting, visibility, solar shading, and exposure), Green Building Studio (CO<sub>2</sub> emission, energy consumption), and IES (airflow, sound and acoustic quality). As the use of these applications becomes popular, it becomes expedient to allow them to read and create models usable by others. As such, to facilitate interoperability among these applications and BIM software, BIM

open standards were developed to represent the information in a building information model and openly exchange this information. These standards include the Industry Foundation Classes (IFC, 2008), Green Building XML (gbXML, 2013) and the newer Construction Operations Building Information Exchange (East, 2007) for level 2 UK BIM adoption. As such, the increasing uptake in the adoption of BIM (RIBA, 2016) suggests that BIM is now becoming a valuable tool in facilitating successful collaboration and coordination among the team members throughout the lifecycle of both existing and new buildings.

In view of this, project teams expend much effort in carefully selecting appropriate BIM software for effective collaboration and communication. As such, the use of IFC standard (BuildingSMART, 2013) has improved model exchange among BIM software for design analyses (Pazlar and Turk, 2008). It is worth noting that IFC schema allows the extension of its tags to capture various parameters for building objects (Laakso *et al.*, 2012). Despite this opportunity, IFC schema has not been equipped with adequate mechanism to streamline CW analytics. This gap calls for a closer look into how IFC could be extended to support data exchange between CW management tools and BIM software. As such, information exchange requirement of CW analytics processes need to be identified and captured within existing BIM and IFC models.

### **3.6 BIM Development Tools**

Recent innovation in ICT has resulted in tremendous breakthroughs in the development and deployment of BIM software solutions. So considering the need for software interoperability and various application areas of BIM, it becomes necessary to provide means of extending the functionalities of BIM software. This section of the chapter covers the state-of-the-art on BIM software development. Accordingly, a comparative analysis of the tools and techniques were carried out to reveal of their potentials in developing tools for BIM. The review covers IFC development tools, IFC query languages, and BIM software Application Programming Interfaces (APIs).

### 3.6.1 IFC Development Tools

IFC standard captures 3-D parametric information as well as metadata describing other aspects (such as thermal performance, lighting, costing, and fire safety performance) of the model. This feature makes IFC semantically rich. IFC is the industrial open standard for exchanging BIM models and it is the most supported by major BIM software vendors (Autodesk, Graphisoft, Bentley, and Nemetschek). The IFC schema was developed on the EXPRESS definition language (ISO10303-11:1994) which contains about 327 data types, 653 entity definitions, and 317 property set, and thousands of attributes (Steel, Drogemuller and Toth, 2012). Considering the size and complexity of this schema, it needs to be properly managed for optimal usefulness. As such, several IFC development tools and query languages were developed to maximise the potentials of the IFC schema.

Existing IFC development tools include BIMServer, Solibri Model Checker, IFC Webserver, IFCHub, Constructivity Model Server, BIM Collaboration Hub, EDM Server, cBIM Manager, HOOPS Exchange, IFC OpenShell, IFC Gear, Open IFC Tools (Beetz and Berlo, 2010; Solibri, 2016; IFCWebServer, 2016; IFChub, 2017; Constructivity, 2016). A comparison of these tools is presented in *Table 3.2*. All these tools could source IFC data from BIM software for interpretation, verification, and analysis. In choosing among these tools, the support for the import and export of IFC is important. Thus, this makes BIMServer a popular choice for IFC development.

BIMServer provides a robust platform to extract details of objects from an IFC model by providing a global unique identifier. BIMServer was developed to provide a low cost open collaboration platform for small business and to support research and development. This was achieved by providing multi-domain model repositories for concurrent creation, visualisation, and maintenance of BIM data by all stakeholders. Being an open source project, it is easy to integrate more functionalities. BIMServer provides support for IFC, ifcZIP and ifcXML formats, IFC versioning, support for Geographic Information System, Model merging capabilities, revision management, and simple queries and filters through a robust web service interface. BIMServer also supports selective retrieval of building models. It is also compatible with NoSQL key-value store based on the BerkeleyDB and it provides means of connecting to other databases backend (Beetz and Berlo, 2010). Several IFC applications have been

developed using the BIMServer framework. These include automated validation of building models (Zhang *et al.*, 2014); clash detection (van den Helm, Böhms and van Berlo, 2010); location-based applications (Hijazi, Ehlers and Zlatanova, 2010; de Laat and van Berlo, 2011) ; and energy efficiency simulation (Yu *et al.*, 2013).

Several query languages have been developed to allow Create, Read, Update, and Delete (CRUD) operations on object and attributes of building models. These include Express Query Language – EQL (Koonce, Huang and Judd, 1998), Partial Model Query Language – PMQL (Adachi, 2003), Generalized Model Subset Definition – GMSD (Weise, Katranuschkov and Scherer, 2003), Spatial query language (Borrmann, Van Treeck and Rank, 2006), Building Environment Rule and Analysis - BERA (Lee, 2011), Model View Definition – mvdXML (Chipman, Liebich and Weise, 2012), BIMQL (Mazairac and Beetz, 2013). These languages and schema provide several ways of selecting and viewing parts of the building information models.

### **3.6.2 BIM Application Programming Interfaces**

Application Programming Interface (API) provides the means of extending the functionalities of software applications and it also serve as a means of data exchange among heterogeneous software systems. As such, BIM software APIs provide the means of providing functionalities that are not available in out-of-the-box BIM software. This is made possible through add-ins, which utilise CAD and visualisation capabilities of the existing BIM software to achieve specialised tasks. The ability to extend BIM software functionalities allows for automation of repetitive tasks and time-consuming tasks. Examples of BIM software APIs include Revit .NET API, MicroStation Development Library (MDL) API, ArchiCAD Geometric Description Language (GDL), VectorWorks Vectorscript, and Digital project .NET API. A comparison of features of BIM software and their APIs is presented in *Table 3.1*. These APIs serve as building blocks for software applications thereby providing developers with the ability to customise application by leveraging functionality of existing BIM platforms. Software developers could therefore tailor BIM software to suit the needs of businesses.

Table 3.2: IFC Development Tools

	Data Servers							IFC Tools				
	BIM Server	IFC Webserver	IFC Hub	Constructivity Model Server	BIM Collaboration Hub	EDM Server	cBIM Manager	HOOPS Exchange	IFC OpenShell	IFC Gear	Open IFC Tools	
<b>Language</b>	Java, PHP, Javascript	Ruby	Java	.Net, Java	EDMdeveloper SDK	Java	C#	C#	Java	Java	C++	
<b>Database</b>	BerkeleyDB	None	None	OLE-DB, Access	Access	Access	ODBC, Access	None	None	None	None	
<b>Input Support</b>	ifc, ifcxml, ifczip, cityGML, Cobie	ifc, dae, exp	ifc	ifc, .ifcxml, .ifczip, 3DS, dae	Ifc	Ifc, ifcxml	Ifc, IFCxml, gbXML, KML, Excel,	ifc	ifc	ifc	ifc	
<b>Output Support</b>	ifc, ifcxml and ifczip,	ifc, html, xml, csv, collada, svg	ifc	.ifc, .ifcxml, .ifczip, 3DS, dae	Ifc	Ifc, ifcxml	Ifc, IFCxml, gbXML, KML, Excel	None	None	ifc	ifc	
<b>Visualisation</b>	3D	3D, Tree, List	Yes	Yes	3D	3D	Yes	No	No	No	No	
<b>Semantic Checking</b>	Yes	No	Yes	Yes	No	Yes	No	No	No	No	No	
<b>Revisioning</b>	Yes	Yes	Yes	Yes	No	No	Yes	No	No	No	No	
<b>Model Compare</b>	Yes	No	Yes	Yes	No	No	No	No	No	No	No	
<b>Model Merging</b>	Yes	Yes	Yes	Yes	No	Yes	No	No	No	No	No	
<b>Query Language</b>	Java, BIMQL, MVDxml	High level declarative query	Javascript	MVDxml	None	Java	MVDxml	None	None	None	None	
<b>Application Programming Interface (API)</b>	SOAP, JSON, REST, Protocol buffer	JSON	BIMsie, JSON, HTTP, SOAP, REST	GET/POST/DEL ETE Methods	None	None	HTTP(s), FTP, , SSH, SOAP, XML-RPC, RMI, CORBA,	None	None	None	None	
<b>User Management</b>	Yes	Yes	Yes	Yes	No	No	Yes	No	No	No	No	

After a careful review of the existing BIM software and their APIs, it was evident that Revit API offers more flexibility in integrating third party tools. This is because Revit API provides a highly customisable .NET Software Development Toolkit (SDK) for user interface and software logic development. In addition, Revit utilises a Global Unique Identifier (GUID), which the API could access to identify and characterise every unit of a building model. The Revit API also has full support for IFC and IFCXML import and export. These capabilities coupled with the robust database and parametric modelling embedded within Revit provides the API with a rich platform for add-in development. All these reveal opportunities to harness the strengths of Revit API for rapid BIM application development. A number of studies (Goedert and Meadati, 2008; Schlueter and Thesseling, 2009; Nepal *et al.*, 2009; Cheng and Ma, 2011; Kota *et al.*, 2014) have leveraged on the Revit API to simulate, analyse, and visualise several aspects of BIM.

Examples of existing Revit plugins include: (a) *COBie Toolkit*: Extends Revit to support COBie BIM data standard; (b) *BIMObject*: Allows the search and filtering of BIM objects from real-world manufacturers; (c) *CADtoEarth*: Integrates BIM models with Google earth and Google maps; (d) *IFC 2015*: Improves IFC import and export capability of Revit; (e) *Lighting Analysis*: Provides a cloud-based service to expose electric and solar details of Revit models; and (f) *Solibri Model Viewer*: Allows improved IFC and Solibri files processing.

### **3.7 Artificial Intelligence System Development**

The term Artificial Intelligence (AI) was first adopted during the Dartmouth conference (McCarthy and Hayes, 1968) organised by researchers with keen interest in machine intelligence. Major issues in the field of AI were discussed to answer fundamental questions relating to machine intelligence such as neuron nets, self-improvement, automatic computing, computer use of language and abstraction. The term AI broadly describes machines that exhibit a degree of intelligence (Russell and Norvig, 2010). This include machine that mimic human decision making and thought process to solve a problem. The influence of AI cuts across several fields and applications, which include game playing, natural language processing, image processing, speech recognition, computer vision, clustering, and others.

### **3.7.1 Review of Relevant Theories in Artificial Intelligence and Associated Areas**

Several theories are evaluated for their theoretical and methodological relevance to the study. Although several theories contribute to construction management studies, only theories that are relevant to understand and address the theoretical and methodological issues in design based CW management practice are reviewed. On this basis, four theories were adopted to satisfy the theoretical requirements of the study. These theories were chosen from different fields, which include machine intelligence (theory of AI), resource management (tragedy of the commons), evaluative practices (Scriven's logic of evaluation), evidential reasoning (fuzzy set theory). How these theories influence the theoretical underpinning of study is represented in *Figure 3.6*.

The theory of AI offers philosophical lenses to issues in machine intelligence in terms of epistemologically and heuristically adequacy of AI systems. Theories of evidential reasoning provide mechanisms for dealing with uncertainties and imprecise information in intelligent systems. Tragedy of the commons is associated with concepts of sustenance of finite resources and interdisciplinary resource management. A full discussion of tragedy of the common is provided in Section 3.7.1.3. Theories of evaluation practices specify a systematic way for assessing the merit, worth or significance of processes or artefacts based on a set of criteria.



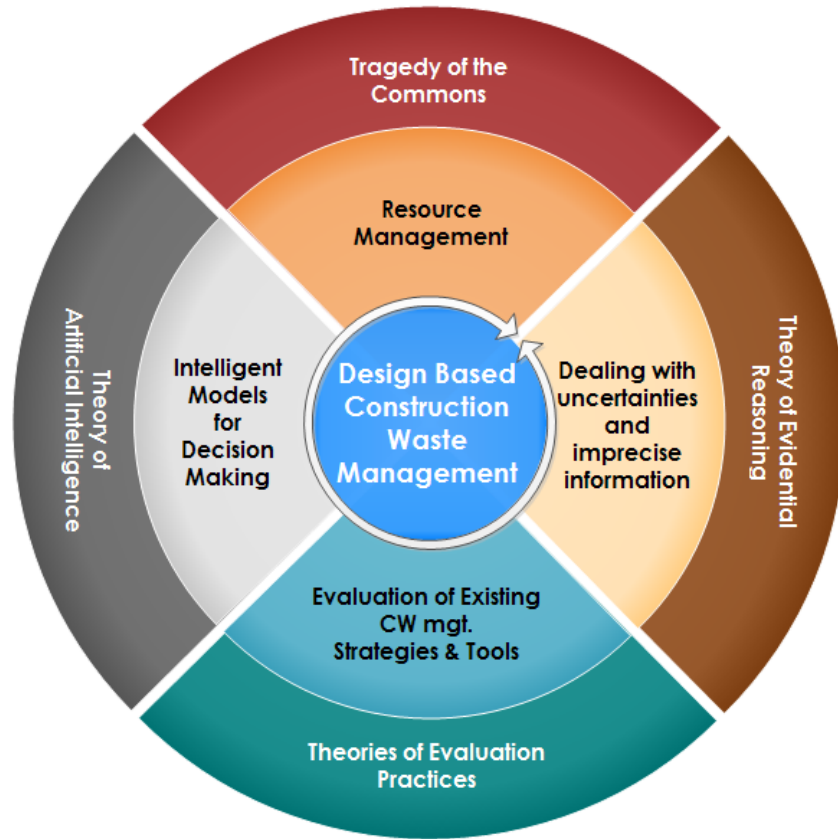


Figure 3.6: Theoretical Underpinning of Study

### 3.7.1.1 Theory of Artificial Intelligence

This study draws majorly on the proposition of the Dartmouth conference in 1956 (McCarthy and Hayes, 1968). The conference was organised by researchers with keen interest in Artificial Intelligence (AI). It was organised to discuss major AI issues and to provide answers to fundamental questions relating to machine intelligence such as neuron nets, self-improvement, automatic computing, computer use of language and abstraction. The major issue of discussion was whether machines can act intelligently (Russell, Norvig and Intelligence, 2003). As such, the Dartmouth proposal opined that:

*“that every aspect of learning or any other feature of intelligence can in principle be so precisely described that a machine can be made to simulate it.”*

This presupposition however raises serious philosophical issues on whether machines could act intelligently as humans. This is still hotly debated and the question of whether machines can think or have a mind is beyond the scope of the current discussion. However, the concern of the current study is to explore two forms of machine intelligence i.e. epistemological part and heuristic part (McCarthy and Hayes, 1990). The epistemological part of AI is concerned with the nature of information about the world or a phenomenon that could be represented in a machine and the information that should be sufficient to find a solution in the problem space. On the other hand, the heuristic part is concerned with mechanisms that use the information stored in the memory of machines to solve problems and to interpret the solutions. The heuristic adequacy of a machine also requires the ability to express the reasoning process unambiguously using a language.

The foregoing implies that epistemological and heuristic adequacy is required to formalise existing design-out-waste strategies into a computational tool. In this case, the information stored in memory must be sufficient to determine a strategy for predicting CW output of a BIM design and must possess adequate mechanism to find the strategy to minimise the predicted waste output.

### ***3.7.1.2 Theories of Evidential Reasoning***

A major challenge in the development of an intelligent system is how plausible decisions are made using both quantitative and qualitative information that have a level of uncertainty and imprecision. To deal with these uncertainties and imprecise information in computation, it is important to adopt evidential reasoning mechanisms to draw out plausible course of actions. This allows the collection and combination of evidence in support or against some hypotheses (Sii, Ruxton and Wang, 2002). As such, computational intelligence techniques employed in handling uncertainty and imprecision in evidential reasoning include: (i) Bayesian Probability Theory (BPT) (ii) Fuzzy Set Theory (FST) (Zadeh, 1965), and (iii) Dempster-Shafer Theory of Evidence (DST) (Dempster, 1967, Shafer, 1976).

BPT, influenced by the traditional probability theory, is by far the most understood of these theories but has very low performance when it comes to using imprecise evidence for decision-making (Sii, Ruxton and Wang, 2002). However, the strength of FST lies in its ability to represent

and process imprecise information and it enables the representation of concepts using linguistic variables (Zadeh, 1965). A number of fuzzy sets variants have been developed, notably Intuitionistic Fuzzy Sets (IFS) (Atanassov, 1986) to extend the applicability of FST in decision making (Qian, Wang and Feng, 2013). With the recent advancements in the application of fuzzy sets variants to decision making, it becomes important to harness the strengths of these systems in every human endeavour, including construction.

DST on the other hand is a generalisation of the Bayesian theory of subjective probability, which came to the attention of researchers in the early 1980s, for dealing with uncertainty in expert systems (Zadeh, 1986). DST originates from the idea of lower and upper probability induced by a multivalued mapping by computing a belief function for aggregating evidence from various sources (Dempster, 1967). This empowers DST to measure the degree of likelihood using a probability interval rather than point probabilities used in BPT, thereby providing a useful measure for the evaluation of the subjective evidence. Zadeh (1986) provided an extensive discussion of DST and its application in the development of expert systems. As a result, a synthesis of FST and DST has been shown to be useful with knowledge-based systems.

Since real-world decision making requires different sources of evidence and their combination, Dempster's rule of combination becomes useful (Zadeh, 1986) to aggregate decision alternatives in a multi-criteria environment. This shows a strong link between fuzzy based systems and DST (Dymova and Sevastjanov, 2010); and that a synthesis of FST and DST is useful within knowledge based systems (Ishizuka et al., 1982; Yager, 1982; Binaghi et al., 2000; Yen, 1990); though it may provide counter intuitive results (Dymova and Sevastjanov, 2012). However, Dymova and Sevastjanov (2014) demonstrated that an interpretation of IFS in DST's framework provides more information during the evidential reasoning process; thus, making the synthesis of IFS and DST a viable option for evidential reasoning in a multi-criteria environment.

### ***3.7.1.3 Tragedy of the Commons***

Resources are inevitably depleted when a limited shared resource is accessed by several individuals acting independently of each other's interest contrary to the group's interest. Avoiding

such situation underpins tragedy of the commons theory (Hardin, 1968). Tragedy of commons is associated with concepts in sustenance of finite resources and interdisciplinary analysis of resource management. Hardin (1968) articulates a broad class of common pool resources and seeks to integrate multiple disciplines to produce a balanced coexistence with the environment. Illustrating the idea with grassing land (as a shared common pool of resources), which is accessible to every herdsman with no restrictions. The impulse of competitive individualism sets in and the greediest of the herdsmen have the greatest benefit for a while. However, with increase demand for the limited resources, the resources are brought to a mutual ruin as noted:

*“Therein is the tragedy. Each man is locked into a system that compels him to increase his herd without limit? In a world that is limited. Ruin is the destination toward which all men rush, each pursuing his own best interest in a society that believes in the freedom of the commons.”*

Therefore, tragedy of the commons could be explored to understand how construction materials, as finite common resources, could be optimised for maximum sustainability and productivity. This is to ensure more proactive strategies rather than remedial measures to waste management in the construction industry. Everyone must contribute towards the sustenance of finite virgin resources and help to maintain a close material flow loop. This idea of resource conservation is closely related to the balanced theory recycling of construction and demolition wastes (Wong and Yip, 2002), which proposes that the amount of waste produced from a project must be proportionally equivalent to the amount of recycled/reused materials as illustrated in

Figure 3.7. This will help to instil the culture of sustainable development within construction industry to recover waste for recycling and reuse. Thus, this will help to reduce CDW and to create appropriate market for recycled/reusable materials.

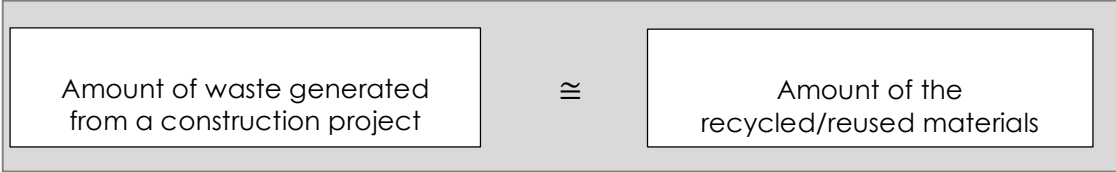


Figure 3.7: Balance Theory for Recycling of Construction and Demolition Wastes

### 3.7.1.4 Theories of Evaluation Practices

Evaluation is a process of assessing the merit, worth or significance of objects based on a set of criteria (Scriven, 1967). The objects could include services, personnel, products, services, organisations, and others. According to Shadish *et al.* (Shadish, Cook and Leviton, 1991), the theories of evaluation practices specify, in a systematic way, feasible approaches that could be adopted by evaluators. In applying any of the available theories of evaluation practices, Davidson (Davidson, 2005) argued that it is important to start with a clear understanding of the purpose for which the evaluation is carried out. According to Scriven (Scriven, 1991), two purposes of evaluation exist, i.e., summative and formative. Summative evaluation is carried out to pass judgement on something while formative evaluation is a form of constructive assessment to improve the performance of the evaluands. In this study, the evaluation of CW management was carried out towards a formative purpose to identify shortcomings of existing tools to improve current and future tools. As such, the identification of the evaluation criteria for existing CW management tools and the development of the holistic BIM framework for CW management are underpinned by theories of evaluation practice.

While the existence of several evaluation approaches is acknowledged, the current study takes a cue from Scriven's logic of evaluation (Scriven, 1967), which starts by identifying the objects to be evaluated and proceeds to establish criteria for merit for the objects. Thereafter, the performance of the objects in relation to the criteria of merit must be determined before drawing valid conclusions. To achieve the objectives of this logic of evaluation, a social agenda approach, which favours constructivist evaluation (Guba and Lincoln, 2001) and qualitative methodology, was adopted. According to Bryson *et al.* (2011), it is important to consider stakeholders' views and needs in a valid evaluation. Constructivist evaluation therefore allows the engagement of relevant stakeholders in obtaining an in-depth understanding of a phenomenon. The logic of constructivist evaluation practice employed in this study is enumerated below:

- 1) Determine the purpose of evaluation
- 2) Seek stakeholders' involvement to build learning capacity and seek understanding from multiple perspectives

- 3) Identify list of evaluative criteria during stakeholders' engagement.
- 4) Organise list of evaluative criteria into common themes and choosing sources of evidence.
- 5) Determine the performance merit of evaluands based on the evaluative criteria
- 6) Produce outcome of evaluation process

### **3.7.2 Implications of the Theories for the Study**

Theories that have theoretical and methodological relevance to the study were reviewed and analysed in this chapter. The theories provide a common framework coordinating the research process of the study. As such, theories from other fields of study were adopted in the context CW management. As such, five theories from various areas were adopted to satisfy the theoretical requirements of the study. These theories include theory of AI, tragedy of the commons, theories of evaluative practices, and theories of evidential reasoning.

Theory of AI offers philosophical lenses to philosophical issues in machine intelligence in terms of epistemological adequacy and heuristic adequacy of intelligent systems. This is required to understand how a system could be developed to capture mechanisms required for design based CW management and to guide decision-making for CW minimisation. Theories of evidential reasoning provide mechanisms for dealing with uncertainties and imprecise information in intelligent systems. As such, three intelligent techniques for handling uncertainty and imprecision in evidential reasoning were reviewed, i.e., Bayesian Probability Theory, Fuzzy Set Theory (FST), and Dempster-Shafer Theory of Evidence. It was revealed that an interpretation of IFS in DST's framework provides more information during evidential reasoning process; thus, making the synthesis of IFS and DST a viable option for evidential reasoning in a multi-criteria environment.

Tragedy of the commons is associated with concepts of sustenance of finite resources in an interdisciplinary environment. The discussion reveals that tragedy of the commons could be employed to understand how construction materials could be optimised for maximum sustainability. This is to encourage more proactive strategies rather than remedial measures to waste management. Theories of evaluation practices specify a systematic way for assessing the merit, worth or significance of processes or artefacts based on a set of criteria. The study takes a

cue from Scriven's logic of evaluation. To achieve the objectives of this logic of evaluation, a social agenda approach, which favours constructivist evaluation and qualitative methodology, was adopted. This is to consider stakeholders' view and needs in evaluation practices. Constructivist evaluation therefore allows the engagement of relevant stakeholders in obtaining an in-depth understanding of a phenomenon. Scriven's logic of evaluation was therefore employed to assess the performance of existing CW management practice and tools in relation to criteria of merit.

### **3.7.3 Types of Artificial Intelligence Systems**

Within the construction industry, several computational models have been employed for different purposes such as cost estimation (Cheng, Tsai and Hsieh, 2009), occupational risk prediction (Tsoukalas and Fragiadakis, 2016), time estimation (Hong *et al.*, 2011), constructability analysis (Yu and Skibniewski, 1999), and insolvency prediction (Jackson and Wood, 2013; Alaka *et al.*, 2016). After a review of extant literature, it was discovered that AI intelligent model development methods that are commonly used in the construction industry could be categorised under four groups, which are: (a) machine learning techniques, (b) knowledge-based techniques, (c) evolutionary techniques, and (d) hybrid systems. Each of these groups was explored to identify their strengths and weaknesses. A comparison of the four group is presented in Table 3.3. AI Techniques in Construction Studies are presented in Table 3.4.

#### **3.7.3.1 Machine Learning Techniques**

Machine Learning (ML) techniques are intelligent techniques that can learn from data (Russell and Norvig, 2010). ML techniques have become so popular because of their inherent abilities to handle uncertainty and to perform efficiently with incomplete data. ML techniques works by judging new case using acquired experiences from similar cases. However, a major disadvantage of ML techniques is that they lack technical justification for results and decisions. As such, ML techniques are called black-box systems (Russell and Norvig, 2010). Despite this limitation, ML techniques have been widely used in the construction industry. Out of the numerous ML

Table 3.3: Comparison of Artificial Intelligence Techniques

AI Techniques	Description	Key Strengths	Key Limitations	Example
<b>Machine Learning Techniques</b>	Machine Learning techniques learn from data	Inherent abilities to handle uncertainty and to perform efficiently with incomplete data	Lack technical justification for results and decisions	Artificial Neural Network (ANN), Fuzzy Logic (FL), Support Vector Machines (SVM), Rule-based Learning (RBL), Association Rule learning (ARL)
<b>Knowledge Based systems</b>	Knowledge based systems mimic human domain experts in finding solutions to complex problems.	Knowledge based possess strong explanation abilities	Knowledge based systems have poor learning and knowledge discovery abilities	Expert Systems (ES), Rule Based Reasoning (RBS), Case Based Reasoning (CBR), Semantic Networks (SN), Ontologies
<b>Evolutionary algorithms</b>	Evolutionary techniques are bio-inspired AI techniques that use heuristics to find solution to highly complex problems	Evolutionary techniques require little domain-specific information and they are easy to implement.	Heuristics used in evolutionary techniques are very difficult to generalise	Genetic Algorithm (GA), Ant Colony Optimisation (ACO), Artificial Bee Colony (ABC), Particle Swarm Optimisation (PSO), Differential Evolution (DE), Evolutionary Programming (EP)
<b>Hybrid systems</b>	Hybrid systems integrate multiple AI techniques to provide synergetic solution to a specific problem	Hybrid Systems overcomes specific limitations of individual techniques and to combine their strengths	Hybrid systems could be complex to design and implement.	Neuro-Fuzzy systems (NN+FIS), Genetic Fuzzy Systems (EC+FS), Fuzzy Expert Systems (FIS-ES), Evolutionary Neural Networks (EC+NN)

approaches available, Artificial Neural Network (ANN), Fuzzy Logic (FL), Support Vector Machines (SVM), Rule-based machine learning, and Association Rule learning are the most common. However in the construction industry, ANN, SVM, and FL appear to be the most widely employed (Irani and Kamal, 2014).



Table 3.4: Artificial Intelligence Techniques in Construction Studies

AI Technique	Area of Study and Source	Technique
<b>Machine Learning</b>	Cost estimation (Wilmot and Mei, 2005)	ANN
	Cost estimation (An <i>et al.</i> , 2007)	SVM
	Cost estimation (Petroutsatou <i>et al.</i> , 2011)	ANN
	Cost estimation (Jafarzadeh, Ingham and Wilkinson, 2014)	ANN
	Time-Cost estimation (Hola and Schabowicz, 2010)	ANN
	Prediction of cost performance (Son, Kim and Kim, 2012)	SVM
	Interval cost estimation (Cheng and Hoang, 2014)	SVM
	Building energy performance assessment (Kabak <i>et al.</i> , 2014)	FS
<b>Knowledge Based Systems</b>	Construction cost estimation (Ji, Park and Lee, 2011)	CBR
	Cost estimation for public road planning (Choi <i>et al.</i> , 2013)	CBR
	Construction bid decision making (Chua, Li and Chan, 2001)	CBR
	Overcoming problems in pavements (Mosa <i>et al.</i> , 2013)	ES
	Checking of models and schedules (Zhang <i>et al.</i> , 2013)	DSS
	Cost estimation (Kim and Kim, 2010)	CBR
	Building cost estimation (Lee, Kim and Yu, 2014)	Ontology
<b>Evolutionary Algorithms</b>	Cost estimation (Kim <i>et al.</i> , 2013)	CBR
	Cost optimization (Augusto, Mounir and Melo, 2012)	GA
	Construction time-cost optimization (Li and Wang, 2009)	ACO
	Optimization of composite structures (Omkar <i>et al.</i> , 2011)	ABC
	Optimising building thermal design (Wright, Loosemore and Farmani, 2002)	GA
	optimizing supply locations (Tam, Tong and Chan, 2001)	GA
	Time-cost-resource optimization (Ghoddousi <i>et al.</i> , 2013)	GA
	Water resource management (Afshar <i>et al.</i> , 2015)	ACO
	Construction time-cost optimization (Zhang and Ng, 2012)	ACO
<b>Hybrid Systems</b>	Estimating Construction Waste (Lee, Kim and Kim, 2016)	ANN+ACO
	Optimization for building retrofit (Asadi <i>et al.</i> , 2014)	GA+ANN
	Prediction of cost estimates (Kim, Seo and Kang, 2005)	ANN+GA
	Cost estimation (Yu and Skibniewski, 2009)	ANN+FS
	Cost estimation (Cheng, Tsai and Hsieh, 2009)	ANN+GA+FS
	Time-cost-quality trade-off in construction	FS+PS
	Prediction of cost and schedule (Zhang and Xing, 2010)	ANN+SVM
	Construction cost estimation (Cheng and Hoang, 2014)	LS+SVM

ANN – Artificial Neural Networks, SVM – Support Vector Machines, FS – Fuzzy System, CBR – Case Based Reasoning, ES – Expert Systems, DSS – Decision Support Systems, GA – Genetic Algorithm, ACO – Ant Colony Optimisation, ABC – Artificial Bee Colony, PS – Particle Swarm, LS – Least Square

ANN is an ML technique that imitates the learning capability of human brain using a collection of artificial neurons. Evidence from literature shows that ANN outperforms SVM in construction related tasks (Zade and Noori, 2008; Kim *et al.*, 2013). The most common ANN algorithm is backpropagation, which helps to train the ANN quickly. As highlighted by Hegazy *et al.* (1994), a

major setback of backpropagation is that it does not have efficient methodology for identifying suitable parameter settings. As such, optimisation methods such as gradient-descent, Genetic Algorithm (GA), Ant Colony Optimisation (ACO) are used to overcome this challenge.

Deep learning is also becoming popular because of its capacity to extrapolate new features from a limited set of features. Based on the concept of neural networks, deep learning is creating renaissance in the Artificial Intelligence (AI) world. Deep learning allows the development of computational models with multiple processing layers to learn data representation with multiple levels of abstraction. This equips the technique to identify intricate structures in large datasets. As such, the internal parameters are changed to compute the representation in each layer from the representation in the previous layer. Types of deep learning architectures include deep neural networks, deep Boltzmann machines, recurrent neural networks, deep neural networks, convolutional deep neural networks, deep belief networks, and long short-time memory.

Another ML technique that is becoming popular is Association Rule Learning (ARL). Since the introduction of association rule learning by Agrawal *et al.* (1996), it has been employed in several field especially in market basket analysis. The idea behind association rule learning is to uncover shared attributes among objects of a database. Association rules learning seeks to find associations and correlation among set of objects in the database. Uncovering associations in a large database is a difficult and expensive procedure because it requires series of iterations of database scans. As such, efficient algorithms are required to achieve the association rule-learning task.

### ***3.7.3.2 Knowledge Based Systems***

Knowledge based system (KBS) are software programmes that mimic human domain experts in finding solutions to a complex problem. KBS are developed to provide high intelligence level and to simulate real-life scenarios in unknown situations (Turban and Aronson, 2005). Types of Knowledge Based Systems include expert systems, Decision Support Systems (DSS), intelligent agents, intelligent tutoring systems. DSS uses interactive, flexible, adaptable, computer based information system to replicate human's ability to analyse decision alternatives for optimum performance in a situation. DSS and ES could be distinguished within four primary areas, which

are objectives, operation, users and development methodology (Ford, 1985). While Expert Systems (ES) aim at replacing human efforts, DSS focuses on supporting rather than replacing human effort in the decision making process (Arnott and Pervan, 2005).

The architecture of a KBS is presented in Figure 3.8. The architecture shows the components of a KBS, which are knowledge base, inference engine, working memory, self-learning, explanation engine and user interface. The knowledge base stores knowledge of various forms as elicited from several sources by the knowledge engineer. The inference engine is engaged to find solutions to specific problems using computational intelligence and reasoning capabilities (Sahota and Jeffrey, 2005). The explanation engine provides explanation of the reasoning process or a justification for a decision. The users interact with the system via a user interface, which uses human computer interactions and human language processing facilities (Liang, 1987). During the problem solving process, there is a self-learning mechanism, which serves as a feedback to modify the content of the knowledge base as required (Liu *et al.*, 2009).

The development process of a DSS and ES are shown in Figure 3.9. The process starts with the characterisation of the domain, identification of knowledge sources as well as the gathering of the users' requirements. Thereafter, techniques such as literature review, interviews, and protocol analysis are employed to elicit knowledge from various source. The elicited knowledge is then represented within a knowledge base using approaches such as rules, frames, semantic networks, ontologies, and graphs. After which the implementation of the inference engine commences by employing reasoning techniques such as rule based reasoning, case based reasoning, artificial neural networks, and evolutionary computation.

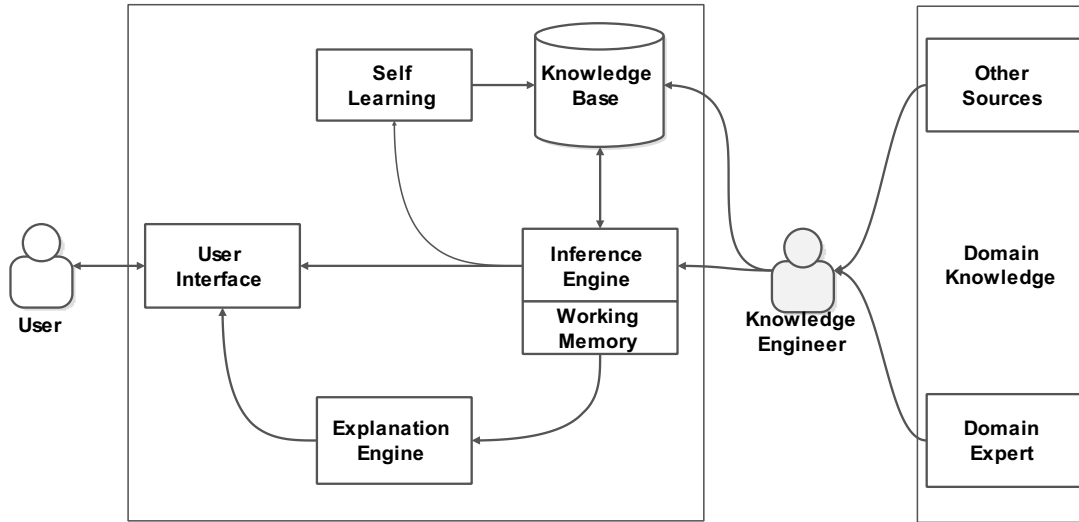


Figure 3.8: Architecture of a Knowledge Based System

A key task in the development of knowledge-based systems is knowledge representation. The process involves the representation of adequate information about a domain of interest in a form that is usable by computers to solve complex problems (Boose, 1989). Knowledge representation primitives include rules, frames, semantic networks, and ontologies. The aim of these primitives is to organise knowledge in a way that could be effectively manipulated and interpreted. In addition, hybrid primitives exist, which combine basic knowledge primitives to create more complex knowledge elements. The knowledge representation primitives are discussed below.

Rules organise knowledge into precedent-antecedent (premise-conclusion) pairs, which are built using IF-THEN blocks (Lanzola, Quaglini and Stefanelli, 1995). The precedent is a condition that must be met and the antecedent describes the tasks that must be executed in sequence. The precedent is a Boolean expression, which must result into a TRUE or FALSE. The Boolean expression could contain multiple clauses, which are connected by logical operations like NOT, AND, OR, XOR, and XNOR. For example:

$$\text{IF mat is Timber OR mat is Concrete THEN façade is Aluminium Cladding} \quad (3.1)$$

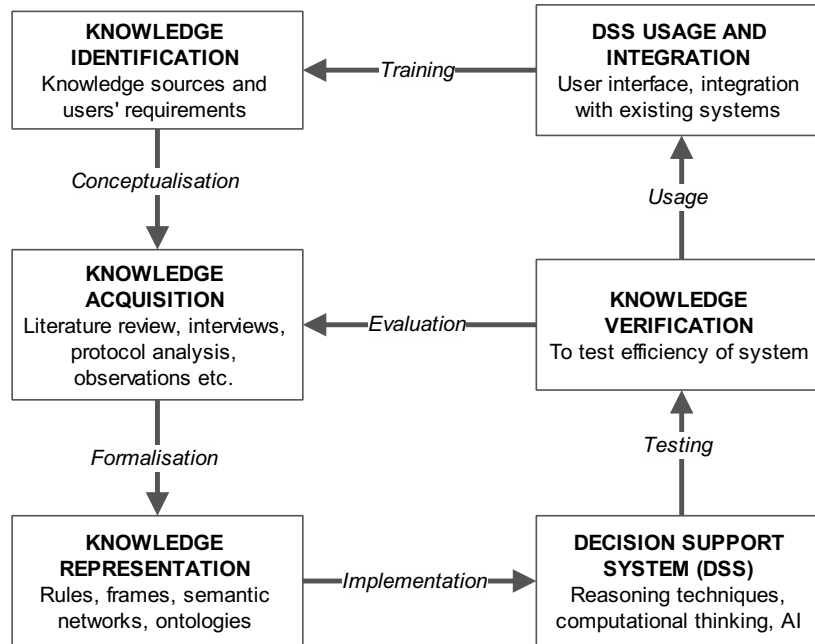


Figure 3.9: Processes in Knowledge Based System Development

The statement in Equation 3.1 clearly represents a piece of reusable knowledge because it states that Aluminium cladding will be used if the condition that “*material is timber or concrete*” is TRUE. This form of structure is a simple knowledge representation scheme, which is well understood. However, a large rule-based knowledge representation model will require an equal amount of rules and time to maintain its consistency (Akerkar and Sajja, 2010).

Using frames is a hierarchical way of mimicking human knowledge and reasoning, which organises knowledge using IS-A relationships (Minsky, 1975). This makes a frame more structured way of knowledge representation than rules (Davis, Shrobe and Szolovits, 1993). The main strength of frame is that it allows a combination of procedural and declarative knowledge within the same structure and reduces complexity by allowing hierarchical organisation of frames. However, using frames could be inefficient as it does not provide an efficient way to store data (Russell and Norvig, 2010).

The limitation of rules and frames led to the development of more structured knowledge representation techniques. Structured knowledge encapsulates the conceptual notion that knowledge relies on entities to be represented as well as the interrelationships among the entities. In most cases, this type of structure is achieved through a graph by representing entities as nodes and relationships as edges/vertices. As such, semantic networks allow knowledge to be represented as directed graphs to represent conceptual relationships among entities. A more robust structured knowledge network is ontology (Corcho, Fernández-López and Gómez-Pérez, 2003). Ontology is a commonly used term in analytical philosophy and computer science with conflicting definitions. The broad use of ontology from a philosophical perspective is associated with the study of being. However, in computer science studies, ontology refers to formal structured systems used to represent knowledge about a particular concept (Gruber, 1993).

### **3.7.3.3 Evolutionary Algorithms**

Evolutionary techniques are bio-inspired AI techniques that use metaheuristics to find solution to a complex problem (Fogel, 2006). According to Blum and Roli (2003), metaheuristics combines basic heuristics to explore search space of a problem for a solution at a reasonable computational cost. However, heuristics are very difficult to generalise (Fogel, 2006). This means that evolutionary techniques cannot guarantee optimality and it cannot determine how far a solution is from optimum. Despite this limitation, evolutionary techniques are very effective for solving highly complex problems such as optimisation and classification problems (Banzhaf, 2013; Eiben and Smith, 2015). The main strength of evolutionary techniques is that they require little domain-specific information and that they are easy to implement.

According to de la Fraga *et al.* (2011) the process of general evolutionary algorithm is as follows:

- a) Generate the population of Parents: The first step in the identification of potential parents for reproduction. This involves the identification of a set of possible solutions to the problem using a random process. The solutions are benchmarked with the objective functions and the solutions that best represent the function are selected

- b) Produce new breeds of offsprings by evaluating the fitness of parent: A selection mechanism is used to select mating individuals. The selection process is usually based on the fitness of each individual.
- c) Generate new offsprings: The selected parents are mated to produce new offsprings. These offsprings are evaluated in the next iteration.
- d) Repeat the regenerational steps until termination: Process (1) to (3) are repeated until a termination condition is met.

Most evolutionary algorithms are based on a variation of the above process. For example, GA performs crossover whereas evolutionary programming uses only mutation. Other evolutionary algorithms include Ant Colony Optimisation (ACO), Artificial Bee Colony (ABC), Particle Swarm Optimisation (PSO), and Differential Evolution (DE).

#### ***3.7.3.4 Hybrid Systems***

The development of hybrid systems is a promising research field of modern AI that is concerned with the creation of next generation of intelligent systems (Abraham, 2005). Hybrid systems integrate multiple AI techniques to find a synergetic solution to a specific problem. According to Grosan and Abraham (2011), Hybrid Systems are employed to overcome specific limitations of individual techniques and to combine their strengths. For example, intelligent systems such as Fuzzy Inference System (FIS), which provides human-like problem solving mechanism, may be more suited to domain knowledge representation, uncertainty handling, and adaptation to noisy data but lack good learning ability (Zadeh, 1998). However, machine learning techniques such as NN are uncertainty nor imprecision intolerant. According to Mohanty et al. (2013), hybridization of these AI techniques could therefore produce a more powerful intelligent system for tackling practical computing problems. The motivation to the development of intelligent systems is the awareness that combined approaches might be necessary for solving complex AI problems. Abraham (2003) noted that hybridization of AI techniques has resulted into outstanding results in different areas of study, which include decision support, image recognition, and process control. According to Abraham (2005), the integration of AI techniques has evolved to the development of several intelligent system architectures. Examples of common hybrid systems include Neuro-

Fuzzy systems (NN+FIS) (Jang, 1993), Genetic Fuzzy Systems (EC+FS) (Gordon *et al.*, 2001), Fuzzy Expert Systems (FIS-ES) (Otto, 1990), and Evolutionary Neural Networks (EC+NN) (Yao, 1993; Abraham, 2004). Hybrid systems employ an ad-hoc design methodology that is justified by the success of the system in certain application domains (Abraham, 2005). Comparison of strengths and weaknesses of specific AI techniques alongside hybrid systems is shown in Table 3.5.

Evidence shows that it is crucial in the development of hybrid systems to focus on the integration of existing AI techniques than creation of new techniques (Abraham, 2005; Melin *et al.*, 2007; Heemels *et al.*, 2009). As such, well-understood techniques should be integrated to address weaknesses of complementary methods. This makes the development of hybrid intelligent systems an open-ended concept rather than restricting it to the possible combination of a few AI techniques. The architecture of hybrid system could be classified into four, which are stand-alone, transformational, hierarchical hybrid and integrated hybrid systems (Abraham, 2003) as presented in Table 3.6.

Table 3.5: Comparison of Different AI Techniques


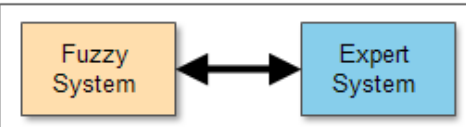
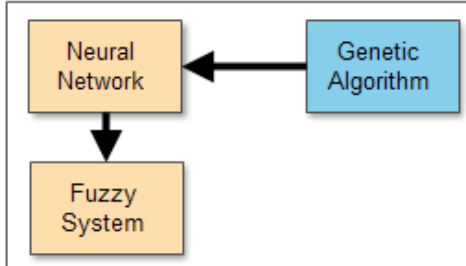
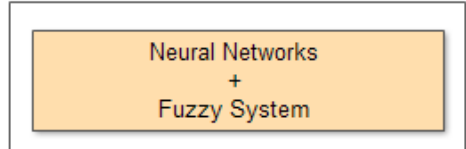
	NN	FIS	ES	GA	NN+FIS	FIS+ES	GA+NN
<i>Adaptability</i>	■	■	■	■	■	■	■
<i>Expert knowledge</i>	■	■	■	■	■	■	■
<i>Explanation ability</i>	■	■	■	■	■	■	■
<i>Fault tolerance</i>	■	■	■	■	■	■	■
<i>Imprecision tolerance</i>	■	■	■	■	■	■	■
<i>Knowledge discovery</i>	■	■	■	■	■	■	■
<i>Knowledge representation</i>	■	■	■	■	■	■	■
<i>Learning ability</i>	■	■	■	■	■	■	■
<i>Maintainability</i>	■	■	■	■	■	■	■
<i>Mathematical model</i>	■	■	■	■	■	■	■
<i>Non-linearity</i>	■	■	■	■	■	■	■
<i>Optimisation ability</i>	■	■	■	■	■	■	■
<i>Real-time operation</i>	■	■	■	■	■	■	■
<i>Uncertainty tolerance</i>	■	■	■	■	■	■	■

Fuzzy symbolic terms used for ranking: ■ – Bad; ■ – Slightly bad; ■ – Slightly good; ■ - Good



According to Abraham (2003), integrated architectures are the true form of hybrid systems. They include systems, which combine different AI techniques into one single system. This approach allows the AI techniques to share data structures and knowledge representations. According to Grosan and Abraham (2011), the benefits of integrated models include robustness, improved performance and increased problem-solving capabilities. In addition, fully integrated hybrid models provide capabilities such as adaptation, generalization, noise tolerance, and justification (Abraham, 2005). Major limitation of integrated hybrid systems is the increased complexity of the inter-module interactions and specification. As such, designing, and building fully integrated hybrid models is a complex task.

Table 3.6: Classification of Hybrid Systems

Classification	Description	Graphic
1 <i>Stand-alone</i>	Stand-alone hybrid models consist of independent AI techniques, which do not interact, in any way. This approach is efficient for comparing the problem solving capabilities of different AI techniques.	
2 <i>Transformational</i>	Transformational hybrid system begins with an AI technique and ends up with the other.	
3 <i>Hierarchical</i>	Hierarchical hybrid system is built in a hierarchical fashion, associating a different functionality with each layer.	
4 <i>Integrated</i>	Integrated hybrid systems combine different techniques into one single computational model. The techniques share data structures and knowledge representations.	

### 3.8 Summary

This chapter presents a detailed discussion of the concepts and benefits of BIM in the construction industry. The three underpinning concepts of BIM are collaborative practices, technology as digital delivery vehicle, and integrated project data. UK BIM maturity levels and the significance of BIM in the changing UK construction industry were also discussed. Thereafter, review of BIM platform was presented. The review of BIM platforms reveals the dominant market position of Revit and its popular choice for BIM application development. This is because Revit platform provides robust API that helps to extend Revit functionalities and it is compatible with several BIM and CAD platforms. Afterwards, key features of BIM that are relevant for CW management were identified and discussed. The key BIM features for CW management are: (i) team communication and integration, (ii) parametric modelling and visualisation, (iii) building performance analysis and simulation, (iv) automatic document generation, (v) improved building lifecycle management, and (vi) software interoperability with other applications. BIM development tools were also discussed. The categories of tools that were discussed include IFC development tools and BIM software API.

The chapter also discusses the theoretical underpinning for the study. The study integrates theories from various field to fulfil the epistemological and heuristic requirement of the study. It was pointed out that the study majorly stems from the Dartmouth conference on the issue of machine intelligence. Other theories include tragedy of the commons, theories of evaluation practices, and evidential reasoning theories. These theories were used to formalise design-out-waste strategies and to develop a mechanism to predict areas of possible waste reduction in the early design stages. Pointedly, none of the theories is robust enough to fulfil the requirements of the proposed system. As such, the goal of the study is not to verify these theories or use them to develop another theory. However, their combination was employed to accomplish the aim of the study.

The last part of the chapter focuses on AI system development techniques. This part discusses four main groups of AI models, which are machine learning techniques, knowledge based systems, evolutionary algorithms, and hybrid systems. After a review of extant literature on AI model development techniques, it was revealed that integrated hybrid systems provides the robustness

needed for solving complex real-life problems. Integrated hybrid models combine different AI techniques into one single system for the AI techniques to share data structures and knowledge representations.

The next chapter contains the research methodology adopted to achieve the objectives of the study. As such, the next chapter presents the research design for the mixed methods study. The justification for employing the research strategy as well as the data collection and analysis procedure are also discussed.

## 4 RESEARCH METHODOLOGY

### 4.1 Overview

This chapter presents a detailed discussion of critical choice of methodology adopted to accomplish the objectives of the study. The chapter presents the research design adopted for the mixed methods study that incorporates results from qualitative data analysis into the design of the quantitative inquiry. The justification for employing this research strategy as well as the data collection and analysis procedure are also presented. An overview of the research methodology is given in Table 4.1. The study adopted critical realism as a theoretical perspective in the spirit of methodological plurality, which allows retrofitting of methods from competing paradigms. The chapter starts with a discussion of the philosophical perspective adopted in the study and presents justifications for the choice of critical realism. After this, discussion of the following is presented: rationale for research approach, description of research sample, details of the research design, data collection and analysis methods, ethical considerations, and issues of data validity and reliability.

The later part of the chapter contains model and software development methodologies. A review of extant literature on software development reveals that there are several methodologies and deciding among the available options is not trivial. As such, five software development methodologies, which are waterfall model, incremental development, spiral development, agile programming, and Rapid Application Development (RAD) were reviewed. RAD methodology was adopted because the project is of small-to-medium scale and of short duration. In addition, the objectives of the study and the user groups are well defined.

Table 4.1: Critical Choice of Methodology

<b>Area of Choice</b>	<b>Available Methodology</b>	<b>Methodology</b>	<b>Justification</b>
<b><i>Theoretical Perspective</i></b>	Positivism, constructivism, critical theory, critical realism	Critical Realism	Critical realism allows the retrofitting of methods from positivism and constructivism.
<b><i>Methodology Strategy</i></b>	Narrative research, phenomenology, grounded theory, ethnography, action research, case study, experiment, survey research	Phenomenology Survey Research	Phenomenology is suitable as it recognises the importance of human experience regarding a phenomenon as elicited from a domain expert. Survey research allows the verification of claims over a large population sample.
<b><i>Method of Enquiry</i></b>	Qualitative, quantitative, mixed methods	Mixed Methods	Mixed method allows the use of both qualitative and quantitative data in the same research.
<b><i>Type of Mixed Methods Design</i></b>	Exploratory sequential, explanatory sequential, parallel sequential	Exploratory Sequential	The study started with qualitative approach and proceeded to quantitative approach, (Creswell, 2014).
<b><i>Research Logic</i></b>	Inductive, deductive, retroduction	Retroduction	The study builds on theoretical frameworks as a way of exploring the mechanisms responsible for a phenomenon. Thus, the adoption of retroduction.
<b><i>Data Collection Methods</i></b>	Archival records, interviews, focus group interviews, direct observation, physical artefacts, questionnaire, participatory observations	Archival Records Focus group interviews Questionnaire	Qualitative data was collected through interviews, focus group interviews, and direct observations to provide an insightful understanding of the phenomenon under study. Quantitative data was collected through questionnaires to verify the identified factors using a larger sample size.
<b><i>Data Analysis Methods</i></b>	Various techniques	Thematic analysis, reliability analysis, factor analysis	Thematic analysis was used to uncover recurring themes in FGI transcripts. Factor analysis was used to identify dimensions in quantitative data
<b><i>System Development Framework</i></b>	Dynamic systems development method Rapid Application Development Evolutionary rapid development	Rapid Application Development	Rapid application development starts with the development of a prototype that was modified and adapted to fit the specific needs of stakeholders. This encourages the reuse of software components and rapid response to users' needs.

## **4.2 Research Paradigms**

Research Paradigms determine how the world and associated phenomena are perceived, understood, and interpreted. Within social science field of study, paradigms are also referred to as theoretical perspectives (Crotty, 1998), research methodologies (Neuman, 2009), and worldviews (Creswell, 2014). However, the term research paradigm is adopted in this study to represent the perceived view of the world. Paradigms are set of logically organised assumptions, concepts, and propositions that shape the thinking of researchers (Bogdan and Biklen, 1998). This therefore necessitates the adoption of a paradigm to ground a research in a consistent way. As such, paradigms provide foundational beliefs that guide the frames of reference that researchers use to choose of research strategies and methods as well as ontological and epistemological requirements (Guba and Lincoln, 1994). This means that research paradigm addresses issues in research that relates to ontology, epistemology, research methodology, and logic of reasoning.

### **4.2.1 Ontological and Epistemological Requirements of the Study**

Ontology provides explanation about the nature of social reality (Crotty, 1998). It is a study of being and it reflects how researchers interpret a phenomenon. As such, ontology helps to know what actually exists, the nature of what exists, the constituents of what exists, and the interactions amongst the constituents (Blaikie, 2007). This helps individuals to ascertain whether an entity is real or relative in a social setting. Realism holds when social phenomenon could exist independent of social actors. On the other hand, relativism holds when reality is constructed in active correspondence with social actors. Based on the aim of the study to construct an instrument for CW management at the design stage, a realist ontology was adopted. This is because it is widely believed in the AEC industry that CW could be managed using well-established procedures. This assumption reveals that there exist design-based approaches (either known or unknown) that could be used to achieve low waste building project. This brings to the fore the need to develop a tool that is independent of any social actor. The foregoing reveals that relativism could not underpin the study as an ontological assumption.

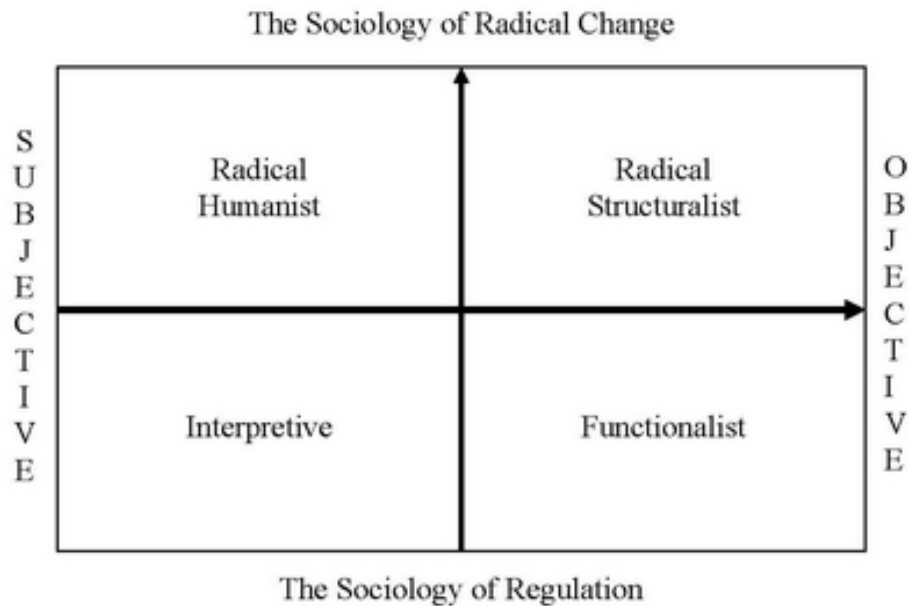
The epistemological stance of a study depicts the ways through which knowledge could be apprehended (Neuman, 2009). There are two basic epistemological perspectives, which are objective and subjective epistemologies (Crotty, 1998). Objective epistemology requires that research should be independent of the researcher and that an entity could be studied without being influenced or influencing the entity (Guba and Lincoln, 1994). As such, Objectivists use pre-defined research instrument, such as questionnaires and structured interview among others, for data collection. Subjective epistemology requires that the researcher ensure a distance from the phenomenon being investigated. This means that the phenomenon under study must be investigated without influencing it (Burrell and Morgan, 1979). Thus, this makes the research independent of the researcher because subjective epistemology opined that reality and meaning are inter-subjectively constructed (Burrell and Morgan, 1979). This means that the world can only be socially reconstructed while understanding it. Thus, subjective epistemology advocates adequate interaction between the researcher and the phenomenon being studied.

Based on the objectives of the study, the two ways of knowing are relevant to the study. At the start of the study, subjective epistemology is employed to gain in-depth understanding into existing CW management practices and tools. In addition, it provides insights into the expectations of industry practitioners on the use of BIM for CW management. This helps to identify list of factors, which could be further tested through an objective epistemology. As such, the later part of the study adopts objective epistemology to ensure that the results are representative of the research population (Creswell, 2014). A research instrument was thereby developed and distributed to many participants.

#### **4.2.2 Available Research Paradigms**

Several frameworks exist for understanding research paradigms. Two key frameworks are those proposed by Burrell & Morgan (1979) and Guba & Lincoln (1994). The framework proposed by Burrell and Morgan (1979) organises research into ‘mutually exclusive views of the social world’, which include functionalist, interpretive, radical structuralist, and radical humanist paradigms as shown in Figure 4.1. This classification has a much narrower perspective on paradigms and incommensurability debate than Kuhn’s definition (Kuhn, 1970). However, this rigid view

requires researchers to adopt a single paradigm and strictly adhere with the thinking and methods the paradigms offers. As such, researchers are confined within the paradigmatic box and are forbidden to use strategies and methods from other research philosophy. This is because the four paradigms are contradictory to each other.



*Figure 4.1: Paradigms Framework Proposed by Burrell and Morgan (1979)*

On the other hand, the framework proposed by Guba and Lincoln sees paradigms as interrelated network of basic assumptions. The framework therefore addresses, to an extent, paradigmatic commensurability that is forbidden in Burrell and Morgan’s framework. Guba and Lincoln’s framework provides a succinct discussion of degree of accommodation allowed among the paradigms. Four paradigms were proposed, which are: positivism, postpositivism (critical realism), critical theory, and constructivism. A comparison of available paradigms in Guba and Lincoln’s framework is shown in Table 4.2. The framework proposed by Guba & Lincoln is adopted as a pivotal reference for this study and a brief discussion of these positions is presented in the following sections.



Table 4.2: Comparison of Alternative Inquiry Paradigms

Item	Positivism	Critical Realism	Critical Theory	Constructivism
<b>Inquiry Aim</b>	Explanation: Prediction and Control		Critique and emancipation	Understanding reconstruction
<b>Nature of Knowledge</b>	Verifiable hypotheses	Non-falsifiable hypotheses	Historical insights	Individual reconstruction
<b>Ontology</b>	Naïve realism	Realism	Historical realism	Relativism
<b>Epistemology</b>	Objectivist: Findings true	Modified Objectivist: Finding probably true	Subjectivist: Value mediated finding	Subjectivist: Created findings
<b>Methodology</b>	Quantitative methods: Experiments/surveys	Quantitative + qualitative methods: Convergent interviews, triangulation	Dialogic/ dialectical: A transformative activity to change the social world	Hermeneutical/ dialectical:
<b>Quality criteria</b>	Internal and external validity, reliability		Historical situatedness	Trustworthiness and authenticity
<b>Accommodation</b>	Commensurable		Incommensurable	

Adapted from Guba & Lincoln (1994)

#### 4.2.2.1 Positivism

Positivism, as a dominant paradigm in social science inquiry (Gray, 2009), represents the belief that the world exists independent of the researcher. As such, the researcher measures entities without influencing them. Moreover, findings in positivist paradigm are considered valuable if only it could be tested empirically (Crotty, 1998). Literature review reveals that construction project management as a research area developed from a positivist paradigm and realist ontology (Crawford and Pollack, 2004; Pollack, 2007). Philosophical links has been established among positivism, Project Management Book of Knowledge (PMBOK), and project management as a field of inquiry (Bredillet, 2004). Many construction project management studies place emphasis on reductionist techniques and objectivity that is underpinned by naïve reality. This may be because of project management is perceived as a measure of performance and a rejection of subjectivity (Leandri, 2001). While focusing on objectivity and perfectly apprehendable reality, the world is seen as a measurable entity in positivism (Neuman, 2009). This allows the researcher to collect quantitative data using an instrument (such as sampling measurement, archival

documents, and questionnaires) and use the data objectively rather than relying on subjective judgements. In such studies, the researcher ensures a distance from the phenomenon being investigated without influencing it (Guba & Lincoln, 1994).

Positivism remains the dominant methodological perspective in construction management studies. As such, researchers employ quantitative methods such as questionnaires (Ahadzie, Proverbs and Sarkodie-Poku, 2014; Hartono *et al.*, 2014), regression analysis (Ghapanchi, Wohlin and Aurum, 2014; Liu and Wang, 2014), structural equation modelling (Bernroider, Wong and Lai, 2014; Ding, Ng and Li, 2014), and experimental designs (Iorio and Taylor, 2014; Ishii, Takano and Muraki, 2014).

#### **4.2.2.2 Constructivism**

Constructivism is in total contrast with positivism; thus, rejecting its objectivist claims. This stance opposes the claim that there is a single truth, which could be accurately discovered or apprehended. As such, constructivism sees meaning as entities constructed through the active engagement of human beings with the phenomenon being studied (Crotty, 1998). Thus, findings and meanings are creations of the researcher's mind through a subjectivist lens (Neuman, 2009). In rejection of the positivist view, more studies in construction project management are becoming aligned towards constructivism paradigm. This clearly shows a "paradigm shift" within the construction project management inquiry, which has been dominated by positivism for a long time. Researchers adopting constructivism as a paradigm employ methodologies such as grounded theory (Aubry, Richer and Lavoie-Tremblay, 2014; Davies and Mackenzie, 2014) and ethnography (Maier and Branzei, 2014; Musca *et al.*, 2014). In addition, adopting qualitative methods such as interviews (Ahern, Leavy and Byrne, 2014; Fulford and Standing, 2014), direct observation (van den Ende and van Marrewijk, 2014; Liu and Wilkinson, 2014), and focus group discussion (Magnaye *et al.*, 2014).

A major criticism of constructivism is that, the concept of truth is socially constructed and relative (Guba and Lincoln, 1994). As such, what is considered true in a social setting may be regarded as false in other social formations. This therefore could be illustrated with the notion of "*we may see*

*the same thing and have different experiences.*” Beliefs therefore may simultaneously exhibit a true and false status. Another criticism is the issue of generalizability in social constructs. Findings of constructivism within a small group may lack applicability to a wider population.

#### **4.2.2.3 Critical Theory**

Critical theory has a completely different perspective from positivism, constructivism, and critical realism. Critical theory is a critique to currently held values and it challenges prevailing social structures (Gray, 2009). Critical research is best seen as a conquest for change and empowerment of the marginalised. As such, research within a critical theory perspective takes the form of criticism of ideologies. Critical theory therefore employs dialogic and dialectic methodologies (Guba & Lincoln, 1994). Dialogic in the sense that the perspective requires a dialogue between the researcher and the subject of inquiry, and dialectic by providing a reasoning mechanism that obtains the truth through exchange of logical arguments. This may be to transform ignorance or emancipate marginalised small voices (Guba and Lincoln, 1994). Critical theory studies employ methods such as historical insights (Lenfle, 2014; Kwak *et al.*, 2014), dialectic methods (Winch, 2014; Braglia and Frosolini, 2014), case study (Sage, Dainty and Brookes, 2014; Yang and Fu, 2014).

#### **4.2.2.4 Critical Realism**

Owing to the discussions of the limitations of both positivism and constructivism, a way out is the adoption of a view that allows a retrofitting of the two approaches. This is in support of the adoption of critical realism. Critical realism therefore allows a combination of methods from positivism and constructivism. Critical realism is a criticism to positivism; in fact, critical realism seeks to amend the limitations of positivism. Nevertheless, objectivism stands as an epistemological view of both positivism and critical realism. Pointedly, critical realism amends the conventional positivist belief system to accommodate elements of constructivism (Guba and Lincoln, 1994). Positivism is concerned with a single real reality and constructivism is concerned with multiple specific constructed realities, therefore critical realism is essentially concerned with multiple perception of a single conscience-independent reality (Healy and Perry, 2000). As such,

critical realism combines features of both positivism and constructivism. This perspective therefore subjects real objects to value laden observations.

Critical realism as a paradigm extends positivism beyond the conscience-free reality, which is probabilistically discoverable, to allow experience based mechanisms. Therefore, both quantitative and qualitative methodologies are permissible in critical realism researches. As such, a mixture of methods such as case studies, interviews, surveys, and statistical analysis techniques are allowed. This approach is known as triangulation (Denzin, 1970). In the current literature, critical realism is also referred to as neopostpositivism or realism (Krauss and Putra, 2005). However, the term critical realism encompasses current discussions on realism, postpositivism, and neopostpositivism.

Critical realism researchers may choose to combine interviews with questionnaire survey (Cheng, 2014; Tasevska, Damij and Damij, 2014), experimental designs (Yang, 2014), structural equation modelling (Yang, Huang and Hsu, 2014; Feng *et al.*, 2014), or system dynamics (Zhang *et al.*, 2014). This perspective is becoming popular because it gives researchers more freedom in the choice of methods.

#### **4.2.3 Adopted Research Paradigm for the Study**

From the critical evaluation of the paradigms, a positivist paradigm is not a viable choice. This is because the researcher needs to immerse himself/herself in the experience of the researched to understand how he thinks. As such, the study is not only concerned with prediction and control, in fact understanding too plays a major role in this case. Reconstructing the designers' world is needed to understand the form of knowledge for designing out waste. This therefore points in the adoption of constructivism in the construction of the design out waste strategies; however, it is also confronted by challenges that have been discussed. Owing to the rigour and flexibility that critical realism paradigm offers, the study therefore adopts a critical realism philosophical standpoint that focuses on applications that work in obtaining a solution to a problem (Onwuegbuzie and Leech, 2005). Thus, critical realism empowers researchers with all available resources to understand the research problems. This helps researchers to focus their attention on

the research problems and using pluralistic approaches to extract knowledge to the solution of the problem (Morgan, 2007).

Critical realism, as a philosophical underpinning, is not committed to one system of reality. As a result, it confers on the researcher the freedom of choice among methods, procedures, tools, and techniques that best suit the need and purpose of the research. Thus, this gives the researcher the liberty to use data collection and analysis methods from both quantitative and qualitative approaches. This therefore makes critical realism the most appropriate for this study within a mixed methods research design.

Within a critical realism viewpoint, mixed methods research combines both quantitative and qualitative research approaches to meet the needs of a larger audience (Smith, 1997). A comparison of qualitative and quantitative research methodologies is presented in Table 4.3. A mix of this research approaches is beneficial as organisational decisions are mostly made by multiple individuals with different philosophical background and diverse interests and perspectives on the validity or/and credibility of information (Patton, 1997). Some of the individuals may believe that positivist studies are the most reliable information while others may believe that constructivism provides a more authentic representation of information. This may result to a conflict of interest on which of the two types of information, quantitative or qualitative, will be used for decision-making.

Critical realism, as a mixed methods philosophy, is equipped to address the practical challenges and uncertainties of research (O’Cathain, Murphy and Nicholl, 2007). Thus, critical realism allows researchers to combine the benefits of conflicting philosophical perspectives in seeking solution to a particular problem. As popularly acknowledged in the literature, positivist and constructivist philosophical worldview have serious limitations. Critical realism therefore addresses these limitations by allowing critical retrofitting of beneficial strategies from the two paradigms.

*Table 4.3 Comparison of Qualitative and Quantitative Research*

<b>Property</b>	<b>Qualitative</b>	<b>Quantitative</b>
<b>Philosophical assumptions</b>	Constructivist, Interpretivist	positivist, functionalist
<b>Epistemological positions</b>	Subjective	Objective
<b>Nature of data</b>	Textual	Numerical
<b>Research Focus</b>	Meanings	Facts
<b>Reasoning</b>	Inductive: Theory generation	Deductive: Theory testing
<b>Purpose</b>	To gain understanding of underlying prevalent trends in social or human problems.	To examine the relationship among variables.
<b>Sample</b>	A small number of non-representative cases.	A large number of cases representing the population of interest.
<b>Research Design</b>	Narrative research, grounded theory, ethnography, phenomenology, case study	Experiment designs and survey research
<b>Data Collection</b>	Participant observation, semi and unstructured interview, focus group interviews, case study	Structured interview, questionnaires, experiments
<b>Data Analysis</b>	Non-statistical	Statistical
<b>Scope of Findings</b>	Nomothetic	Ideographic

### 4.3 Research Strategy and Methods

There are several strategies to conducting research and the literature abounds with contradictory claims regarding the appropriate research approach for specific research problems (Creswell, 2014; Neuman, 2009). As such, considerable effort is required in choosing the appropriate research approach and methods in response to the research questions. This is to enable the researcher to properly plan while considering the research paradigm, research strategies and methods. Three types of research approaches are commonly used in social science enquiries, which are quantitative, qualitative, and mixed methods.

### 4.3.1 Qualitative Research

Qualitative research mostly adopts an inductive approach that is concerned with theory generation. In this form of research approach, textual data are most appropriate. The research process starts data collection and analysis to identify themes towards theory creation (Gray, 2009). The major strength of qualitative research strategies is that they provide more depth into the phenomenon under investigation; however, it requires a long time to accomplish. The most widely used qualitative research strategies are ethnography, grounded theory, phenomenology, and case study.

*Ethnography* is a research methodology where the researcher is in contact with a cultural group in natural settings over a long time (Denscombe, 2014). This allows researchers to collect observational data as well as artefacts in support of a fact. Thus, the strategy provides an in-depth understanding of the research questions. Ethnography allows researchers to understand what the cultural groups under study do and how they do it. The major strength of ethnography is its flexibility and access for lived realities (Walford, 2010); however, it requires a long period to conduct. Primary research methods often employed include observation (participant and non-participant) and interviews.

*Grounded theory* is a research strategy in which a theory of process or behaviour is derived and grounded in the views of the participants (Creswell, 2014). This strategy adopts an inductive reasoning approach towards theory generation. On the other hand, *phenomenology* involves an investigation into participant's worldview and experiences. As such, the researcher's experience is suppressed to understand the experience of the participants. Research methods commonly in grounded theory and phenomenology include semi-structured and unstructured interviews.

Stake (2005) and Simons (2009) argues that *case study* is not a method of choice but a choice to focus on the case for a period for an in-depth exploration. According to Yin (2009), case studies are employed in research for several reasons that include: (a) when the focus of a research study is to seek answers to "how" and "why" types of questions; (b) when the researchers have no control over the behaviour of those under study; (c) when researchers want to learn more on the contextual conditions relevant to the phenomenon under study; and (d) when researchers need to understand the boundaries between the subject of study and the context. All these four reasons provide a

justification for the inclusion of case studies in this study. Pointedly, case studies help to demonstrate how theories work in reality and to test whether a particular theoretical approach will work under specific settings. Two varieties of case study approaches exist, which are single, case study and multisite case studies. Single case study employs a single site of study while multiple case studies employs data from multiple sites using multiple methods and multiple data analysis approaches. A multisite case study is selected for this study because it provides a holistic view of a complex phenomenon and provides a wide range of generalizability (Denscombe, 2014).

### **4.3.2 Quantitative Research**

Quantitative research mostly adopts a deductive research approach that is concerned with hypothesis/theory testing and examining relationships among variables. The research process starts with the formulation of hypotheses or conceptual models, informed by theories and literature, and followed by data collection and analysis to verify the prior formulations (Gray, 2009). This approach is in support of the adoption of a positivist theoretical perspective (Creswell and Clark, 2007). The major strengths of quantitative research strategies are that they do not require a long time in data collection and quantitative data analysis techniques are quite familiar.

The most widely used quantitative research strategies are experimental designs and survey research. Survey is the most widely adopted research strategy in construction project management studies. Survey research provides a powerful mechanism to investigate a phenomenon using a representative sample of the entire population. Survey enables the numeric description of opinion and trend (Creswell, 2014), as such, helping to generalise from a sample to a population. Galiers (1992) argues that surveys help to identify more variables/factors than experimental approaches. The major data collection instrument used in surveys is questionnaire, which could contain closed-ended and/or open-ended questions.

The most common questionnaire surveys are self-administered and posted questionnaires but web-based questionnaire (using services such as SurveyMonkey, QuestionPro, and KwikSurveys) are becoming popular. Using a web questionnaire helps to ensure good practice, encourage



completion, reduce potential errors and to aid data processing/analysis (Bhaskaran and LeClaire, 2010).

### 4.3.3 Mixed Methods Research

Mixed methods research strategy involves the combination of both qualitative and quantitative data in a research. In this way, both forms of data are collected and analysed to gain a deeper insight into the research problem. Although several terms are used to refer to this approach, such as multi-methods, mixed methodology, integrating methodology, and quantitative and qualitative methods, however, the term mixed methods strategy is the most used in recent times (Tashakkori and Creswell, 2007). Mixed methods became popular in the early 1990 (Creswell, 2014) among researchers in education, health sciences, demography, sociology, and management. This is because mixed methods allow the comparison of different perspectives drawn from both qualitative and quantitative data. And the use of both qualitative and quantitative research methods in a single study has been proved to be more effective than a single strategy (Sandelowski, 2000; Brannen, 2005). As such, maximising the merits of both qualitative and quantitative strategies while minimising the limitations of both strategies. As such, mixed methods strategy primarily draws on the concept of triangulation where different data sources are examined for evidence to build research themes.

Although there are several typologies for classifying mixed methods strategies, three basic classifications are common, which are: (i) ***Convergent Parallel Mixed Methods***: Which starts with both qualitative and quantitative data concurrently and comparing results; (ii) ***Explanatory Sequential Mixed Methods***: which starts with quantitative data collection and analysis followed by qualitative data collection and analysis; and (iii) ***Exploratory Sequential Mixed Methods***: Which starts with qualitative data collection and analysis followed by quantitative data collection and analysis (Creswell, 2014).

#### 4.4 Exploratory Sequential Mixed Methods Design

This study adopts an exploratory sequential mixed method design as shown in Figure 4.2. An exploratory sequential mixed method is a research design that starts with the exploration of qualitative data and then using the findings to inform the quantitative data collection and analysis. It is generally believed that qualitative data provides an in-depth understanding of the research problem with specific samples of the population. Exploratory sequential therefore allows the researcher to test whether the results from few individuals can be generalized to a larger population.

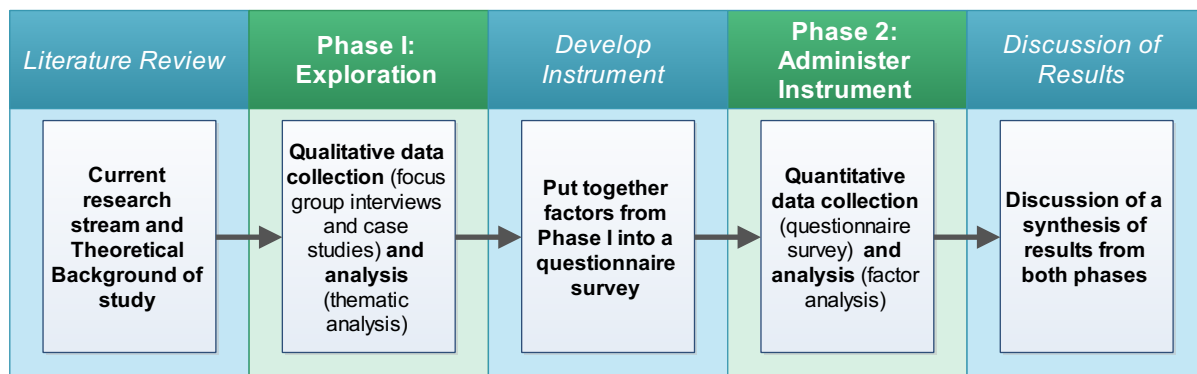


Figure 4.2: An Overview of the Sequential Exploratory Mixed Method Design Process

The purpose of the exploratory sequential mixed methods study is to formalise and represent design-out-waste strategies, and provide an artefact (such as software) equipped with adequate mechanism to support architect during the design process. The study starts with a review of extant literature to identify prevailing design-out-waste strategies, strength, and weaknesses of existing construction waste management tools. This is with the intention of compiling a list of evaluation criteria and waste management expectations of BIM into a holistic framework.

Multiple data collection methods were used to obtain an in-depth understanding of the phenomenon and triangulation strategy was used to corroborate evidence obtained from data (Denzin and Lincoln, 2000). The sequential exploratory mixed method design approach consists of two distinct phases, which are:

**PHASE 1: Qualitative data collection and analysis** – After an extensive review of literature, this phase used phenomenology approach to collect textual data through focus group interviews. The data was analysed using appropriate coding scheme to uncover the themes and structures within the data. The results of the analysis from this phase was used to develop an instrument with good reliability and validity.

**PHASE 2: Quantitative data collection and analysis** – This phase built on the results of the initial qualitative data collection and analysis. Quantitative data was collected using questionnaire survey and the data was subjected to exploratory factor analysis. The goal of this phase is to help rank the factors obtained from Phase 1 according to their significance in designing-out construction waste.

The results obtained from the two phases were then synthesised and used to discuss the outcome of the entire study. Prior to the qualitative phase 1 of the study, review of extant literature was done by compiling of relevant papers (on construction waste management strategies and tools) from peer reviewed journals. This was followed by a filtering process to ensure the papers match the research scope. This was done by scanning the titles and abstract, and imposing certain exclusion criteria to remove papers outside the scope of this study. As such, publications on nuclear/radioactive waste, municipal solid waste and waste from electronic and electrical equipment were excluded. The scope of the literature review is to include publications that have direct impacts on construction waste reduction. After the filtering process, a cross-examination of the identified papers was done by manually scanning through the references cited. The literature review was done with the aim of identifying: (a) current research streams in CW management, (b) current strategies for designing out construction waste, (c) strengths and weaknesses of existing CW management tools, and (d) BIM requirements for CW management. All these provide an expository overview of the current waste management practices within the construction industry.

Methods of collecting qualitative data include interviews, focus group interviews, direct observation, participatory observation, and case studies (Hancock, Ockleford and Windridge, 1998). These qualitative data collection methods facilitate in-depth study and detailed understanding of a phenomenon using a small sample size. However, qualitative data collection requires a great deal of time to plan and the data analysis/interpretation also requires a level of

expertise and experience. Therefore, after a thorough review of extant literature on existing waste management strategies and tools (software and toolkits), a qualitative study involving Focus Group Interviews (FGI) with professionals within the top UK construction industry was carried out. The FGIs provide the avenue to bring together real-life project team participants with the aim of discussing different ways by which construction waste related issues are addressed. The choice of FGIs were made as over individual interviews with participants, since it allows participants to express their personal opinions based on their experiences and allows participants to build on responses by others. Thus, FGIs enables deeper insights into group thinking and shared beliefs (Creswell, 2014).

FGI was selected to provide a wide access to a range of evaluation criteria beyond those identified in the literature. It would also help to confirm the validity and applicability of the criteria discussed in the literature before been used to develop a BIM framework for waste management. The FGIs would also help to identify the perception and expectations of BIM and industry needs of construction waste management tools, and to understand the role of BIM-based technologies in the adoption and implementation of construction waste management strategies and tools. The FGIs was proactively moderated by the research team to maintain openness and contributions from every member of each FGI.

The discussion by each group was based on how the team have employed strategies and tools in mitigating against construction waste in different projects. The participants were encouraged to discuss openly the attributes that have been useful for effective construction waste prevention and reduction. Interaction among the participants of the FGIs was recorded and later compared alongside all the notes taken to ensure important information is captured. After this exercise, a list of design-out-waste factors was compiled and put together in a questionnaire survey. The questionnaire survey was carried out to validate our finding from the literature review, FGIs and case studies on a larger sample.

## **4.5 Ethical Considerations**

The research does not target any group of people that require special ethical considerations. Since the research involves professionals (contractors, architects, suppliers, and lean practitioners), only the privacy, confidentiality, and anonymity of FGIs participants and questionnaire respondents are required. During the literature review, all sources of scholarly information was accurately referenced. Sources of data was also acknowledged during research dissemination to ensure data reliability.

During the FGIs, the research complies with the Economic and Social Research Council (ESRC) ethical requirements by seeking appropriate ethical permission for the study. Accordingly, the consent of the participants was sought before conducting the FGIs. A consent note was developed to provide participants with the purpose of the research, their role in the research, how the data was protected, and how their privacy and confidentiality was ensured. The consent note provides an opportunity to participants to see the interview transcript before analysis. The analysis of the interview transcripts adopts a coding scheme to protect the respondents' privacy, confidentiality, and anonymity. Data from the FGIs was also securely protected against theft or unauthorised usage. Likewise, the first section of the questionnaire survey provides respondent with information such as the purpose of the research as well as how data will be stored, used, and destroyed.

## **4.6 Software Development Methodologies**

Following the development of appropriate hybrid system for CW prediction is the development of BIM software to implement the models. As such, a software development methodology is required to plan and manage the activities of the development process. It also provides a means of tracking specific deliverables across the software development lifecycle (Livermore, 2007). Geambaşu *et al.* (2011) highlights that there are several factors that could influence the choice of software development methodology. These factors include software complexity, team size, cost, and clarity of requirement. A review of extant literature on software development reveals that there are several and deciding among the available options is not trivial. This section reviews five software

development methodologies, which are waterfall model, incremental development, spiral development, agile programming, and Rapid Application Development (RAD).

#### **4.6.1 Waterfall Model**

Waterfall model is a traditional and the most basic methodology in software development. It is a sequential methodology where software development is carried out as a steady flow of activities. According to Royce (1970), basic principle of waterfall model follows three stages, which are: (a) Division of project into sequential phases, (b) Planning of time, cost, and resources for the entire system at the beginning, and (c) Tight control of resources is maintained over the development lifecycle of software. Despite its simplicity, a major criticism of waterfall methodology is that it does not allow a prior phase to be revisited after completion. This makes the approach to be inflexible and it seldom result in cost overrun. In addition, waterfall methodology requires clarity of system specification and requirement at an initial stage. Therefore, clients that do not know the exact requirement and may change their requirement as development progresses may hinder the success of this approach (Parnas and Clements, 1986). Changes during development could eventually lead to system redesign, and redevelopment, which will eventually increase the costs. It has also been shown that cost overrun may be inevitable because software developers may be unaware of future challenges that would be encountered as the development process proceeds in a strict waterfall model framework.

#### **4.6.2 Incremental Development**

Incremental software development reduces project risk by breaking software development project into series of linked mini projects. Each mini project helps to add specific functionality to the system. The mini projects also provide ease of incorporating changes to requirements during the software development process. Incremental development could be done in different ways. The first variant is completing a series of mini-waterfall tasks for various parts of the system. The second variant is defining the overall requirement for the system before starting series of mini-waterfall development for each component. A major weakness of incremental development is that there is no consideration of the business needs and the technical requirements for the entire system

especially when parts of the system are implemented using waterfall approach (CMS, 2005). Another limitation is that difficult tasks tend to be implemented towards the end of the project to demonstrate early success.

### **4.6.3 Spiral Development**

Spiral development methodology combines some key aspect of the waterfall model and rapid prototyping methodologies (Boehm, 1988). As such, spiral development helps to combine the strengths of top-down and bottom-up software development concepts. CMS (2005) highlights four principles of spiral development as follows:

- 1) Risk assessment: This is done by dividing the project into smaller segment. This enables ease of incorporating changes and risk evaluation
- 2) A cycle involves the same sequence of steps.
- 3) Each segment transverses a spiral using the following steps: (i) determine objectives and alternatives (ii) evaluate alternatives, (iii) verify deliverables, and (iv) start next iteration (Boehm, 1988)
- 4) Stakeholders are identified and a new cycle begins.

A key limitation of spiral development methodology is that it is difficult to know the composition of methodologies to adopt during each cycle (CMS, 2005). As such, project managers that are highly skilled and with many years of experience are required to apply spiral development in projects. In addition, since there are no firm deadlines, the cycles continue with no clear termination condition. This means there is the risk that the project may not be completed to budget or to time (Boehm, 2000).

### **4.6.4 Agile Programming**

According to Nerur *et al.* (2005), Agile software development seeks to overcome the limitations of traditional development methodology such as Waterfall, iterative, and spiral developments. The term "Agile Programming" was coined in the Agile manifesto of 2001 (Fowler and Highsmith,

2001). The basic principle of agile programming is using simple practices to encourage the engagement of developers, managers, and clients (Thomas, 2005). As such, the software evolves over time as client's and managers' requirements change without need for application rebuild. The main Agile programming methods are Extreme Programming (XP), Crystal methodologies, Dynamic Software Development Methods, Feature-driven development, Lean Software development and Scrum (Abrahamsson *et al.*, 2002). However, Extreme Programming (XP) is most widely used because it shares the same values of the Agile Manifesto (Lindstrom and Jeffries, 2004).

According to Beck (1999), XP is a software development methodology that mitigates risk at all levels and to the needs of small teams dealing requirements that are vague and that could change. Kircher *et al.* (2001) highlights 12 practices of XP, which are planning game, small releases, metaphor, simple design, testing, refactoring, pair programming, collective ownership, continuous integration, 40-hour week, on-site customer, and coding standard. These XP practices are based on assumptions that developers have close physical proximity with each other and that the development theme has close customer engagement. Although it is possible for team members to work in a distributed environment (Kircher *et al.*, 2001). According to Turk *et al.* (2002), limitations of agile programming methods is limited support for: (i) subcontracting, (ii) reusable artefacts, (iii) large teams (iv) developing safety-critical software, and (v) developing complex software.

#### **4.6.5 Rapid Application Development**

Rapid Application Development (RAD) methodology condenses software development process to produce high quality system with relatively low costs than traditional (Beynon-Davies *et al.*, 1999). This methodology enables software developers to adjust quickly to changing customers' needs in a dynamic market (Agarwal *et al.*, 2000). Changes are allowed during the development process because the methodology divides software development into smaller components and it associates specific deliverable and deadline to each component. Accordingly, priority is assigned to the components to know which of the requirement can be completed within the time assigned (Coleman and Verbruggen, 1998). RAD could be seen as a hybrid methodology, which has



features of spiral development process. RAD requires active correspondence between the development team and users to obtain software delivery in a quick way. Key steps in the development of software system using RAD are:

- a) User requirement gathering using methods such as case studies and focus group;
- b) Development of a prototype and early iterative involvement of end-users in design testing.
- c) Design and user interface improvement to next software version release using a rigidly paced schedule; and
- d) Active correspondence with end users for software reviews. This runs in parallel to the software development process.

RAD methodology was adopted due to the nature of the study. Considering that the project is of small-to-medium scale, of short duration favours the choice of RAD, and that the objectives of the study and the user groups are well defined. Considering that functionalities of the proposed system are clearly visible at the user interface also reveals that RAD will engender active user involvement. In addition, RAD methodology offers several benefits, which include quick software delivery time, reduction in development costs, and mitigation of risks by including the end users in the development team. As such, RAD allows end users to interact with prototypes of the system from early development stages. This seamlessly helps to incorporate changing requirements into the system in a quick way.

## **4.7 Summary**

In summary, this chapter provides a detailed description of the research methodology for the study. The study adopted a critical realism philosophical viewpoint and employed a mixed method research design. The sequential exploratory mixed method study starts with qualitative data collection and analysis followed by the quantitative data collection and analysis. Two data-collection methods were employed, including focus group interviews, and questionnaire survey. The data were reviewed against literature as well as emergent themes. Validation and reliability were accounted for through various strategies, including source and method triangulation. As such, the result of the qualitative analysis was developed into a questionnaire survey to verify the

identified factors with a larger population. The later part of the chapter focused on model and software development methodologies. A detailed discussion of ANFIS as an integrated hybrid system was presented. The structure and description of the components of ANFIS were also presented. After that, software development methodologies were discussed. A review of extant literature on software development reveals that there are several and deciding among the available options is not trivial. As such, five software development methodologies, which are waterfall model, incremental development, spiral development, agile programming, and Rapid Application Development (RAD) were compared. RAD methodology was adopted due to its nature of the study. Considering that the project is of small-to-medium scale and of short duration favours the choice of RAD.

This next chapter assesses the expectations of stakeholders on BIM strategies for CW management analytics. Understanding the expectations of stakeholders is an important consideration for the deployment and acceptance of BIM-based practices for CW management within the construction industry. As such, the next chapter contains a discussion of the data collection and analyses processes.

# 5 HOLISTIC BIM FRAMEWORK FOR CONSTRUCTION WASTE MANAGEMENT

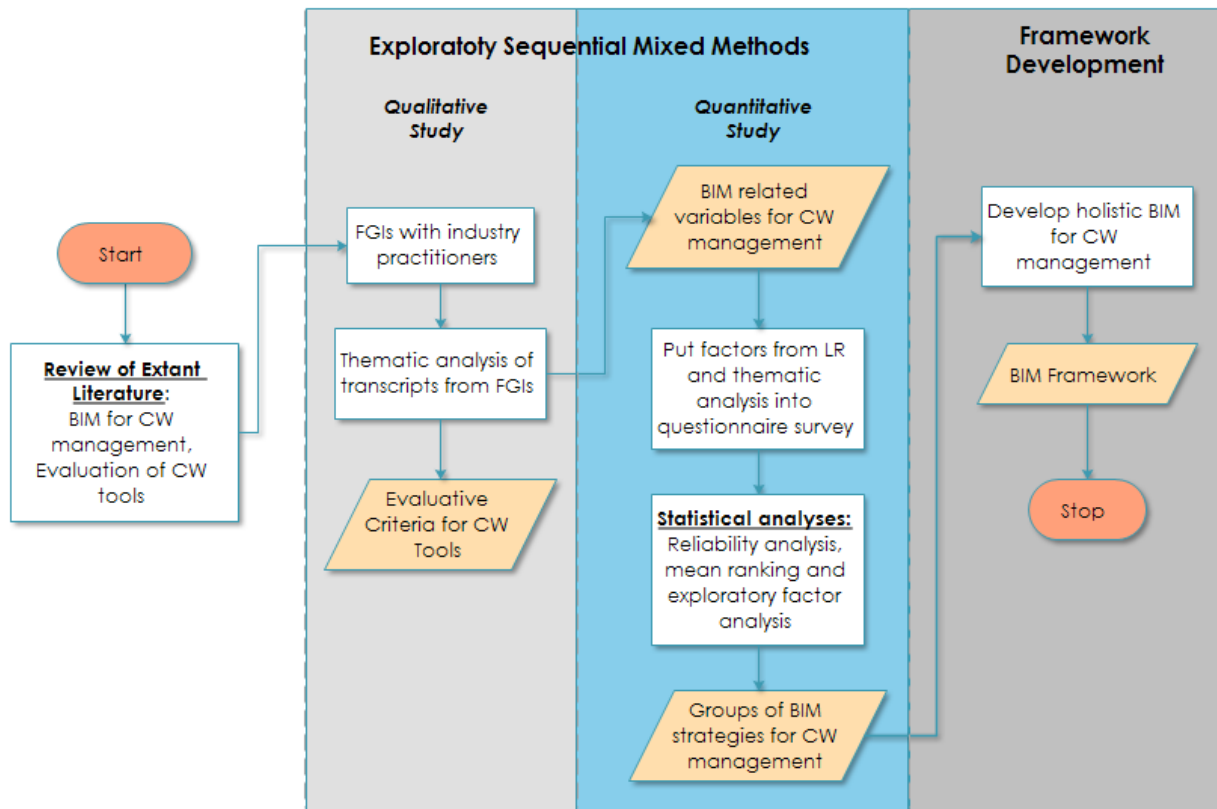
## 5.1 Overview

The need to use BIM for CW management is well documented but most of the existing CW management tools still lack BIM functionality. This chapter therefore assesses the expectations of stakeholders on BIM strategies for CW management analytics. The methodological flowchart for the process is shown in Figure 5.1. After a review of extant literature on the limitations of existing CW management tools and, qualitative FGIs were conducted with professionals who are familiar with the use of BIM. The variable identified from the qualitative data analyses were then developed into a questionnaire survey. The exploratory factor analysis of the responses reveals five major groups of factors, which include “*BIM-based collaboration for waste management*”, “*waste-driven design process and solutions*”, “*lifecycle waste analysis*”, “*Innovative technologies for waste intelligence and analytics*”, and “*improved documentation for waste management*”. Considering these groups of factors is key to meeting the needs of the stakeholders regarding the use of BIM for CW management. These groups of factors are also important considerations for the deployment and acceptance of BIM-based practices for CW management within the construction industry. Taking into the expectations of industry practitioners, a holistic BIM framework for a CW management system was developed to integrate industrial and technological requirements for waste management.

## 5.2 Sampling Techniques

Following Creswell (2014) critical sampling was used during the Focus Group Interviews (FGIs) to the yearning for generalisation and applicability of finding from this study. Critical sampling allows researchers to use a set of criteria to select information-rich participants (Gay, Mills and Airasian, 2006). As such, four FGIs was conducted with 23 participants from the construction industry. These participants were selected owing to their responsibilities in mitigating against

waste generation and ensuring best practices for waste management. In addition, the participants were chosen from construction companies who have incorporated BIM completely or partially into all their activities' stream. Conducting five FGIs with these four themes was based on the rule of triangulation, which ensures wider validity of the research and its findings, to give more depth and balanced view of the phenomenon being studied.



*Figure 5.1: Methodological flowchart*

In the administration of the questionnaire survey, the directories of waste practitioners within the UK construction industry, provided by the industrial partner was used. Thus, this helps to reach a larger research sample. First, a purposeful selection strategy was used based on certain distinguishing criteria. The criteria include technical experience of construction waste management, year of experience, occupation (architects, design engineers, sub-contractors, material suppliers, waste contractors, project managers, and site managers), and practitioners from

companies that have fully or partially implemented BIM. After this, a random selection strategy was employed to administer the questionnaire survey.

### **5.3 Qualitative Data Collection**

After identifying the limitations of existing CW management tools, a qualitative interpretative study was carried out to understand how effective design out waste process could be achieved by employing current capabilities of BIM. According to Creswell (2014), a qualitative interpretative methodology seeks to extract common meaning from the experiences of several individuals. According to Moustakas (1994), two data collection methods dominates qualitative interpretative research are in-depth interviews and FGIs. In-depth interview is conducted to elicit participants' perspective of a phenomenon, while focus group interview particularly involves discussion among selected group of participants regarding a common experience (Hancock, Ockleford and Windridge, 1998). This study employed FGIs over individual interviews with participants since FGIs allow participants to discuss their personal opinions based on their experiences. Conducting an FGI also allows participants to build on responses of others. This provides deeper insights into a wide range of perspectives within a short time.

Accordingly, multiple FGIs were conducted with participants selected from the UK construction companies who have partially or fully implemented BIM on their projects. The sampling was done in a way that individuals who are directly involved in building design, BIM, and construction waste management were chosen. Although the stakeholders are not specialists in BIM tool development, understanding their views and expectations could help to uncover and analyse the industry requirement of BIM in CW management across different disciplines. In addition, end users are key in the engineering of any useful innovation development (Oyedele, 2013) and their views and expectations need to be taken into consideration. Accordingly, 23 professionals were selected based on suggestion of Polkinghorne (1989) who recommended that FGI participants should not exceed 25. The distribution and the range of years of experience of the participants of the focus groups are shown in Table 5.1.

Table 5.1: Overview of the focus group discussions and the participants

<i>FG</i>	<i>Categories of participants</i>	<i>No of participants</i>	<i>Years of experience</i>
<i>FGI1</i>	<i>Architects and design managers</i> <ul style="list-style-type: none"> <li>• 3 design architects</li> <li>• 1 site architects</li> <li>• 2 design managers</li> </ul>	5	12 – 20
<i>FGI2</i>	<i>M&amp;E Engineers</i> <ul style="list-style-type: none"> <li>• 2 design engineers</li> <li>• 2 site engineers</li> </ul>	4	9 – 22
<i>FGI3</i>	<i>Construction project managers</i>	5	12 – 22
<i>FGI4</i>	<i>Civil and structural engineers</i> <ul style="list-style-type: none"> <li>• 1 design engineer</li> <li>• 3 site based engineers</li> </ul>	5	8 – 18
<i>FGI5</i>	<i>BIM specialist</i>	4	8 - 12
<b>Total</b>		23	

Participants of the FGIs were encouraged to discuss expectations of BIM concerning construction waste management. This was done with the aim of understanding the possibilities of addressing limitations of existing waste management tools with the current capabilities of BIM. The question guide for the FGIs is shown in Appendix A. Discussion and interactions among participants were recorded on a digital recorder and later compared with notes taken. This is to ensure that all important and valuable information to the study were captured. Afterward, the voice recordings were transcribed and segmented for thematic analysis. These tasks were conducted to develop clusters of meanings by themes identification.

## 5.4 Qualitative Data Analysis

In descriptive interpretive research, data analyses follow structured methods, which starts with the description of researchers' own experiences followed by the description of textual and structural discussions of participants' experiences (Creswell, 2013). This allows the researcher to move from a narrow unit of analysis to broader units. According to Moustakas (1994), descriptive interpretive research follows a concise analytical approach as summarised in Table 5.2.

Thematic analysis was carried out using appropriate coding scheme to identify units of meaning from significant statement and to classify them into recurring themes. The coding scheme employs four tags, which are discipline, context, keywords, and theme category. Discipline coding classification shows the job role of the participant that provided a transcript segment. Context coding depicts the circumstances informing a transcript segment. The context coding classification include: (i) *New* – marks the start of a new subject of discussion; (ii) *Response* – signifies a response to a question; (iii) *Build-up* – shows when a contribution to an ongoing discussion is made; and (iv) *Moderator* – marks a control segment provided by the moderator. Keyword coding classification depicts a summary of the main issue raised within a segment. This helps to identify prevalent issues and concerns across the transcript. The keywords are underlined within the quotation segments. The theme category shows the principal theme under which the issue discussed in the transcript segment falls. Example of quotation classification based on this coding scheme is shown in Table 5.3.

*Table 5.2: Descriptive interpretive analysis process*

<b>Step</b>	<b>Analytical Method</b>	<b>Activity</b>
1.	Describe personal experience with phenomenon.	This is important to set aside personal experiences and to focus on participants' experiences.
2.	Develop a list of significant statements from interview transcripts.	<ul style="list-style-type: none"> <li>• Transcribe voice data to written statements.</li> <li>• Identify quotations that explain participants' experiences with phenomenon.</li> </ul>
3.	Develop coding scheme for thematic analysis	<ul style="list-style-type: none"> <li>• Identify units of meaning using thematic analysis</li> <li>• Group significant statements into themes using coding scheme</li> </ul>
4.	Describe "what" participants experience with phenomenon	Carry out a textual description of participants' experiences with verbatim quotations.
5.	Describe "how" the experiences happened.	Carry out a structural description of the setting and context in which phenomenon was experienced.
6.	Synthesise "what" the participant experienced and "how" they experienced it	Carry out a composite description that contains the textual and structural descriptions

Table 5.3: Example of classification based on the coding scheme

No.	Quotation	Source	Discipline	Context	Theme category
1.	<i>“...We can then use the tools to determine the type and <u>volume of materials</u> that can be reused after deconstruction”</i>	<i>FGI 2</i>	<i>Design engineer</i>	<i>New</i>	<i>Quantification of recoverable material</i>
2.	<i>“...BIM can allow the <u>visualisation of building demolition and deconstruction process</u> during the design”</i>	<i>FGI 1</i>	<i>Design architect</i>	<i>Build-up</i>	<i>Visualisation of deconstruction process</i>

The results of the analyses suggest that it is important to adopt solutions available within tools used throughout the entire lifecycle of buildings in the implementation of a robust tool for CW management. This is to ensure effective management of CW scenarios right from the planning stages, through subsequent stages, i.e., design, construction, commissioning, usage, and maintenance stages. Arguably, the participants of FGI1 pointed out directions for the adoption of BIM for CW management as follows:

*A major breakthrough in the construction industry is the use of BIM packages to model, visualise and simulate building forms and performances. In fact, any useful innovation in the AEC industry must embrace BIM...*

*“... it is important that tools [construction waste management tools] are accessible within current BIM design tools used throughout the lifecycle of buildings...”*

These assertions imply that the CW management tools must be BIM compliant considering the current rate of BIM adoption in the industry. The participants echoed that integrating CW management into BIM would offer greater flexibility to influence waste performance analytics of buildings at a stage where design change is cheaper.



## **5.5 Evaluative Criteria for Construction Waste Tools**

Results of the thematic analysis reveal a list of 40 criteria that could be used to evaluate the performance of existing waste management tools and this was grouped under six categories, which are: (a) Group 1 denoted by waste prediction related criteria; (b) Group 2 denoted by waste data related criteria; (c) Group 3 denoted by commercial and procurement; (d) Group 4 denoted by BIM related criteria; (e) Group 5 denoted by design related criteria; and (f) Group 6 denoted by technological related criteria.

The evaluation criteria in each category are presented in the framework shown in Figure 5.2. To determine the performance merit of each tool, the 40 criteria were further used to evaluate the 32 waste management tools identified from the literature shown as shown in Tables 5.4 and 5.5. This is required as a major step in the logic of evaluation to benchmark the performance of the tools before a logical conclusion could be drawn. Thereafter, the identified evaluation criteria were used to develop a holistic BIM framework for construction waste management.

## **5.6 Quantitative data collection**

After the review of extant of literature and FGIs, 22 variables that relate to the use of BIM for CW management were identified. These variables were then organised into a questionnaire survey and a pilot study was carried out before sending the questionnaire out to the respondents. The participants of the pilot study include five architects and two construction project managers. The final version of the questionnaire is the developed by considering the comments received from the pilot study. The final questionnaire is shown in Appendix B.

### **5.6.1 Questionnaire Design**

The questionnaire survey started with a pilot study using a preliminary questionnaire. The preliminary questionnaire contains the compiled list of BIM strategies for CW management. A pilot study was conducted to assess the relevance, length, complexity, and layout of the questionnaire. The respondents of the pilot study were chosen from the UK construction industry

and they include architects, projects managers, site managers, and waste practitioners. The comments of the respondents were then used to produce the final questionnaire

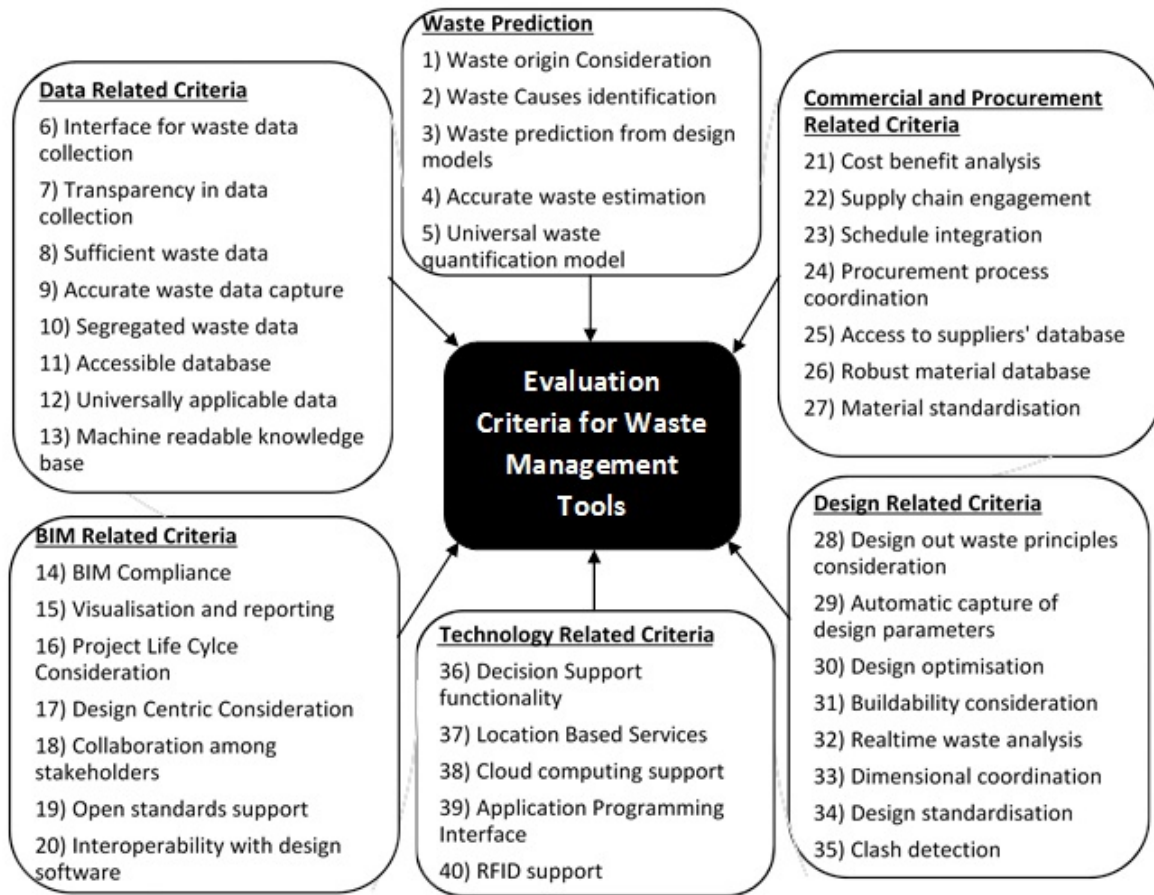


Figure 5.2: A Framework of Criteria for Evaluating the Performances of Waste Management Tools

The final questionnaire has three sections, which are:

**SECTION A: SURVEY COVER LETTER** - This section explained the purpose of the survey. The respondents were informed that the data collected would be used solely for academic purposes to encourage a high response rate. Likewise, the respondents were assured that the confidentiality of all individual's responses would be maintained.

Table 5.4: Evaluative Criteria for Existing Waste Management Tools (a)

Evaluation Criteria	Data Collection and Audit Tools	Waste Prediction Tools	GIS Tools	WM Quantification Models	WMP Templates and Guides
	1) Waste Control Tool (Formoso, 1999) 2) WMP Tool (McDonald and Smith, 1998) 3) CALIBRE (Chrysostomou, 2000) 4) Webfill (Chen <i>et al.</i> , 2003) 5) ConstructClear (Bluewise, 2010) 6) SMARTStart (BRE, 2007) 7) SMARTAndii (BRF, 2008) 8) True Cost of Waste Calc. (BRE, 2007)	9) SMARTWaste (Hobbs <i>et al.</i> , 2011) 10) Net Waste Tool (WRAP, 2009) 11) DoWT-B (WRAP, 2011c) 12) CW Estimation Sys. (Li and Zhang, 2013) 13) DeconRCM (Banias <i>et al.</i> , 2011) 14) Demolition Waste Tool (Cheng and Ma, 2013)	15) BREMan (BRE, 2009) 16) GPS-GIS Technology (Li <i>et al.</i> , 2007) 17) GIS-BIM Supply Chain Sys. (Irizarry <i>et al.</i> , 2013)	18) Waste Index (Poon <i>et al.</i> , 2001); 19) RWAS (Fikanavake and Ofori, 2005) 20) FPS (Shen <i>et al.</i> , 2005) 21) Component-Global Indices (Jalili, 2007) 22) Stock-Flow Model (Beragsdal <i>et al.</i> , 2007) 23) Spanish Model (Solis-Guzman <i>et al.</i> , 2009) 24) Mat. Flow Analysis Model (Cochran and Townend, 2010) 25) Universal Waste Ratio (Llatas, 2007) 26) System Analysis Model (Wang <i>et al.</i> , 2014)	27) Cost Effective WMP (Mill <i>et al.</i> , 2008) 28) SWMP (WRAP, 2008) 29) Material Logistic Plan (WRAP, 2007) 30) Design out Waste Plan (WRAP, 2007) 31) Procurement Guide (WRAP, 2010) 32) Demolition Protocol (ICE, 2008)
<b>Waste Prediction Related Criteria</b>					
1. Waste origin consideration	✓ ✓	✓ ✓ ✓			✓ ✓ ✓
2. Waste causes identification		✓ ✓ ✓			✓ ✓ ✓
3. Waste prediction from design		✓ ✓		✓ ✓ ✓ ✓ ✓ ✓ ✓	
4. Accurate waste estimation					
5. Universal waste quantification model				✓	
<b>Waste Data Related Criteria</b>					
6. Interface for waste data collection	✓ ✓ ✓ ✓ ✓ ✓	✓			✓ ✓
7. Transparency in data collection	✓	✓			✓ ✓
8. Sufficient waste data					
9. Accurate waste data capture					
10. Segregated waste data					
11. Accessible waste database					
12. Universally applicable data				✓ ✓	
13. Machine readable knowledge base					
<b>BIM Related Criteria</b>					
14. BIM compliance*			✓		
15. Visualisation and reporting			✓		
16. Project lifecycle consideration			✓		
17. Design Centric consideration*		✓ ✓	✓		✓
18. Collaboration among stakeholders*			✓		
19. Open standards support			✓		
20. Interoperable with design software*			✓		

Table 5.5: Evaluative Criteria for Existing Waste Management Tools (b)

Evaluation Criteria	Data Collection and Audit Tools	Waste Prediction Tools	GIS Tools	WM Quantification Models	WMP Templates and Guides
	33) Waste Control Tool (Formoso, 1999) 34) WMP Tool (McDonald and Smithers, 1998) 35) CALIBRE (Chrysostomou, 2000) 36) Webfill (Chen <i>et al.</i> , 2003) 37) ConstructClear (Bluewise, 2010) 38) SMARTStart (BRE, 2007) 39) SMARTAudit (BRE, 2008) 40) True Cost of Waste Calc. (BRE, 2010) 41) SMARTWaste (Hobbs <i>et al.</i> , 2011) 42) Net Waste Tool (WRAP, 2009) 43) DoWT-B (WRAP, 2011c) 44) CW Estimation Sys. (Li and Zhang, 2012) 45) DecomRCM (Banias <i>et al.</i> , 2011) 46) Demolition Waste Tool (Cheng and Ma, 2013) 47) BREMap (BRE, 2009) 48) GPS-GIS Technology (Li <i>et al.</i> , 2005) 49) GIS-BIM Supply Chain Sys. (Irizarry <i>et al.</i> , 2013) 50) Waste Index (Poon <i>et al.</i> , 2001; 2004) 51) BWAS (Ekanayake and Ofori, 2004) 52) EPS (Shen <i>et al.</i> , 2005) 53) Component-Global Indices (Jalili, 2006) 54) Stock-Flow Model (Beragsdal <i>et al.</i> , 2006) 55) Spanish Model (Solis-Guzman <i>et al.</i> , 2006) 56) Mat. Flow Analysis Model (Cochran and Townend, 2010) 57) Universal Waste Ratio (Llata, 2011) 58) System Analysis Model (Wang <i>et al.</i> , 2011) 59) Cost Effective WMP (Mill <i>et al.</i> , 2000) 60) SWMP (WRAP, 2008) 61) Material Logistic Plan (WRAP, 2007) 62) Design out Waste Plan (WRAP, 2007; 2009) 63) Procurement Guide (WRAP, 2010) 64) Demolition Protocol (ICE, 2008)				
<b>Commercial and Procurement Related Criteria</b>					
21. Cost Benefit Analysis Functionality*	✓ ✓	✓			✓
22. Supply chain engagement*				✓	✓
23. Schedule integration					✓
24. Procurement process coordination					✓
25. Access to suppliers' database*					✓
26. Robust material database*					✓
27. Material Standardisation					✓
<b>Design Related Criteria</b>					
28. Design out waste principles considerations		✓ ✓ ✓ ✓ ✓		✓	✓
29. Automatic capture of design parameters*					
30. Design optimisation*					
31. Buildability consideration					
32. Real-time design waste analysis*					
33. Dimensional Coordination*					
34. Design standardisation					
35. Clash detection					
<b>Technology Related Criteria</b>					
36. Decision support functionality*		✓ ✓ ✓			
37. Location based services			✓ ✓ ✓		
38. Cloud computing support					
39. Application Programming Interface (API)					
40. RFID support			✓		

Note: \*Additional criteria identified from focus group interviews

**SECTION B: PARTICULARS OF RESPONDENT** - This section captures information about respondents. The respondents were asked to indicate information such as type of organisation, job title, and years of experience. This would enable the research team to identify the roles of the respondents within the construction industry.

**SECTION C: BODY OF QUESTIONNAIRE** - This section allows respondents to rate the BIM strategies for CW management factors. The respondents were asked to consider each factor with relevance to their perceived competence and to rank their importance on a five-point Likert scale ranging from 1 (not Important) to 5 (most Important). This section also includes a textbox for additional comments from the respondents.

The respondents of the survey were required to indicate the importance of the variables on a five-point Likert scale, where 1 represents '*not important*' and 5 represents '*most important*'. The questionnaire was then developed into a web-based questionnaire to encourage completion, reduce potential errors and to aid data analysis. By employing the directory of a UK construction company, 130 respondents were randomly selected for the survey. Table 5.6 shows the demographic distribution of the respondents. The response rate of the survey was 47.7%, which indicates that only Sixty-two (62) completed questionnaires were submitted. Three of the submitted questionnaires were incomplete and discarded, thus leaving only 59 usable responses for analyses (45.4%).

## **5.7 Quantitative Data Analyses**

The variables from the qualitative data analyses and from the literature review were then put together into a questionnaire survey and analysed accordingly. The responses of the questionnaire survey were then subjected to a rigorous statistical process to identify the expectations of industry stakeholders for BIM adoption for CW management. The statistical analyses include descriptive statistics, reliability analysis, and exploratory factor analysis.

Table 5.6: Demographics of survey respondents

Variables	Sample size
Total questionnaire sent out	130
Total of submitted responses	62 (47.7%)
Discarded responses	2
Total number of usable responses	59 (45.4%)
Years of experience in construction industry	
0 – 5 years	6
6 - 10 years	10
11-15 years	20
16-20 years	13
21 - 25 years	6
Above 25 years	4

### 5.7.1 Reliability analysis and Descriptive Statistics

Reliability analysis was carried out to check if the 22 variables in the survey and the associated Likert scale consistently reflect the construct the study is set out to measure (Field, 2005). Accordingly, Cronbach’s alpha coefficient of reliability ( $\alpha$ ) was calculated for the variables using Equation (1).

$$\alpha = \frac{N^2 \overline{COV}}{\sum_{i=1}^N S_i^2 + \sum_{i=1}^N COV_i} \quad (5.1)$$

Where N is the total number of variables;  $\overline{COV}$  is the average covariance between variables;  $S_i^2$  and  $COV_i$  are the variance and covariance of variable ‘i’ respectively. The Cronbach’s  $\alpha$  has a value from 0 to 1 and the higher the value of  $\alpha$ , the greater the internal consistency of the data (Field, 2005). It is generally believed that a value of  $\alpha = 0.7$  is acceptable and  $\alpha > 0.8$  depicts good internal consistency. The calculated  $\alpha$  for this study is 0.915, which demonstrates a very good internal consistency of the data. The “Cronbach’s alpha if item deleted” of each variable was then examined to confirm that all the variables are contributing to the internal consistency of the data. It is good practice to delete variables whose “Cronbach’ alpha if item deleted” is higher than the overall coefficient to improve the overall reliability of the data. Accordingly, one of the variables was deleted. The remaining 21 variables were then ranked using descriptive statistical mean as

ratio of importance. The results of the reliability analysis and ranking of the variables is shown in Table 5.7.

*Table 5.7: Reliability analysis and ranking of critical factors for designing out waste*

No	Variable	Mean	Cronbach's alpha if item deleted	Rank
V14	Computer aided simulation scenario and visualisation of waste performance	4.82	0.909	1
V2	Embedding waste-related information into building model	4.64	0.915	2
V1	Decision-making on waste reduction during design	4.58	0.906	3
V12	Support for whole-life waste analysis	4.50	0.914	4
V7	Interoperability among waste management tools and software	4.48	0.907	5
V9	Early supply-chain integration for waste management decisions	4.36	0.907	6
V18	Foster task harmonisation among stakeholders to reduce duplication of effort	4.24	0.902	7
V6	Automatic generation of waste related documents	4.17	0.907	8
V3	Support for waste management innovations such as RFID, IoT, big data etc.	4.13	0.913	9
V4	Improved cost-benefit analysis of construction waste management	4.02	0.914	10
V13	Preservation of building information in COBie	3.92	0.910	11
V5	Improved materials classification methods	3.87	0.910	12
V19	Improved clash detection in building models to reduce waste	3.80	0.913	13
V11	Improved waste information sharing among stakeholders using BIM	3.73	0.906	14
V8	Automatic capture of design parameters for waste analysis	3.56	0.905	15
V21	Usage of BIM as a co-ordination tool for designing out waste	3.51	0.911	16
V22	Improved contractual document management	3.44	0.904	17
V15	Use of 3D printing for prefabrication	3.36	0.911	18
V10	Improved waste minimisation commitment among stakeholders	3.25	0.903	19
V16	Transparency of responsibilities during design process	3.24	0.903	20
V17	Allows the development of BIM federated model for use by all teams	3.22	0.911	21
V20	*Capability to capture clients' requirements	3.18	0.916	23

Overall Cronbach's alpha is 0.915; \* - Variable deleted based on higher value of Cronbach's alpha if item deleted

The mean ranking reveals that “*simulation and analysis of waste performance*” is the most significant stakeholders’ expectation on the use of BIM for CW management. This is because the construction industry is long overdue for BIM-based prediction and simulation platforms for waste performance of building models (Bilal *et al.*, 2016b). It is not a surprise that “*embedding waste-related information into building model*” was ranked second. This affirms the results of other studies that identified that the need for embedding CW related information into buildings models (Bilal *et al.*, 2016a). A major requirement for this is knowing what information is needed and how to integrate it within existing standards. Achieving this will provide an opportunity to enhance the performances of existing CW management tools and to develop better tools for CW performance

analysis. The other three top factors include “*support for whole-life waste analysis*”, “*interoperability among BIM software*” and “*early supply-chain integration.*”

### **5.7.2 Exploratory Factor Analysis**

To achieve the aim of the study, an Exploratory Factor Analysis (EFA) was used to identify the underlying structure of the factors identified in the literature, and focus group interviews. The exploratory factor analysis identifies the underlying dimension of the variables. This is to replace the entire set of variables with a smaller number of uncorrelated principal factors. This was done by removing redundant (highly correlated) variables from the data set while retaining the validity of original information as much as possible. An EFA is chosen as compared to confirmatory factor analysis due to lack of priori knowledge of the factor structure. EFA was carried out using the Statistical Package for Social Sciences (SPSS). The factor analysis employed principal components analysis (PCA) with orthogonal rotation (varimax) of the 22 variables. The PCA was used for factor extraction and varimax rotation was used as factor rotation. The Kaiser-Meyer-Olkin (KMO) value and the Bartlett tests of sphericity were 0.518 (above 0.5) and  $6.8 \times 10^{-49}$  (less than 0.5) respectively. These values show the suitability of the data for factor analysis. The PCA results reorganises the list of variables into five factors, which account for of the total variance of 84.231% as shown in Table 5.8.

Accordingly, the groups were then interpreted and labelled based on the variables assigned to the groups. The groups include:

- (a) Group 1 denoted by improved collaboration for waste management
- (b) Group 2 denoted by waste-driven design process and solutions
- (c) Group 3 denoted by lifecycle waste analytics
- (d) Group 4 denoted by Innovative technologies for waste intelligence and analytics, and
- (e) Group 5 denoted by improved documentation for waste management



Table 5.8: Component labelling and corresponding criteria from exploratory factor analysis

Variable	Factors and sub-factors	Eigen value	% of variance	Factor loading
	<b><i>A. BIM-based collaboration for waste management</i></b>	14.07	32.246	
1	V11			0.918
2	V18			0.867
3	V10			0.866
4	V16			0.776
5	V9			0.684
6	V17			0.681
7	V21			0.920
	<b><i>B. Waste-driven design process and solutions</i></b>	6.53	24.385	
8	V2			0.957
9	V19			0.928
10	V5			0.692
11	V6			0.619
12	V1			0.912
13	V4			0.589
14	V14			0.714
	<b><i>C. Life-cycle waste analysis</i></b>	4.00	10.971	
15	V12			0.899
16	V13			0.828
	<b><i>D. Innovative technologies for waste intelligence and analytics</i></b>	2.97	9.989	
17	V3			0.943
18	V15			0.942
19	V7			0.604
	<b><i>E. Improved documentation for waste management</i></b>	2.38	6.640	
21	V6			0.866
22	V22			0.680
			84.231	

## 5.8 Data Validity and Reliability

Performing reliability and validity checks in both qualitative and quantitative research is important in establishing confidence in the research findings. Validity shows that the findings are accurate and it measures the concept or phenomenon that was intended (Gray, 2009). Reliability shows whether there is consistency in the researcher's approach (Gibbs, 2007). During the qualitative data collection and analysis, reliability was ensured by:

- a) Proof-reading the interview transcripts to ensure that all mistakes made during the transcription are identified and corrected;
- b) Using the verbatim transcript and demonstrating grounding of the findings in the responses of interviewees. This was done by providing sample quotes from the respondents' own words;
- c) Supporting findings with extant literature to demonstrating theoretical agreement.

On the other hand, quantitative validity measure the accuracy and appropriateness of the questionnaire. Questionnaire validity generally starts with a pilot testing to verify the appropriateness of the questions, scale, and length of the questionnaire (Burkingham and Saunders, 2004). Content validity of quantitative data is concerned with the degree to which a sample could be generalised to a wider population. This is important to verify the assumption that a sample should be an accurate representation of the population. Face validity assesses the extent to which the instrument appears valid on the surface. Construct validity of quantitative data is the appropriateness of the questionnaire's content. Content, face and construct validities were ensured during the pilot study, which was carried out before administering the questionnaire survey. The reliability of the questionnaire, which assesses the extent to which the instrument accurately measures the construct it is designed to measure, was ensured by calculating Cronbach's alpha coefficient of reliability ( $\alpha$ ) for all the variables.

## **5.9 BIM Framework for Construction Waste Management**

Based on the Industry Foundation Classes (IFC) Specification framework (BuildingSMART, 2013), a number of BIM frameworks (Ison, 2008; Succar, 2009; Jung and Joo, 2011; Singh, Gu and Wang, 2011; Cerovsek, 2011) and Cloud-based BIM frameworks (Kumar, Cheng and McGibbney, 2010; Sawhney and Maheswari, 2013; Juan and Zheng, 2014; Abrishami *et al.*, 2014) have been developed. These studies show that an integration of BIM could foster early decision making throughout a project lifecycle (Porwal and Hewage, 2013; Jiao *et al.*, 2013). However, none of the existing BIM frameworks has comprehensively captured the construction waste management domain. So considering the year 2016 deadline for the adoption of full collaborative

3D BIM (CabinetOffice, 2011) and the benefits of CW management, integrating waste minimisation into BIM constitutes a huge opportunity for the construction industry. This will lead to a cultural change within the industry for the adoption of BIM towards sustainable construction (Ajayi *et al.*, 2016). As such, a holistic BIM framework for CW management was developed based on the identified expectations of industry practitioners.

To avoid the complexity of framework development (Garlan, Allen and Ockerbloom, 1995), an architecture-driven approach, which represents a collection of functional components and the description of the interactions amongst the components, was employed as proposed by Garlan and Shaw (1993). This approach identifies the core and common components that are germane to the development of a uniform and functional waste management system. As such, the integrity of the system is maintained by avoiding unnecessary duplication and ensuring the reuse of standard components. This also ensures that all components are loosely coupled (Long *et al.*, 2012) from each other to ensure independence among components thereby encouraging their implementation one at a time. The architecture driven approach also encourages the separation of data from algorithm, and from the technology.

Taking into consideration the factors identified from the literature and BIM strategies for CW management the FGIs and questionnaire survey, a holistic BIM framework for a robust waste management system was developed as presented in Figure 5.3. This was done with the intention of integrating the industrial and technological requirements for waste management. The framework development employed an architecture-based layered approach, where related components are grouped into layers, to ensure hierarchical categorisation of components. This approach also clearly defines boundaries of stakeholders' responsibilities, supports fair and efficient allocation of resources, encourages independent implementation of components, and clearly defines components' interfaces for information exchange. A summary of the framework layers is provided below:

- (a) **Infrastructure Layer**: This layer contains physical and virtual enterprise technologies, i.e., cloud computing platforms, networking, hardware, and GIS technologies.

- (b) **Data Layer**: This layer provides the shared knowledge, which uses decision making throughout the building's lifecycle.
- (c) **Presentation Layer**: The presentation layer defines the open BIM standards to ensure system interoperability and transparency in data exchange.
- (d) **BIM Business Domain Layer**: The BIM business domain layer defines the core features of BIM as a set of concepts on top of the presentation, data, and infrastructure layers.
- (e) **Service Domain Layer**: The service domain layer defines specific concepts and functionalities built on the BIM business domain layer to analyse and simulate various performances of a building project, particularly construction waste analysis and management.
- (f) **Application Layer**: This layer allows various stakeholders to access specific domain services. BIM software resides on this layer.

## 5.10 Summary

The chapter contains a detailed discussion of the development of a holistic BIM framework for CW management in response to the expectations of industry stakeholders. After this, a set of FGIs was conducted with professional from the construction industry to identify their expectations in terms of adopting BIM for CW management. The factors identified from the literature review and the FGIs were then organised into a questionnaire survey to test the opinion of a wider population of stakeholders. The results of the factor analyses reveal five group of factors, which include “*BIM-based collaboration for waste management*”, “*waste-driven design process and solutions*”, “*lifecycle waste analysis*”, “*Innovative technologies for waste intelligence and analytics*”, and “*improved documentation for waste management*”.

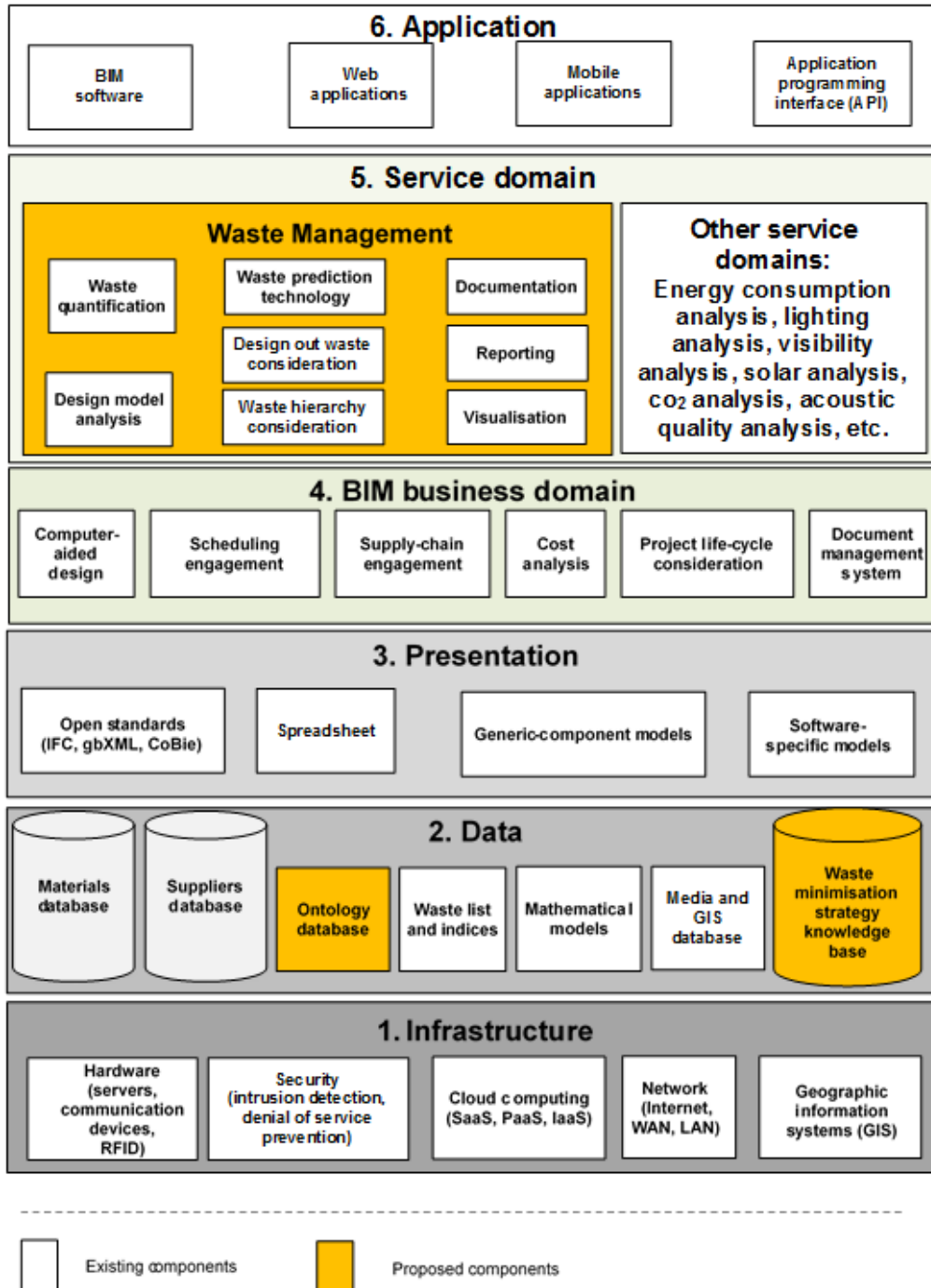


Figure 5.3: Framework for a BIM-Based Construction Waste Management System

Taking into consideration the factors, a holistic BIM framework for a robust waste management system was developed. This was done with the intention of integrating the industrial and technological requirements for waste management. The framework aims at achieving an integrated approach to design for waste management. In a summarised discussion, this chapter presents dual contributions: (i) the results improve the understanding of BIM functionalities and how they could be employed to improve the effectiveness of existing CW management tools, and (ii) the results help to understand industry expectation on the use of BIM for CW management.

The next chapter details how an Adaptive Neuro-Fuzzy Inference System (ANFIS) model, which combines the strengths of ANN and FL into a single hybrid system, was developed for construction waste prediction and minimisation. Accordingly, the model design, the data preparation, the model development, and model evaluation processes are discussed.

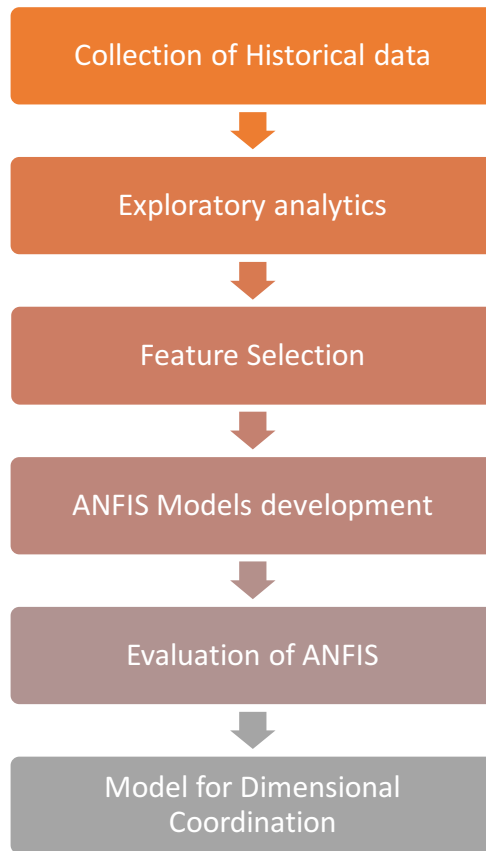
## **6 AI HYBRID MODEL DEVELOPMENT FOR CONSTRUCTION WASTE PREDICTION**

### **6.1 Overview**

This chapter is aimed at the development of AI hybrid models for construction waste prediction and minimisation. First, the system architecture for the proposed BIM-based computational system is discussed. Second, the preparation process of the CW data required for model development is presented. Waste data records from 117 projects was used after the removal of outliers and incomplete data. An exploratory data analysis was then carried out to understand the nature of the data. The frequencies and distribution of the data along four input parameters were explored to establish strong statistical measurement for the predictive model development. After which the data was normalised and split into training and testing data. An Adaptive Neuro-Fuzzy Inference System (ANFIS), which combines the strengths of ANN and FL into a single hybrid system, was then trained and tested using the data. The process of input selection reveals that out of the four input parameters, only two (gross floor area and construction type) are the best predictors for CW output. The final model was evaluated to assess its prediction accuracy. After this, a mathematical model was developed for dimensional coordination of brickworks.

### **6.2 Model Development Process and Experimental Setup**

The process of model development for CW prediction and minimisation is illustrated in Figure 6.1. The process starts with the collection of historical CW data and performing exploratory data analytics on them. Exploratory data analysis helps to understand the nature of the collected data. After which different data normalisation methods were applied to the data to see which normalisation method yields the highest performance. The data was then divided into training and testing data before the development of the ANFIS model.



*Figure 6.1: Process of Model Development*

### **6.3 Construction Waste Data Collection and Exploration**

Historical Waste Data Records (WDR) were collected from reputable waste contractors in the UK. The initial data contains waste record from four work packages, which include (a) groundworks, (b) construction, (c) refurbishment, and (d) demolition. However, only construction related waste data were considered because the focus of the study is on new builds. As such, waste records from 168 projects were collected. Outliers and incomplete data were removed during the data preparation process to increase data consistency and to aid accurate model development. This resulted in the removal of waste data record of 51 projects leaving WDR from 117 projects.



Thereafter, the data was subjected to exploratory data analysis to understand the distribution and structure of the data. Discretisation of two of the input parameters was done to aid data presentation, data exploration and data interpretation. The first discretisation was done for the project cost by employing the cost classification of source of data. The cost classifications and corresponding cost range is shown in Table 6.1. In the same way, the Gross Floor Area (GFA) parameter was also discretised using equal frequency discretisation. The GFA classification and corresponding area range is shown in Table 6.2.

*Table 6.1: Cost Classification Range*

<b>Cost Classification</b>	<b>Range</b>
<i>Micro Small</i>	< £30,000;
<i>Micro Medium</i>	£3,001 - £60,000
<i>Micro Medium</i>	£60,001 - £100,000
<i>Minor</i>	£100,001 - £500,000
<i>Medium</i>	£500,001 - £1,000,000
<i>Major</i>	£1,000,001 - £10,000,000
<i>Mega</i>	> £10,000,000

*Table 6.2: Gross Floor Classification Range*

<b>GFA Classification</b>	<b>Range</b>
<i>Small</i>	< 536.0m <sup>2</sup>
<i>Medium</i>	537.0m <sup>2</sup> – 837.5m <sup>2</sup>
<i>Large</i>	837.6m <sup>2</sup> – 1,713.0m <sup>2</sup>
<i>Mega</i>	> 1,713.0m <sup>2</sup>

Sample records from the discretised WDR is shown in Table 6.3. The frequencies and distribution of the data along the four input parameters were explored to establish strong statistical measurement for the predictive model development. The target parameter is a summation of the entire waste stream, which is made up of bricks, concrete, insulation, inert, metals, packaging, gypsum, binders, plastics, timber, hazardous waste, and mixed waste. From Table 6.4, exploratory data analysis shows that 45.10% of the total waste arising is from mixed waste. This is followed by inert wastes (37.8%), which include waste that does not undergo any significant physical, chemical, or biological transformations. Inert waste includes sand, clay, sub soil, and rubble.

Table 6.3: Sample Construction Waste Data Record

PID	Input Parameters				Target Parameters (tonnes)				
	Cost Classification	GFA Classification	Construction Type	Project Usage	Reuse	Direct Recycle	Recovery	Landfill	Total Waste
1	MAJOR	LARGE	Steel Frame	Commercial Offices	2.00	6.84	8.00	10.00	26.84
2	MEDIUM	MEDIUM	Load Bearing Masonry	Residential	0.00	0.00	5.50	0.00	5.50
3	MINOR	SMALL	Load Bearing Masonry	Healthcare	0.00	0.00	21.00	0.00	21.00
4	MAJOR	SMALL	Load Bearing Masonry	Residential	0.00	0.00	36.40	0.00	36.40
5	MAJOR	LARGE	Load Bearing Masonry	Residential	0.00	0.00	72.97	0.00	72.97
6	MAJOR	MEDIUM	Steel Frame	Public Buildings	0.00	0.00	60.79	0.00	60.79
7	MAJOR	LARGE	Load Bearing Masonry	Residential	0.00	0.00	155.50	0.00	155.50
8	MEDIUM	MEDIUM	Steel Frame	Commercial Offices	0.00	0.00	23.00	0.00	23.00
9	MEDIUM	MEDIUM	Load Bearing Masonry	Civil Engineering	0.00	0.00	79.76	0.00	79.76
10	MAJOR	MEDIUM	Load Bearing Masonry	Residential	0.00	1.50	135.00	0.00	136.50
11	MAJOR	MEGA	Steel Frame	Industrial Buildings	0.00	16.00	19.20	0.00	35.20
12	MAJOR	MEGA	Load Bearing Masonry	Residential	0.00	0.00	204.50	0.00	204.50
13	MAJOR	LARGE	Steel Frame	Industrial Buildings	0.00	0.00	47.43	0.00	47.43
14	MEDIUM	SMALL	Load Bearing Masonry	Education	0.00	0.00	49.66	0.00	49.66
15	MEDIUM	LARGE	Load Bearing Masonry	Healthcare	0.00	0.00	246.35	0.00	246.35
16	MAJOR	MEGA	Load Bearing Masonry	Residential	0.00	33.39	196.40	0.00	229.79

Table 6.4: Total Waste Output by Waste Type

<b>Waste Type</b>	<b>Total Waste Output (tonnes)</b>	<b>Percentage</b>
<i>Binders</i>	110.48	0.45%
<i>Bricks</i>	764.90	3.11%
<i>Concrete</i>	2359.48	9.60%
<i>Gypsum</i>	355.00	1.44%
<i>Hazardous</i>	27.42	0.11%
<i>Inert</i>	9288.79	37.8%
<i>Insulation</i>	14.38	0.06%
<i>Metals</i>	92.24	0.38%
<i>Mixed</i>	11083.02	45.10%
<i>Packaging</i>	25.22	0.10%
<i>Plastics</i>	28.03	0.11%
<i>Timber</i>	426.89	1.74%
<i>Total</i>	24,575.85	100%

Concrete and Bricks contribute 9.60% and 3.11% to the total waste respectively. In terms of WDR distribution with respect to construction type, exploratory analysis reveals that 70.40% of the waste arising is from Load Bearing Masonry, which is mostly residential building as shown in Table 6.5 and Table 6.6. In the same way, Table 6.7 and Table 6.8 show the distribution of WDR by GFA classification and Cost Classification. The tables show that 61.68% of the projects have GFA greater than 1,713.0m<sup>2</sup> and that 56.96% of the projects have cost between £1,000,001 and £10,000,000. To put all this together, a pivot table was constructed to show waste data distribution with respect to construction type, project usage type and waste types. The result is shown in Table 6.9. CW by management routes shows that 91.61% are recovered waste that is sent to transfer station for sorting, energy recovery, compositing, or soil remediation as shown in Table 6.10. Accordingly, CW management routes with respect to waste types and construction type are shown in Figure 6.4 and Figure 6.5 respectively.

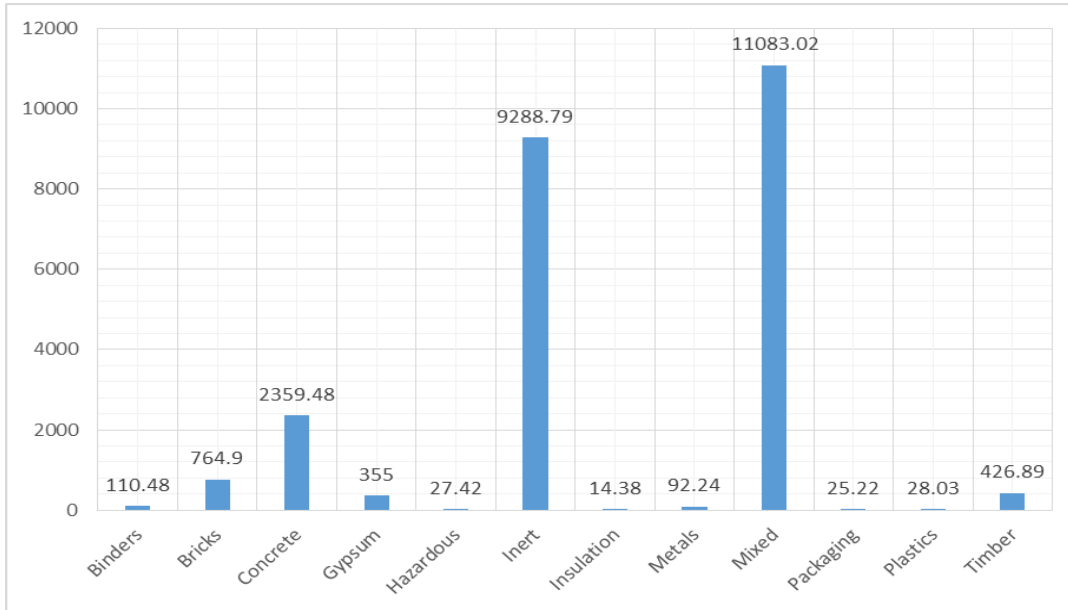


Figure 6.2: Distribution of Waste Data Record by Waste Type

Table 6.5: Total Waste Output by Construction Type

Construction Type	Name	Total (tonnes)
Concrete Frame	<i>Cf</i>	3403.72
Load Bearing Masonry	<i>Ms</i>	17302.49
Steel Frame	<i>St</i>	2407.32
Timber Frame	<i>Tm</i>	1462.32
<b>Total</b>		<b>24575.85</b>

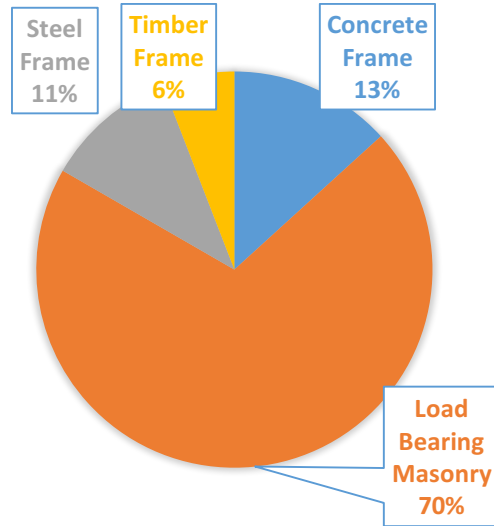


Figure 6.3: Distribution of Total Waste Output by Construction Type

Table 6.6: Total Waste Output by Project Usage

No	Project Usage	Name	Total (tonnes)
1	Civil Engineering	CE	79.76
2	Commercial Offices	CO	1,987.92
3	Education	Ed	2,086.04
4	Healthcare	Hc	247.83
5	Industrial Buildings	IB	391.27
6	Leisure	Ls	90.66
7	Mixed Use Development	MU	2,450.14
8	Public Buildings	PB	86.29
9	Residential	Rs	17,155.94
<b>Total</b>			<b>24575.85</b>

*Table 6.7: GFA Classification of Waste Data Record*

<b>GFA Classification</b>	<b>Total (tonnes)</b>
<i>Small</i>	1,488.88
<i>Large</i>	3,791.22
<i>Medium</i>	4,137.61
<i>Mega</i>	15,158.14
<i>Total</i>	24,575.85

*Table 6.8: Cost Classification of Waste Data Record*

<b>Cost Classification</b>	<b>Total (tonnes)</b>
<i>Major</i>	13,998.33
<i>Medium</i>	4,553.32
<i>Mega</i>	5,056.70
<i>Minor</i>	967.50
<i>Total</i>	24,575.85

Table 6.9: Waste Data Distribution with respect to Construction Type, Project Use Type and Waste Type

Constr. Type	Project Classification	Waste Type (Tonnes)											Total Waste (Tonnes)	
		Binders	Bricks	Concrete	Gypsum	Haz.	Inert	Insulation	Metals	Mixed	Packaging	Plastics		Timber
Concrete Frame	Commercial Offices	0.00	6.40	0.00	2.47	0.00	1374.80	0.00	0.00	137.37	0.00	0.00	0.00	1521.04
	Education	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	30.00	0.00	0.00	0.00	30.00
Load Bearing Masonry	Mixed Use Development	0.00	0.00	0.00	0.00	0.00	47.94	0.00	0.00	101.66	0.00	0.00	0.00	149.60
	Residential	0.00	0.00	486.00	0.00	0.00	81.00	0.00	49.00	1087.08	0.00	0.00	0.00	1703.08
Load Bearing Masonry	Civil Engineering	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	79.01	0.00	0.00	0.75	79.76
	Education	0.00	0.00	6.12	1.18	0.01	530.10	0.00	0.30	124.24	0.00	0.00	0.82	662.77
Steel Frame	Healthcare	0.00	0.00	0.00	10.92	0.00	160.00	0.00	0.00	74.91	0.00	0.00	2.00	247.83
	Leisure	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	32.00	0.00	0.00	0.00	32.00
Steel Frame	Mixed Use Development	0.00	0.00	0.00	0.00	0.00	2260.00	0.00	6.59	32.00	0.00	0.00	0.00	2298.59
	Residential	104.48	323.50	509.34	277.32	9.78	4394.95	13.99	1.72	7918.08	23.35	13.79	391.24	13981.54
Steel Frame	Commercial Offices	0.00	0.00	420.00	4.80	0.15	0.00	0.39	4.84	32.61	0.80	2.54	0.75	466.88
	Education	6.00	0.00	210.00	44.79	1.68	338.00	0.00	7.61	743.92	0.14	11.50	29.63	1393.27
Steel Frame	Industrial Buildings	0.00	0.00	147.00	3.18	0.00	0.00	0.00	8.70	232.39	0.00	0.00	0.00	391.27
	Leisure	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	58.66	0.00	0.00	0.00	58.66
Steel Frame	Mixed Use Development	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.95	0.00	0.00	0.00	0.00	1.95
	Public Buildings	0.00	0.00	11.02	4.84	0.00	0.00	0.00	0.00	69.30	0.93	0.20	0.00	86.29
Timber Frame	Residential	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	9.00	0.00	0.00	0.00	9.00
	Residential	0.00	435.00	570.00	5.50	15.80	102.00	0.00	11.53	320.79	0.00	0.00	1.70	1462.32
<b>Total</b>		110.48	764.90	2359.48	355.00	27.42	9288.79	14.38	92.24	11083.02	25.22	28.03	426.89	24575.85

Table 6.10: Construction Waste Management Routes

Name	Description	Total Waste (tonnes)	Percentage
<i>Reuse</i>	Reusing the material without further processing	98.70	0.40%
<i>Direct recycle</i>	Segregated waste sent directly to be recycled	1,927.85	7.84%
<i>Recovery</i>	Mixed waste sent to transfer station for sorting, or energy recovery, composting or soil remediation.	22,513.09	91.61%
<i>Landfill</i>	Waste sent to landfill	36.21	0.15%
<i>Total</i>		24,575.85	100.00%

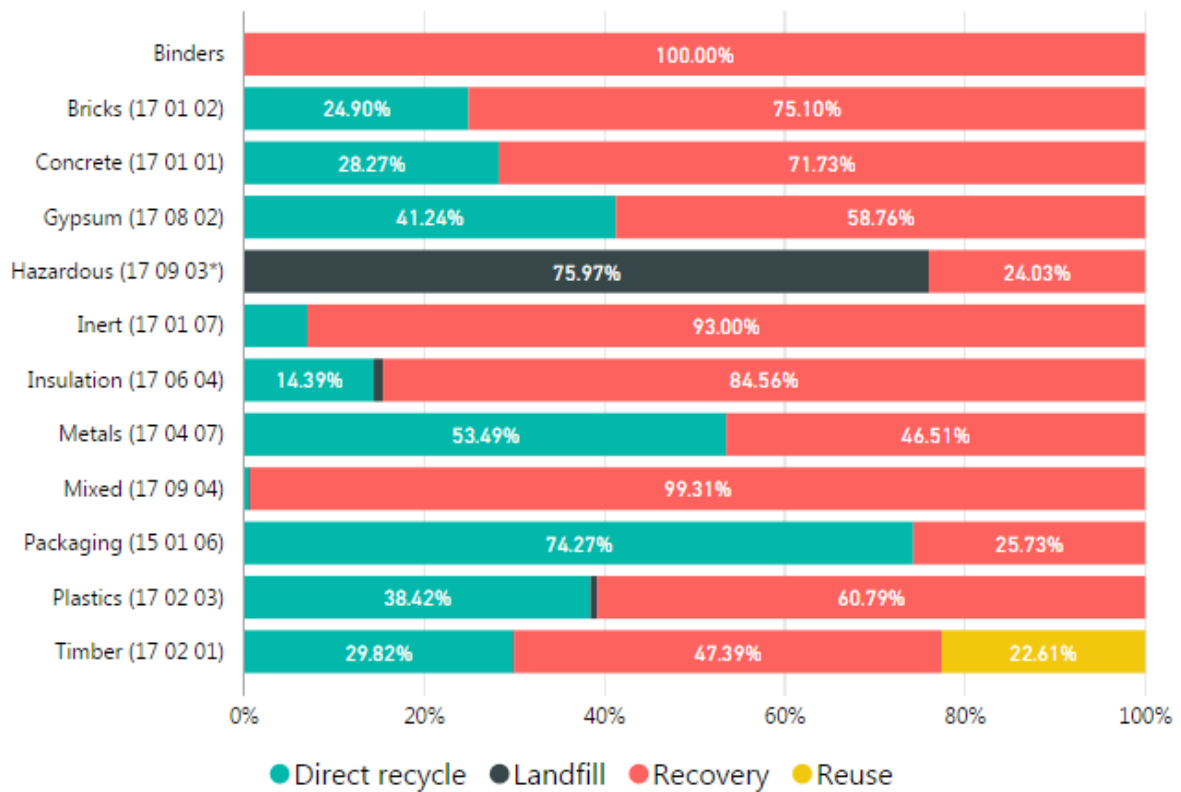


Figure 6.4: Waste Management Routes of Waste Types



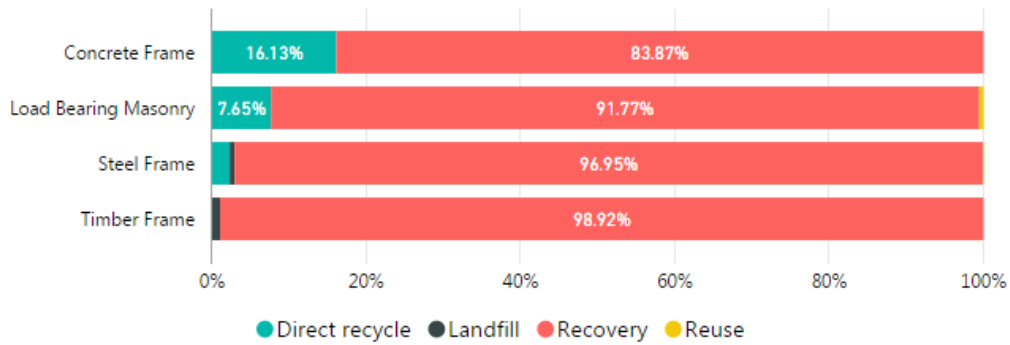


Figure 6.5: Waste Management Routes of Construction Type

To investigate the readiness of the data for analysis, value distribution of the data was assessed to check whether generalised statistics could be drawn from the data. If the parameter is a class variable, the class distribution shows the frequency of the class in the data. This applies to the distribution of construction type, construction use, GFA, and cost categories. However, the distribution of GFA and Cost was assessed using the actual continuous data before discretisation. The distribution of GFA, cost and total waste is shown in Figure 6.6, Figure 6.7, and Figure 6.8 respectively. Although the distributions are slightly positively skewed, the figures show that the distribution is acceptably centred and sufficient for statistical analysis.

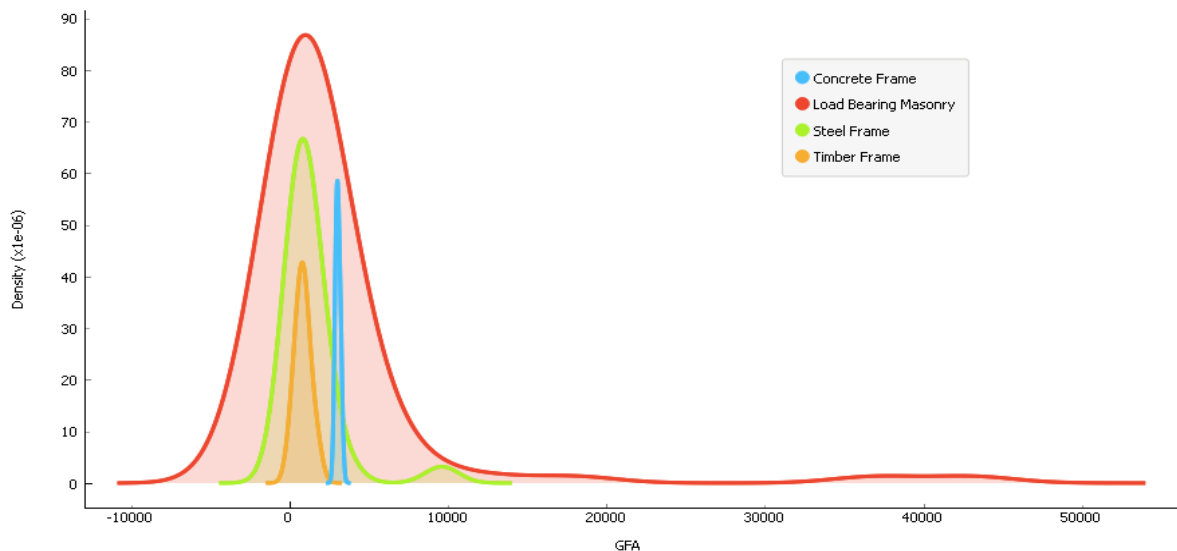


Figure 6.6: Distribution of GFA according to Construction Type

From Figure 6.8, the distributions also reveal that construction type is a major predictor of CW because of the different distribution functions. Load bearing masonry has positively skewed distribution, while steel frame and timber frame projects have slightly bipolar distribution. This variation suggests that construction types influence CW generation differently.

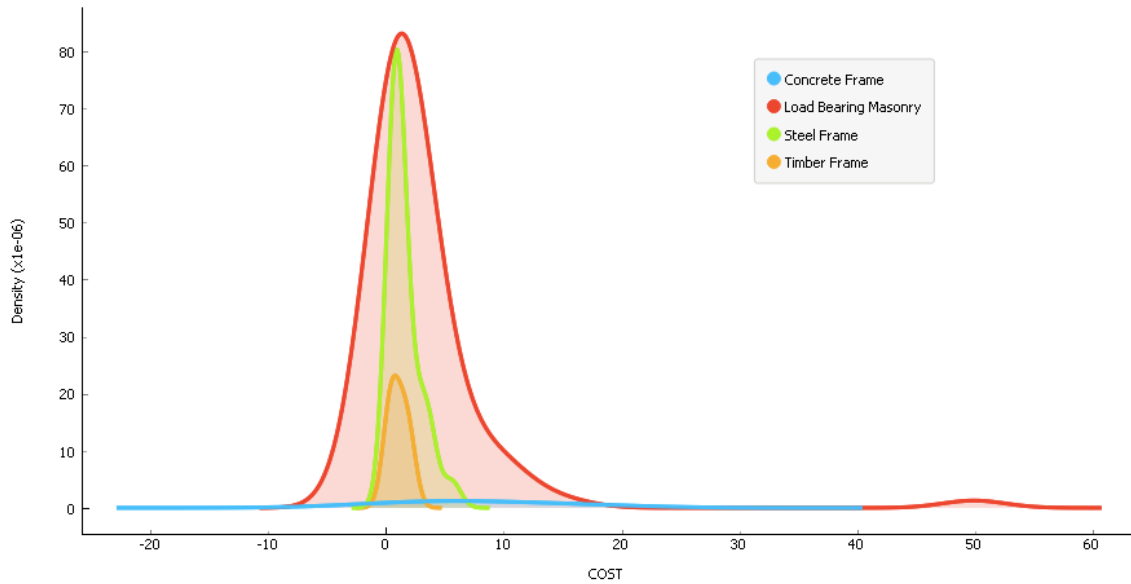


Figure 6.7 Distribution of Cost according to Construction Type

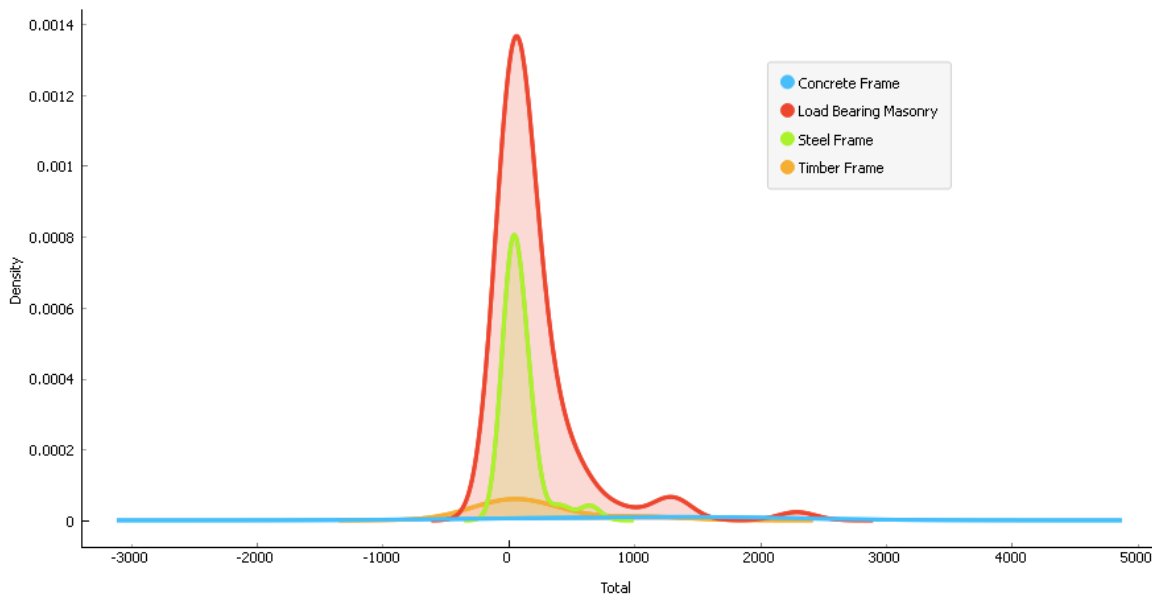


Figure 6.8: Distribution of Total Waste Output according to Construction Type

## 6.4 Data Preparation for ANFIS Model Development

The block diagram for the proposed Adaptive Neuro-Fuzzy Inference System (ANFIS) model is shown in Figure 6.9 and the development process of the ANFIS model is shown in Figure 6.10. A description of ANFIS is provided in Section 6.5. Sample waste data with four inputs (GFA, cost, Construction Type, and Project Classification) and one output (Total Waste) is shown in Table 6.12. The data was normalised to reduce the noise for better prediction accuracy after the initial exploratory data analysis. As such, three different normalisation methods were tested to find the most efficient normalisation method as suggested by Sola and Sevilla (1997). Possible scaling options include: (a) Z-score (standard score), which normalises data using mean and standard deviation, (b) normalised data in the range [-1, 1], and (c) feature scaling, which normalises data in the range [0, 1]. The results of the comparison show that feature scaling leads to better responses. Accordingly, the data were normalised using:

$$X_{norm} = \frac{X - X_{min}}{X_{max} - X_{min}} \quad (6.1)$$

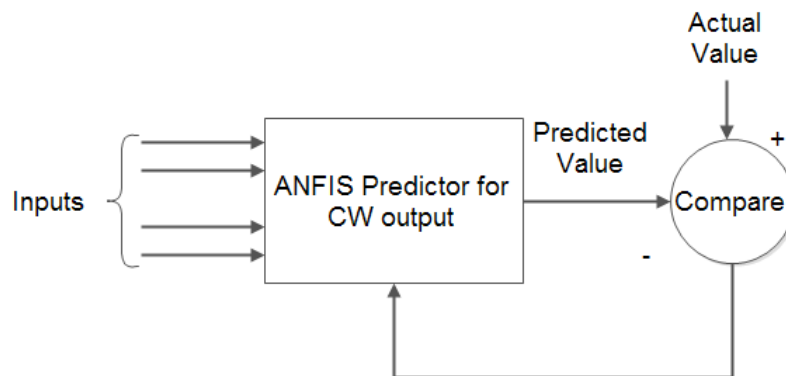


Figure 6.9: Block Diagram of Proposed ANFIS Model

The normalised data were used to develop the model and they were returned to original values during simulation. Accurate train and test data are required to develop and to train the ANFIS model successfully. As such, the data were divided into two distinct groups, i.e., training and testing data. The purpose of the training data is used to develop the ANFIS model and the testing data are used to evaluate the predictive capability of the trained model. As such, 70%

of the whole data was randomly selected as the training data while the remaining 30% was used to test the ANFIS model.

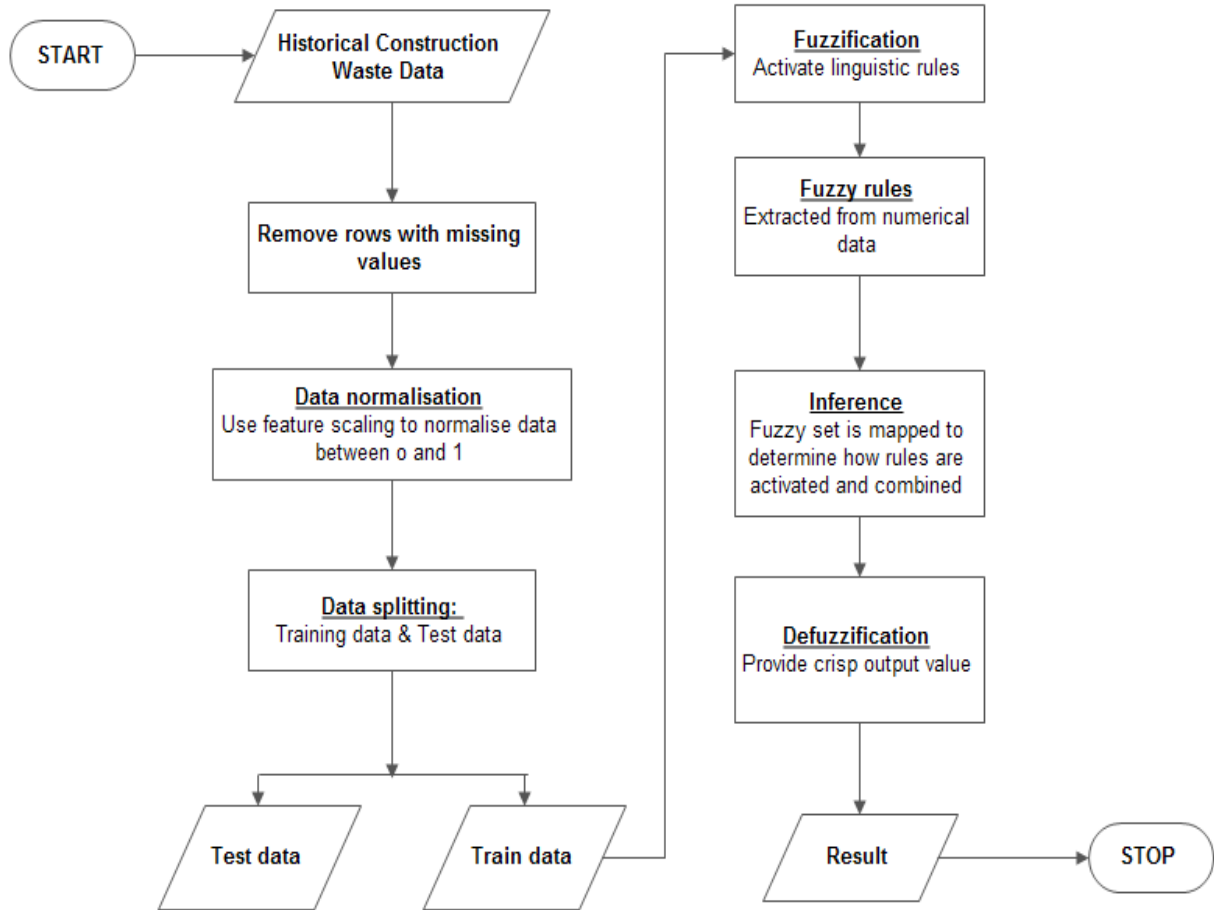


Figure 6.10: ANFIS Model Development Flowchart

## 6.5 Adaptive Neuro-Fuzzy Inference System (ANFIS)

The modelling approach adopted for predicting the total waste output of a building is a hybrid framework that combines the concepts of fuzzy set, fuzzy logic, and neural network. Hybrid frameworks of this nature are generally referred to as neuro-fuzzy systems. Neuro-fuzzy systems are hybrid systems that synergise the human-like reasoning of fuzzy logic with connectionist learning based structure of Artificial Neural Network (ANN). Despite the wide adoption of neural networks, its design and training is plagued by certain challenges. Chief

among the problems that affect the performance of ANN is how weights are assigned to the network structure. Therefore, achieving an optimal performance requires careful network architecture tuning and selection of learning algorithm parameters. As such, other optimisation algorithms such as Genetic Algorithm, Simulated Annealing and Fuzzy Logic have been combined with ANN to improve its performance (Tahmasebi and Hezarkhani, 2009).

According to Zadeh (1965), the fuzzy rule-based modelling approach uses various knowledge and data sources to capture semi-qualitative knowledge in form of if-else rules:

$$R1: \text{if } x \text{ is } A_i \text{ then } y \text{ is } B_i, \quad i = 1, 2, \dots, k \quad (6.2)$$

This study developed a type of neuro-fuzzy system called Adaptive Neuro-fuzzy Inference System (ANFIS) for CW prediction. ANFIS is based on Takagi-Sugeno fuzzy inference system (Jang, 1993). ANFIS combines the strengths of ANN and fuzzy logic into a single hybrid system. To explain the theory of ANFIS, we assume a system with two inputs ( $x$  and  $y$  with three membership functions each) and one output ( $z$ ). Based on a first order of Sugeno-Fuzzy Model, a typical rule set can be expressed as:

$$\text{if } x \text{ is } A_i \text{ then } y \text{ is } B_i, \text{ then } f_1 = p_1x + q_1y + r_1 \quad (6.3)$$

Where  $p$ ,  $r$  and  $q$  are output parameters. As such, the structure of the two inputs and one output ANFIS is shown in Figure 6.11. The structure is made up of five layers and nine if-then rules.

The description of the layers is given below:

**Layer 1 (Fuzzification Layer):**

Nodes of this layer are square and with the node function of:

$$O_i^1 = \mu_{A_i}(x) \quad (6.4)$$

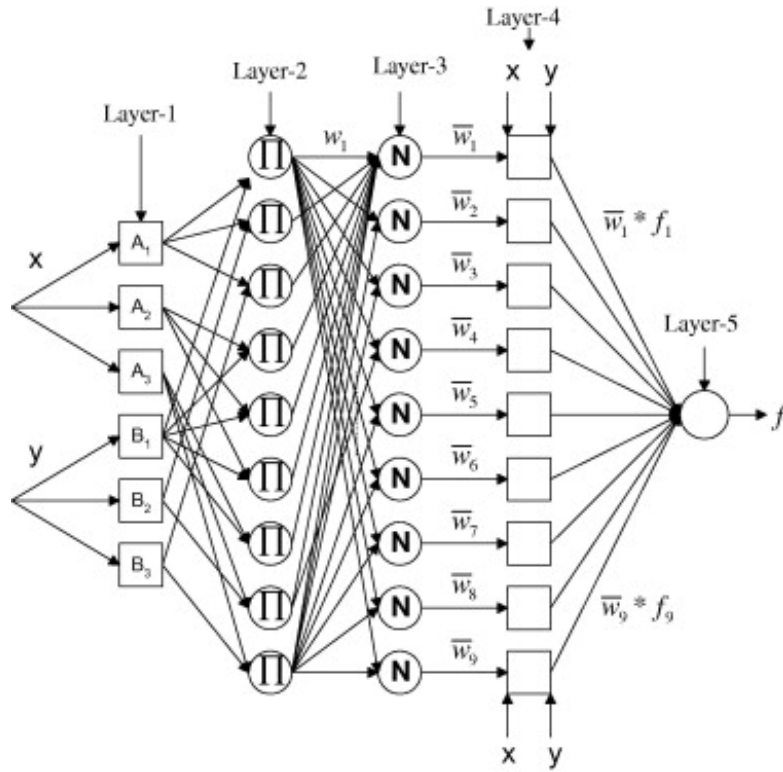


Figure 6.11: A Two Inputs and one Output ANFIS System

Where  $O_i^1$  is the membership grade of a fuzzy set  $A_i$ , and it specifies the degree to which  $x$ , which is the input to node  $i$ , satisfies the quantifier  $A$ .  $\mu_{A_i}$  is Gaussian membership function of linguistic variable  $A$  and it is give as:

$$\mu_{A_i}(x) = \exp \left[ - \left( \frac{x-c_i}{a_i} \right)^2 \right] \quad (6.5)$$

Where  $a_i$  and  $c_i$  are the premise parameters.

**Layer 2 (Multiplication Layer):**

The nodes of this layer are represented as circles that are labelled  $\pi$ . The output of each node is the product of all incoming nodes, such that:

$$O_i^2 = w_i = \mu_{A_i}(x) \times \mu_{B_i}(x), \text{ for } i = 1, 2, 3, \dots, 9 \quad (6.6)$$

Nodes of this layer are the antecedent connectives and their output represents the firing strength of a rule.

**Layer 3 (Normalization Layer):**

All nodes on this layer are represented as circled and labelled "N". The  $i^{th}$  node calculates the ratio of the  $i^{th}$  rule's firing strength to the sum of all rules' firing strength, i.e.:

$$O_i^3 = \bar{w}_i = \frac{w_i}{w_1 + w_2 + w_3 + \dots + w_9}, \text{ for } i = 1, 2, 3, \dots, 9 \quad (6.7)$$

The outputs of this layer are called normalised firing strengths.

**Layer 4 (Defuzzification Layer):**

The fourth layer produces the consequent parameters. All the nodes of this layer are adaptive nodes with a node function:

$$O_i^4 = \bar{w}_i f_i = \bar{w}_i (p_i + q_i + r_i), \text{ for } i = 1, 2, 3, \dots, 9 \quad (6.8)$$

Where  $p_i, q_i,$  and  $r_i$  are the consequent parameters that were adjusted during the training process.

**Layer 5 (Summation Layer):**

The fifth layer is the summation layer and it is made up of a single fixed node labelled  $\Sigma$ . The node sums up all the inputs and computes the overall output by using:

$$\text{Overall output} = O_i^5 = \sum_i \bar{w}_i f_i = \frac{\sum_i w_i f_i}{\sum_i w_i} \quad (6.9)$$

A key strength of ANFIS is that the hybrid learning process estimates the premise and the consequent parameters (Jang, 1993). Accordingly, ANFIS splits the learning process into two independent stages, which are: (a) adaptation of learning weights and (b) adaptation of

nonlinear membership functions. According to Singh *et al.* (2005), this allows ANFIS algorithm to be able to reduce the complexity of the machine learning process while increasing the efficiency of the process.

## 6.6 ANFIS Model Development and Training

This section details the development and training process for the ANFIS model. The section is discussed in four parts, which are: (i) input selection for ANFIS that describes an effective approach for determining the best combination of inputs that describes the output variable, (ii) identifying the ANFIS structure, which determines the efficient network structure for the models, (iii) training of the ANFIS model, which describes how appropriate parameters of the model are determined, and (iv) model evaluation, which assesses the performance of the developed ANFIS model. Characteristics of ANFIS model variables are shown in Table 6.11 and sample data from the waste data record is shown in Table 6.12.

*Table 6.11: Input and Output Variables for ANFIS*

<b>Name</b>	<b>symbol</b>	<b>Attribute</b>
<i>Project cost</i>	<i>Pc</i>	Continuous
<i>GFA of building</i>	<i>GFA</i>	Continuous
<i>Construction Type</i>	<i>Ct</i>	Multi-value discrete
<i>Building Usage Type</i>	<i>Bu</i>	Multi-value discrete
<i>Total Waste</i>	<i>W</i>	Continuous

### 6.6.1 Input selection for ANFIS Models

Modelling real-world problems with large potential inputs is quite complex and it requires huge computational capability and time (Jang, 1996). This difficulty reveals the need to find a way to find out, in a quick and efficient way, which of the potential inputs is important in the prediction process. Jang (1996) proposed an efficient way of achieving input selection and it is based the fact that ANFIS facilitates systematic computation of derivative of the output error with respect to modifiable parameters. ANFIS employs an efficient hybrid learning algorithm



that combines least square methods and gradient descent algorithm in a two-way pass system. Hybrid learning algorithm involves two processes, which are: (a) the forward pass of the hybrid-learning algorithm, which uses the least-squares methods to find the consequent parameters of layer 4 of the ANFIS model, and (b) the backward pass, where the error signals propagate backward and the premise variables are updated by gradient descent (Jang, 1993). The details of the two passes in hybrid learning algorithm for ANFIS are shown in Table 6.13.

Table 6.12: Sample of Waste Data

<i>PID</i>	<i>GFA (m<sup>2</sup>)</i>	<i>P<sub>c</sub> (£)</i>	<i>C<sub>t</sub></i>	<i>B<sub>u</sub></i>	<i>W (tonnes)</i>
1	1386	1374630	Steel Frame	Commercial Offices	26.84
2	780.00	970000	Load Bearing Masonry	Residential	5.50
3	150.00	350000	Load Bearing Masonry	Healthcare	21.00
4	513.01	1400000	Load Bearing Masonry	Residential	36.40
5	983.47	2310000	Load Bearing Masonry	Residential	72.97
6	610.00	1072203	Steel Frame	Public Buildings	60.79
7	1440.20	2000000	Load Bearing Masonry	Residential	155.50
8	700.00	710000	Steel Frame	Commercial Offices	23.00
9	600.00	650000	Load Bearing Masonry	Civil Engineering	79.76
10	604.00	1250000	Load Bearing Masonry	Residential	136.50
11	2200.00	1400000	Steel Frame	Industrial Buildings	35.20
12	18000.00	4000000	Load Bearing Masonry	Residential	204.50
13	1573.00	1017292	Steel Frame	Industrial Buildings	47.43
14	244.00	590000	Load Bearing Masonry	Education	49.96
15	1310.00	998932	Load Bearing Masonry	Healthcare	246.35
16	3482.00	7000000	Load Bearing Masonry	Residential	229.79
17	4206.00	10000000	Load Bearing Masonry	Residential	926.14
18	296.00	535000	Steel Frame	Education	41.63
19	308.00	342150	Load Bearing Masonry	Education	205.44
20	716.00	900000	Load Bearing Masonry	Residential	66.90

Table 6.13: Details of Hybrid Learning Algorithm

<b>Parameters</b>	<b>Forward Pass</b>	<b>Backward Pass</b>
<i>Premise</i>	Fixed	Gradient Descent
<i>Consequent</i>	Least Squares Method	Fixed
<i>Signal</i>	Node Outputs	Error Rates

Identification of the best combination of input parameters largely depends on the strength of least square methods to quickly train models. Gradient descent is then used to slowly change the underlying membership function that generates the basis function for the least square method. The least square method, which is a computationally efficient method, is used to train the model quickly while gradient descent is used to update the MF that generates functions for the least square method slowly. This approach enables ANFIS to generate satisfactory results quickly with few epoch of training (Jang, 1996). Various input configurations of ANFIS can be constructed to choose the model with the best performance for further training. As such, selecting the most influential two inputs (out of 4) for the proposed ANFIS will require  $4C_2 = 6$  ANFIS models with different combinations of 2 inputs. The six ANFIS are then trained on a single pass of least-square method and then picking the models with the smallest training error. However, using grid partitioning will result into  $2^4 = 16$  rules and  $(4+1) \times 16 = 80$  linear parameters with first-order Sugeno-fuzzy model.

The results of the input selection are shown in Table 6.14 and Figure 6.12. The result reveals that the combination of “GFA” and “Construction Type” produces the least Root Mean Square Error (RMSE) from the input selection process. As such, Model 2 was selected for further training to improve its performance.

*Table 6.14: Results of Input Selection for ANFIS Model*

<b>No</b>	<b>Inputs</b>	<b>RMSE</b>
<i>Model 1</i>	GFA-P <sub>c</sub>	0.121984
<i>Model 2</i>	GFA-C <sub>t</sub>	*0.071806
<i>Model 3</i>	GFA-B <sub>u</sub>	0.092198
<i>Model 4</i>	P <sub>c</sub> -C <sub>t</sub>	0.098120
<i>Model 5</i>	P <sub>c</sub> -B <sub>u</sub>	0.079349
<i>Model 6</i>	C <sub>t</sub> -B <sub>u</sub>	0.079349

\*Mode 2 has the least RMSE

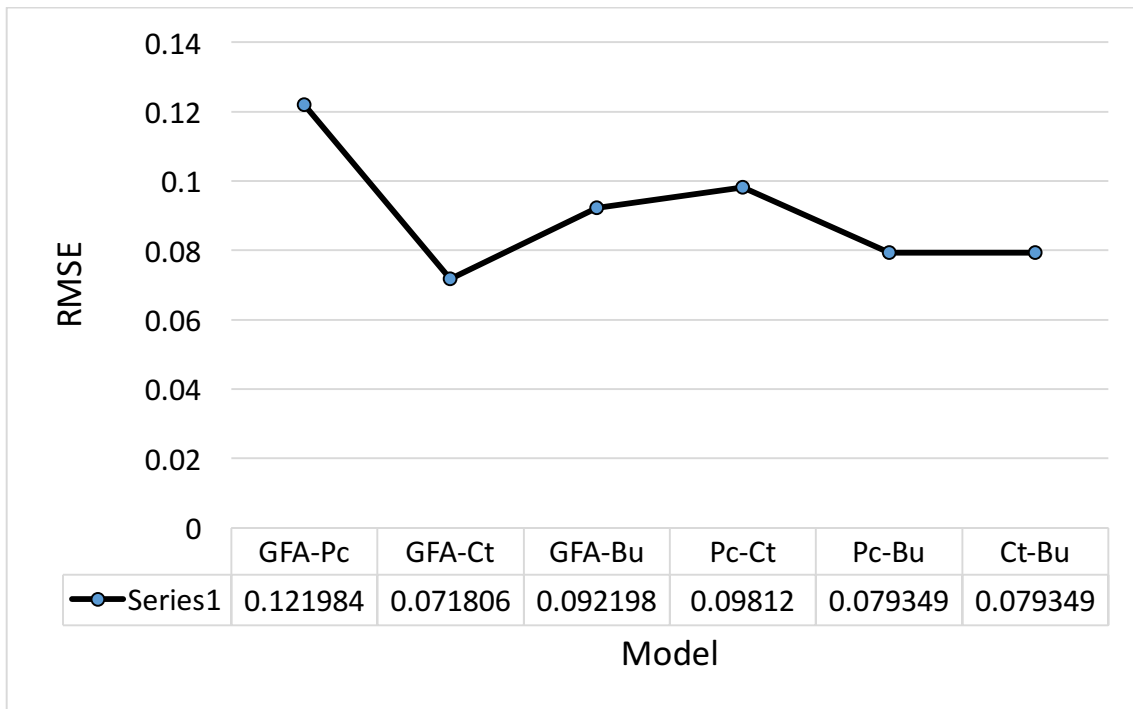


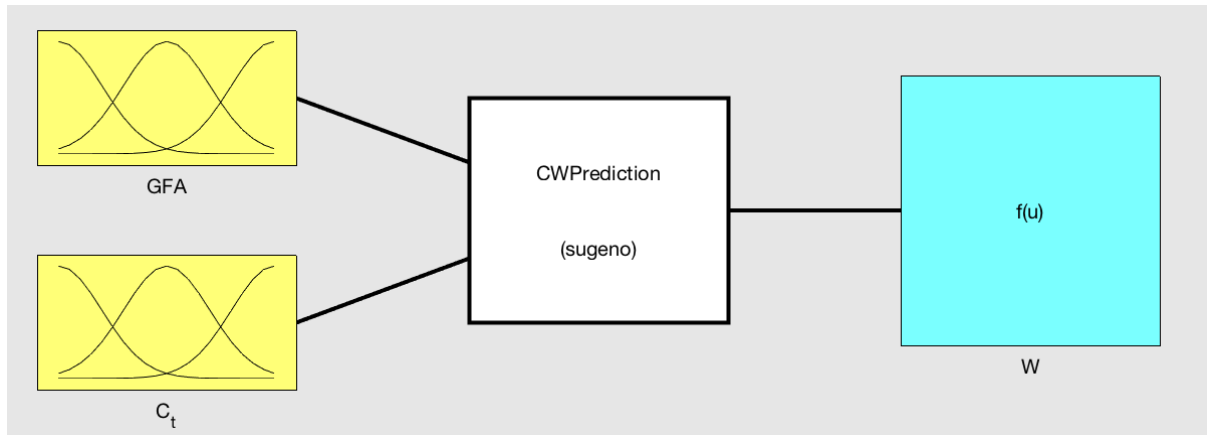
Figure 6.12: RMSE for two-input ANFIS Model for CW Prediction

### 6.6.2 ANFIS Structure and Training

Preceding the model training process is the creation of an efficient structure that best describe the target variable. Two common approaches are employed to generate a fuzzy inference system structure from data, which are grid partitioning and subtractive clustering. Grid partitioning generates rules by enumerating all possible combinations of membership functions of all inputs. This approach leads to an exponential explosion when the number of input is large. For example, a fuzzy inference system with five inputs and each with two membership function will generate  $2^5$  (32) rules. This situation is called “curse of dimensionality” and it is impractical for usage in real-world machine learning methods. Subtractive clustering produces scattering partitions using a more efficient approach than grid partitioning. A key strength of FIS generated by subtractive clustering approach is that it produces good input-output mapping precision especially when the inputs are many.

The structure and membership functions of the final ANFIS model are identified using Grid Partitioning. Although grid partitioning produces more rules than subtractive clustering, it is

selected because input selection has been carried out to reduce the the dimension of the search space. The block diagram and the network structure of the final ANFIS model are shown in Figure 6.13 and Figure 6.14 respectively.



*Figure 6.13: Block Diagram of the Final ANFIS Model*

Creation of fuzzy Membership Functions (MF) and their values is a significant step in the training of ANFIS models. An MF is a curve that depicts how points within the input space are mapped to the degree of membership between 0 and 1. Value 0 depicts no membership while value 1 represents full membership. Several membership functions exist and they depend on piecewise linear functions, polynomial curves, sigmoid curves, and Gaussian distribution function. Input MFs for ANFIS are presented in Table 6.15. However, only two types of output MF exist for ANFIS, which are constant and linear. This is because ANFIS only operates on Sugeno-type systems (Çaydaş, Haşçalık and Ekici, 2009). The ANFIS model was trained using all the eight membership functions and their performance is calculated using root mean square error.

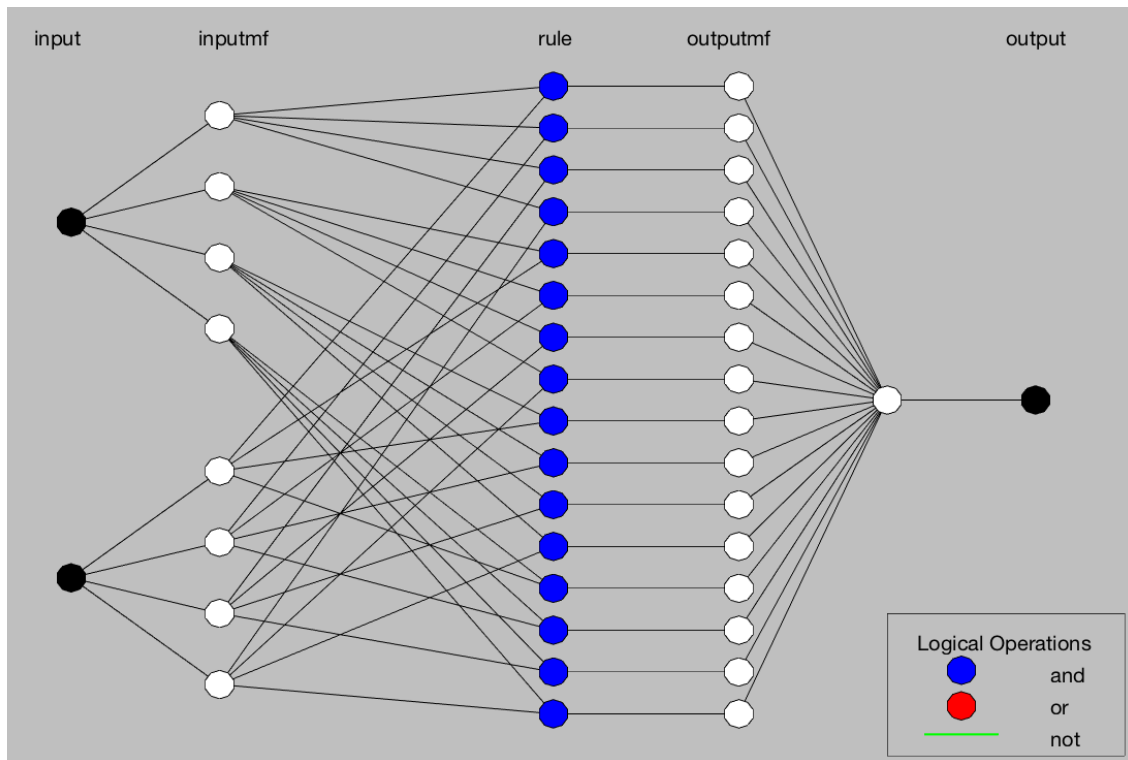
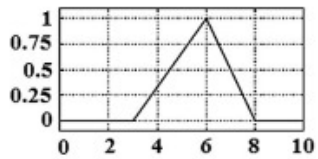
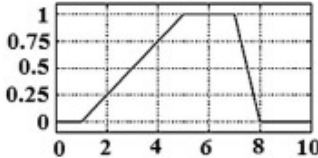
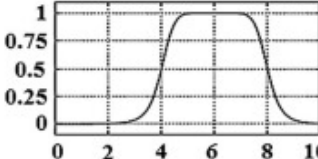

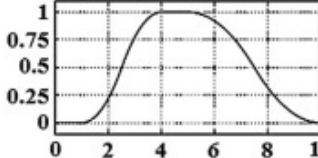
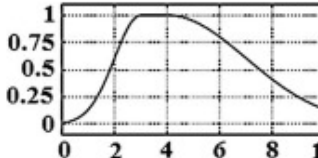

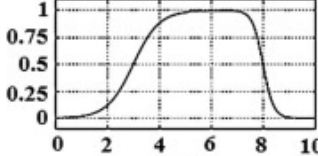


Figure 6.14: Network Structure of ANFIS Model with Grid Partitioning

To ensure efficient learning ability for the ANFIS model, the premise parameters ( $a_i$  and  $c_i$  in layer 1) and the consequent parameters ( $p_i$ ,  $q_i$ , and  $r_i$  in layer 4) are tuned until desired results are achieved. According to Bishop (Bishop, 1995), the most common training methods are back-propagation and hybrid learning algorithms. This study adopts hybrid-learning algorithm as training method because it converges faster and it reduces the dimension of the search space as compared with back-propagation (Jang, 1993) as discussed in Section 6.6.1. Membership functions for “GFA” and “Construction Types” are shown in Figure 6.17 and Figure 6.18 respectively. The fuzzy rules and the rule viewer dialog are also shown in Figure 6.15 and Figure 6.16 respectively.

Table 6.15: Input Membership Functions for ANFIS

Membership function	Description	Illustration
<i>trimf</i>	Triangular membership function	
<i>trapmf</i>	Trapezoidal membership function	
<i>gbellmf</i>	Generalised bell curve membership function	
<i>gaussmf</i>	Gaussian curve membership function	
<i>pimf</i>	Pi-shaped curve membership function	
<i>gauss2mf</i>	Two-sided Gaussian curve membership function	
<i>dsigmf</i>	Difference of two sigmoid membership functions	
<i>psigmf</i>	Product of two sigmoidal membership functions	

The final ANFIS model was implemented, trained, and simulated in Matlab using Fuzzy Logic Toolbox. The final ANFIS model was developed using C# implementation of ANFIS, which provides the flexibility required to integrate the model into BIM platform.

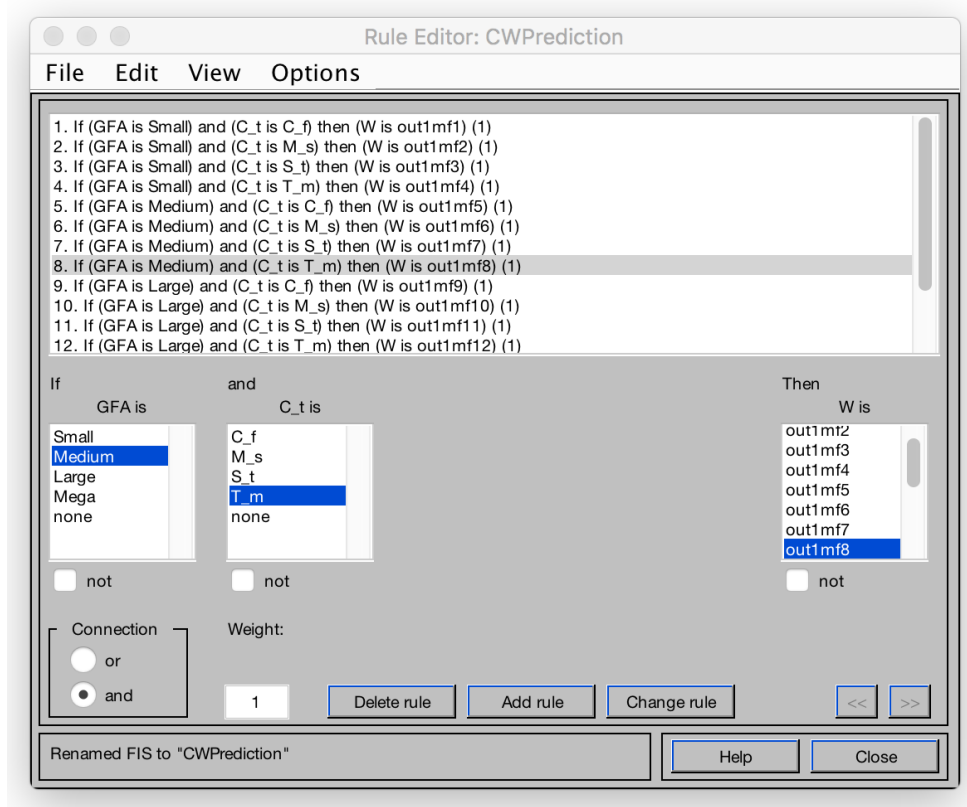


Figure 6.15: Fuzzy Rules for the ANFIS Model

### 6.6.3 ANFIS Model Evaluation

The performance of the ANFIS models is assessed using Root Mean Square Error (RMSE). RMSE is a positive value that represents the root of the mean of squares of the errors. It measures the residual between the actual and predicted values of a given model. *RMSE* is calculated as:

$$RMSE = \sqrt{\frac{1}{n} \sum_{i=0}^n (y_i - \hat{y}_i)^2} \quad (6.10)$$

Where  $y_i$  and  $\hat{y}_i$  are the actual and predicted values for instance  $i$  respectively, and  $n$  is the number of training samples. The value of RMSE that is closer to zero shows a good fit between the actual and predicted values. The RMSE of the different membership functions were compared to select the model with the best performance. The result of the model evaluation is shown in Table 6.16. Comparison of the actual and predicted CW values using the test data is shown in Figure 6.19.

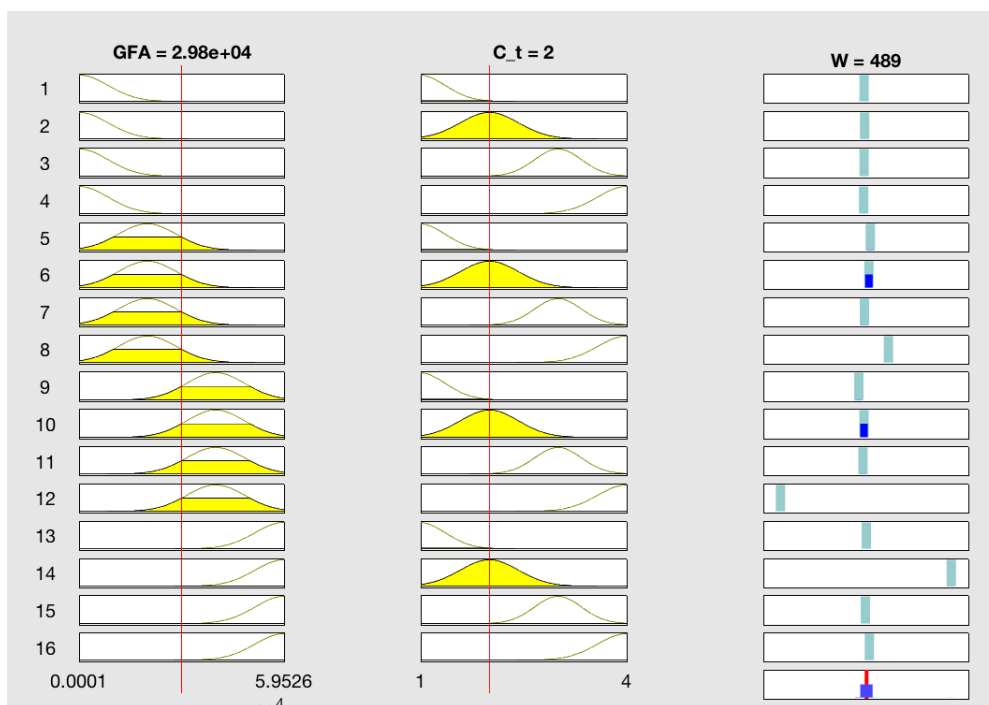


Figure 6.16: Rule Viewer for the ANFIS Model

Table 6.16: Performance of ANFIS Using Different Membership Functions

MF Type	RMSE	
	Constant	Linear
<i>trimf</i>	0.061448	0.059093
<i>trapmf</i>	0.068298	0.059648
<i>gbellmf</i>	0.059810	0.058460
<i>gaussmf</i>	0.053046	*0.051385
<i>gauss2mf</i>	0.060410	0.059035
<i>pimf</i>	0.068587	0.059648
<i>dsigmf</i>	0.061203	0.058637
<i>psigmf</i>	0.061203	0.058637

\*Selected model with minimum RMSE



The results reveal that “*gaussmf*” membership function produces the best performance and that it is accurate enough to predict CW. Gaussian membership function for “*Gross Floor Area*” and “*Construction Types*” are shown in Figure 6.17 and Figure 6.18 respectively. The characteristic of Gaussian membership function is represented by Equation (7.2). The function has two parameters  $c$  and  $\sigma$ , which determine the form of the membership functions.

$$Gaussian(x, c, \sigma) = e^{-\frac{1}{2}\left(\frac{x-c}{\sigma}\right)^2} \quad (6.11)$$

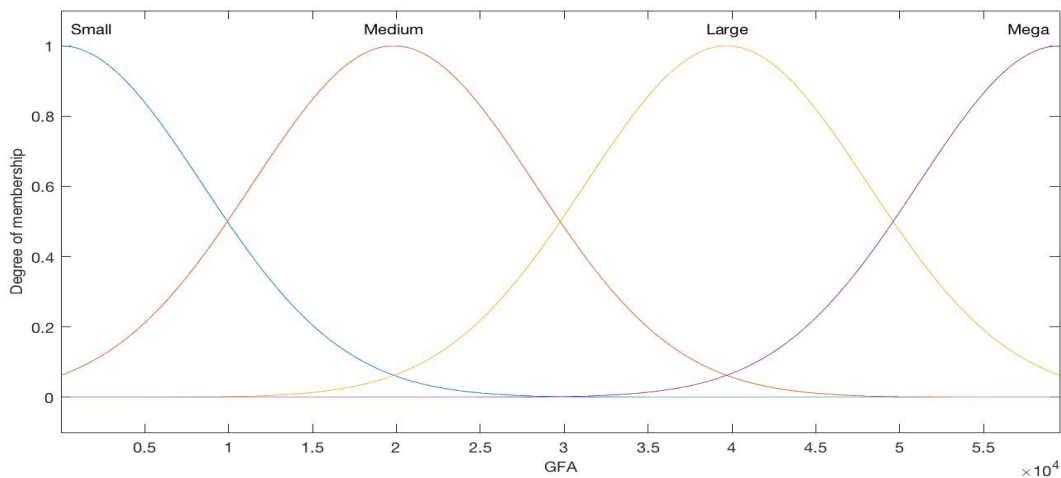


Figure 6.17: Gaussian Membership Function for Variable “Gross Floor Area”

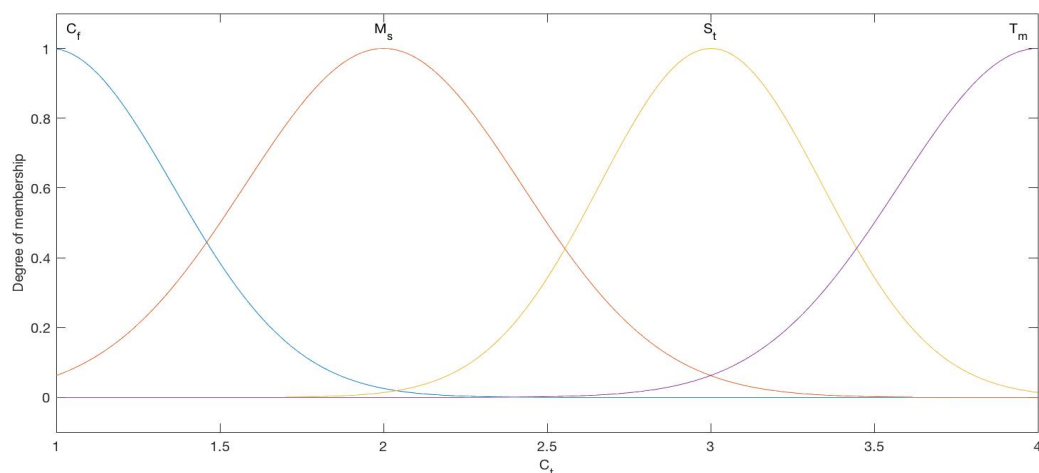


Figure 6.18: Gaussian Membership Function for Variable “Gross Floor Area”

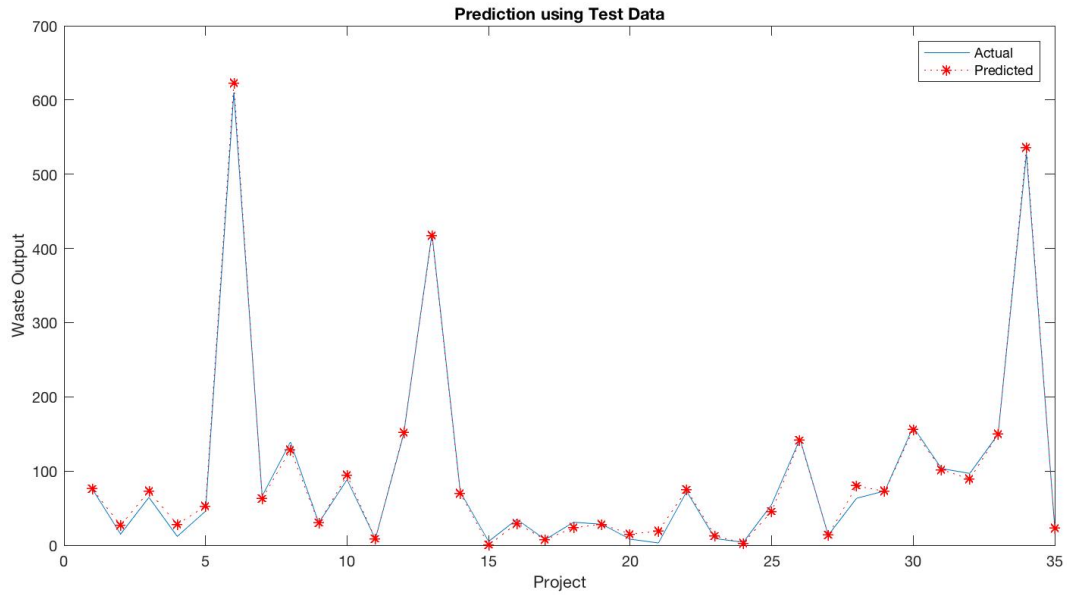


Figure 6.19: Comparison of Actual and Predicted Values

#### 6.6.4 Computing Waste by Material Types and Management Routes

The ANFIS model developed provides an automatic way of predicting the total waste of a building from its total gross floor area and construction type. However, the model was not able to provide the waste output by CW types. It would have been practicable to develop AI models for all the waste types, however, the quality of waste data record obtained did not allow this. To overcome this problem, a standard Waste Distribution Percentage (WDP) for all waste types based on construction type was computed. WDP is the percentage that a material type contributes to the total waste. WDP for all waste types according to construction type is presented in Table 6.17. As such, given a total waste output computed by the ANFIS model, the corresponding waste output by material types can be computed using WDP. In the same way, the distribution of waste management route for each waste type is computed as shown in Table 6.18.

Table 6.17: Construction Waste Output Distribution by Construction Types and Waste Types

Construction Type	Waste Type (tonnes)												Total Waste (tonnes)
	Binders	Bricks	Concrete	Gypsum	Haz.	Inert	Insulation	Metals	Mixed	Packaging	Plastics	Timber	
<i>Concrete Frame</i>	0.00	6.40	486.00	2.47	0.00	1503.74	0.00	49.00	1356.11	0.00	0.00	0.00	3403.72
<i>WDP</i>	0.00%	0.19%	14.28%	0.07%	0.00%	44.18%	0.00%	1.44%	39.84%	0.00%	0.00%	0.00%	100.00%
<i>Load Bearing Masonry</i>	104.48	323.50	515.46	289.42	9.79	7345.05	13.99	8.61	8260.24	23.35	13.79	394.81	17302.49
<i>WDP</i>	0.60%	1.87%	2.98%	1.67%	0.06%	42.45%	0.08%	0.05%	47.74%	0.13%	0.08%	2.28%	100.00%
<i>Steel Frame</i>	6.00	0.00	788.02	57.61	1.83	338.00	0.39	23.10	1145.88	1.87	14.24	30.38	2407.32
<i>WDP</i>	0.25%	0.00%	32.73%	2.39%	0.08%	14.04%	0.02%	0.96%	47.60%	0.08%	0.59%	1.26%	100.00%
<i>Timber Frame</i>	0.00	435.00	570.00	5.50	15.80	102.00	0.00	11.53	320.79	0.00	0.00	1.70	1462.32
<i>WDP</i>	0.00%	29.75%	38.98%	0.38%	1.08%	6.98%	0.00%	0.79%	21.94%	0.00%	0.00%	0.12%	100.00%
<i>Total</i>	110.48	764.9	2359.48	355	27.42	9288.79	14.38	92.24	11083.02	25.22	28.03	426.89	24575.85

Table 6.18: Distribution of Waste Management Route

Waste Type	Waste Management Route				Total (tonnes)
	Reuse	Direct Recycling	Recovery	Landfill	
<i>Binders</i>	0.00 0.00%	0.00 0.00%	110.48 100.00%	0.00 0.00%	110.48 100.00%
<i>Bricks</i>	0.00 0.00%	190.49 24.90%	574.41 75.10%	0.00 0.00%	764.90 100.00%
<i>Concrete</i>	0.00 0.00%	667.03 28.27%	1692.45 71.73%	0.00 0.00%	2359.48 100.00%
<i>Gypsum</i>	0.00 0.00%	150.32 42.34%	204.68 57.66%	0.00 0.00%	355.00 100.00%
<i>Hazardous</i>	0.00 0.00%	0.00 0.00%	6.59 24.03%	20.83 75.97%	27.42 100.00%
<i>Inert</i>	0.00 0.00%	650.65 7.00%	8638.14 93.00%	0.00 0.00%	9288.79 100.00%
<i>Insulation</i>	0.00 0.00%	2.07 14.39%	12.16 84.56%	0.15 1.04%	14.38 100.00%
<i>Metals</i>	0.00 0.00%	49.34 53.49%	42.90 46.51%	0.00 0.00%	92.24 100.00%
<i>Mixed</i>	2.00 0.02%	60.93 0.55%	11005.83 99.30%	14.26 0.13%	11083.02 100.00%
<i>Packaging</i>	0.00 0.00%	18.73 74.27%	6.49 25.73%	0.00 0.00%	25.22 100.00%
<i>Plastics</i>	0.00 0.00%	10.77 38.42%	17.04 60.79%	0.22 0.78%	28.03 100.00%
<i>Timber</i>	96.70 22.65%	127.52 29.87%	201.92 47.30%	0.75 0.18%	426.89 100.00%

## 6.7 Mathematical Model for Dimensional Coordination

A key concept in CW minimisation is dimensional coordination. Dimensional coordination must be ensured for building elements such as walls, ceiling, and floor to conform to standard dimension. This is to reduce waste due to cut-offs. The dimensions of walls must be properly coordinated because a huge amount of waste arises from construction of walls. Although several material combinations exist for walls, a standard wall cavity that is fully filled with insulation as shown in Figure 6.20 was considered for dimensional coordination. This is to

demonstrate the practicality of mathematical modelling in dimensional coordination of building materials. The standard cavity wall is composed of 102.5mm brickwork, 75mm insulation, 100mm blocks, and 12.5 mm dense plaster. Table 6.19 shows the composition of the materials and their standard dimensions.

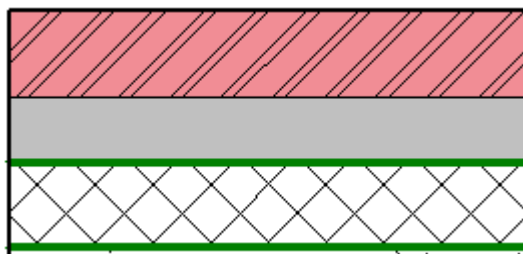


Figure 6.20: Standard Cavity Wall Fully Filled with Insulation

Table 6.19: Composition of Standard Cavity Wall

Material	Purpose	Standard Dimension (mm)
Brick	Finish 1	215x102.5x65
Insulation - Fiberglass batt insulation	Thermal and air layer	-
Block	Structure	440x100x215
Gypsum Plaster	Interior decoration finish suitable for most applications where normal fire, structural and acoustic levels are specified.	1200x2400x12.5

### 6.7.1 Computing Required Bricks

The brick quantification model uses variables, which include (i) kind, quality, and size of bricks; (ii) type of bond, e.g. stretcher, English, Flemish bond, which may determine the number of facing block and mortar used; and (iii) the thickness of joints. Table 6.20 lists the notations used in the dimensional coordination analytical model. Most of the notations are as specified in methods of test for masonry units (BS EN 772-3:1998).

Table 6.20: Metrics for Dimensional Coordination of Cavity Wall

Notation	Description
$l_u$	Length of specimen (mm)
$w_u$	Width of specimen (mm)
$h_u$	Height of specimen (mm)
$B_t$	Type of Bricks (common, facing or engineering)
$M_{au}$	Mass of the specimen in air (kg)
$t$	Thickness of joints ( <i>perp joint and bed size</i> ) (mm)
$B_{bt}$	Brick Bonding Type
$B_{pt}$	Brick Pointing Type
$l_w$	Length of required wall size (mm)
$w_w$	Width of required wall size (mm)
$h_w$	Height of required wall size (mm)
$br$	Total number of bricks required
$f$	Allowance for waste in bricks
$CW_{br}$	Waste from brick (kg)
$CW_m$	Mass of waste generated (kg)

A standard brick of size 215 mm x 102.5 mm x 65 mm was used with a mass ( $M_{au}$ ) of 1.9kg (facing brick) and a stretcher bond as illustrated in Figure 6.21. The joint thickness ( $t$ ) is typically 10mm. The waste allowance  $f$  is the percentage of likely material loss and allowance of waste in bricks is dependent on the nature of the brick (Geddes, 1996). Softer brick tends to generate more waste, however, an allowance of 2.5 to 10% is generally allowed for loss through breakage during transportation, storage, and handling. A value of  $f = 5\%$  was used in this study (Buchan, Fleming and Kelly, 1991, p.108). To simplify the model development process, the following assumptions were adopted:

- Bricks and blocks can be cut into half without damage. The implication of this assumption is that slots requiring less than 0.5 of a standard brick will require half brick and the offcut will result into waste.
- Bricks and blocks are solid with no frogs or perforations, i.e. percentage void of bricks is 0%.

- A brick pack quantity of 400 was also assumed. This informs the quantity of packaging waste generated in-situ.

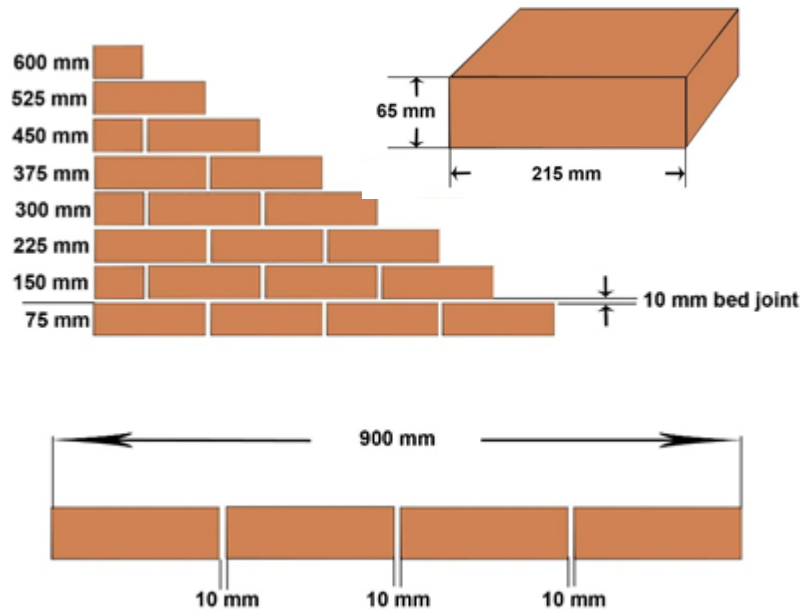


Figure 6.21: Stretcher Bond using 215x102.5x65 Brick

With these assumptions, the total number of bricks ( $br$ ) required to construct a half-brick thick (102.5mm) wall of dimension ' $l_w \times h_w$ ' is:

$$br = \frac{l_w \times h_w}{(l_u + t) \times (h_u + t)} \quad (6.12)$$

Assuming a standard brick wall height  $h_w = 3000\text{mm}$ ,  $t = 10\text{mm}$  and standard brick size,  $br$  become:

$$br = \frac{l_w \times 3,000}{(215 + 10) \times (65 + 10)} \quad (6.13)$$

$$br = \frac{8}{45}l_w \quad (6.14)$$

This reveals a linear relationship between  $br$  and  $l_w$  with a gradient (brick quantification factor) of  $8/45$ . This factor could be employed in obtaining an estimated number of bricks required to construct a wall of  $l_w \times 3000\text{mm}$  using a stretcher bond. However, this calculation does not give room for waste in bricks. To tackle this, an allowance is needed in the amount of bricks procured. Assuming an allowance for waste of  $f$  (typically 5%) in bricks to account for waste during transportation, storage, and handling, a new value of  $br_+$  was computed as:

$$br_+ = \frac{l_w \times h_w}{(l_u + t) \times (h_u + t)} \times \left(1 + \frac{f}{100}\right) \quad (6.15)$$

$$br_+ = \frac{l_w \times 3,000}{(215 + 10) \times (65 + 10)} \times \left(1 + \frac{5}{100}\right) \quad (6.16)$$

$$br_+ = \frac{14}{75}l_w \quad (6.17)$$

This equation also reveals that the relationship between the length of the wall and brick quantification factor with allowance is linear with a gradient of  $14/75$  as shown in Figure 6.22. Considering the first assumption, Algorithm 6.1 computes the actual number of bricks that is required considering that a brick can only be cut in half.



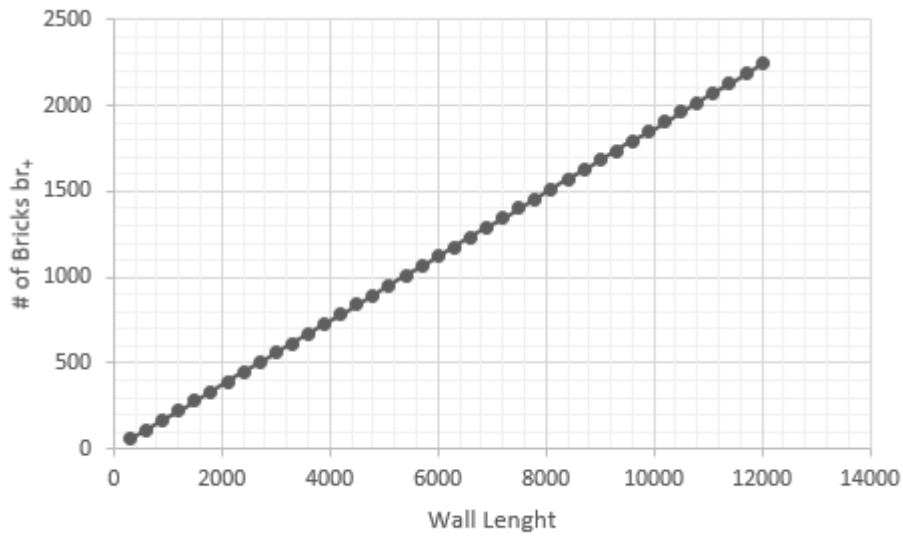


Figure 6.22: Graph of Wall Length against  $br_+$

Algorithm 6.1: Computing Number of Bricks Needed

---

*Input:  $br$*

---

**Result:** Actual number of bricks required ( $br_{actual}$ )

---

start:

```

    if ( $abs(br_+ - round(br_+, 0)) > 0.5$ )
    {
         $br_{actual} = ceil(br_+)$ ;
    }
    else
    {
         $br_{actual} = floor(br_+) + 0.5$ ;
    }
    return  $br_{actual}$ 

```

---

The  $Ceil(x)$  and  $floor(x)$  functions used in Algorithm 6.1 round  $x$  up and down respectively. At this point, CW due to bricks can be computed as the difference between the actual number of bricks and those that get used in the brickwork, i.e.:

$$CW_{br} = br_{actual} - br \quad (6.18)$$

$$\%CW_{br} = \frac{br_{actual}}{br} \times 100\% \quad (6.19)$$

Accordingly, the mass of waste generated from the brickwork could be calculated by multiplying  $CW_{br}$  with the mass of a brick, i.e:

$$CW_m = CW_{br} \times M_{au} \quad (6.20)$$

So, putting Equations (6.12) to (6.20) together yields an overall construction waste quantification function for computing the weight of waste arising from the brickworks, i.e.,

$$CW_m = \begin{cases} \left( \text{ceiling} \left( \frac{14}{75} l_w \right) - \frac{8}{45} l_w \right) \times 1.9 \text{ kg} & \text{if } (abs(br_+ - floor(br_+)) > 0.5) \\ \left( \text{floor} \left( \frac{14}{75} l_w \right) + 0.5 - \frac{8}{45} l_w \right) \times 1.9 \text{ kg} & \text{otherwise} \end{cases} \quad (6.21)$$

The weight of waste arising from the construction of different length of wall is shown in Table 6.21. A common thread that runs across these lengths of wall is that approximately the same percentage of construction waste ( $4.76\% = 5/105$ ) is generated.

*Table 6.21: Bricks Requirement and Potential Waste (height,  $l_h = 3000\text{mm}$ )*

	$l_u$ (mm)	$br$	$br_+$	$br_{actual}$	$CW_{br}$	$\%CW_{br}$	$CW_m$ (kg)
1	3600	640	672	672	32	4.76	60.8
2	7200	1280	1344	1344	64	4.76	121.6
3	8000	1422.22	1493.33	1493.5	71.28	4.77	135.4
4	14400	2560	2688	2688	128	4.76	243.2
5	16200	2880	3024	3024	144	4.76	273.6

A major problem with these figures is that they show the gross number of bricks but it is difficult to know where the actual waste from offcuts will arise. To overcome this challenge,

the number of bricks needed for the height and length of the wall must be computed separately, i.e.:

$$br_h = \frac{h_w}{(h_u + t)} \quad (6.22)$$

$$br_h = \frac{3000}{75} = 40 \quad (6.23)$$

This estimate reveals that 40 standard blocks are required to construct a one-block height of the wall. This reveals that there is no offcut from constructing the height of the wall. As such, the waste arises from the length of the wall. Algorithm 6.2 shows the computational procedure for computing the waste arising from brickworks.

*Algorithm 6.2: Waste arising from Brickwork*

---

**Input:** Brick dimensions ( $l_w, h_u$ ), wall dimensions ( $l_w, h_w$ ), thickness of joint ( $t$ )

---

**Output:** Weight of waste potential ( $CW_m$ )

---

*start:*

$[lu, hu] = [215, 65]$

$h_w = 3000$

$t = 10$

$l_w = \mathbf{input}$  length of wall

$br = \frac{8}{45} l_w$

$br_+ = \frac{14}{75} l_w$

**if** ( $abs(br_+ - round(br_+, 0)) > 0.5$ )

$br_{actual} = ceil(br_+);$

**else**

$br_{actual} = floor(br_+) + 0.5;$

$CW_{br} = br_{actual} - br$

$CW_m = CW_{br} \times M_{au}$

**return**  $CW_m$

---

## 6.8 Summary

This chapter details the waste data collection process. WDR was collected from 117 projects and exploratory data analysis was carried out on them to understand the structure of the data. The frequencies and distribution of the data along four input parameters were explored to establish strong statistical measurement for the predictive model development Based on the data. An AI hybrid model for CW prediction was then developed using ANFIS. A detailed architecture of ANFIS, which combines the strengths of ANN and FL into a single hybrid system, was presented and discussed. The process of input selection reveals that only two parameters, i.e., gross floor area and construction type, are the best predictors for CW output out of the four input parameters. The final model was trained and evaluated to assess its prediction accuracy. A mathematical model was then developed for dimensional coordination of brickworks to optimise material usage and to minimise potential waste output from wall construction.

The next chapter details how the developed models for CW prediction were integrated into BIM platform. The chapter discusses the process of model integration and the development of a BIM-based system for CW prediction and minimisation (BIMWaste).

## **7 BIM-BASED SYSTEM FOR CONSTRUCTION WASTE PREDICTION AND MINIMISATION (BIMWASTE)**

### **7.1 Overview**

The developed models for CW prediction and minimisation were integrated into BIM platform to enable automatic capture of BIM design parameters and to allow seamless integration of CW management into existing BIM software. This chapter therefore discusses the process of model integration and the development of a BIM-based system for CW prediction and minimisation (BIMWaste). The software development environment is discussed in details. The discussion covers the setup of C# programming environment, the Revit 2017 application programming interface, and user interface frameworks. Thereafter, system design for BIMWaste is presented using appropriate diagrams. This is followed with detailed discussion of the modules of the software. The modules are: (a) User Interface Module; (b) Custom parameter module; (c) Material database for BIMWaste; (d) Material Take-Off calculation module; and (e) Report generation module. To minimise the predicted CW output, the development process of BIM-based design advisor for material optimisation is presented.

### **7.2 Software Development Environment**

The Software Development Environment (SDE) is made up of C# programming environment using Visual Studio Community 2015 IDE, Autodesk Revit 2017 and its Application Programming Interface (API), and User Interface (UI) frameworks. The details of the make-up of the SDE is given in the following subsections.

#### **7.2.1 C# Programming Environment**

The Autodesk Revit .NET API uses any of the .NET programming languages, such as VB.NET, C#, and F#. However, C# remains the programming language of choice for most developers because it is easy to use and learn. The software development could be easily coded through

the Visual Studio IDE and exported as a Revit add-in. A screenshot of the Visual Studio Community IDE is shown in Figure 7.1. The add-in is an external application (a *.dll* file) that placed in the Revit add-in folder. Debugging an external application is quite different from debugging a standalone application because the external application requires another program to launch it. Debugging of add-in development requires that Revit is setup as an external command in the debugging properties page as shown in Figure 7.2. After this, the use of Managed Compatibility Mode was activated as shown in Figure 7.3. The debug properties were configured on the options dialog, which can be activated from the Tools menu of Visual Studio.

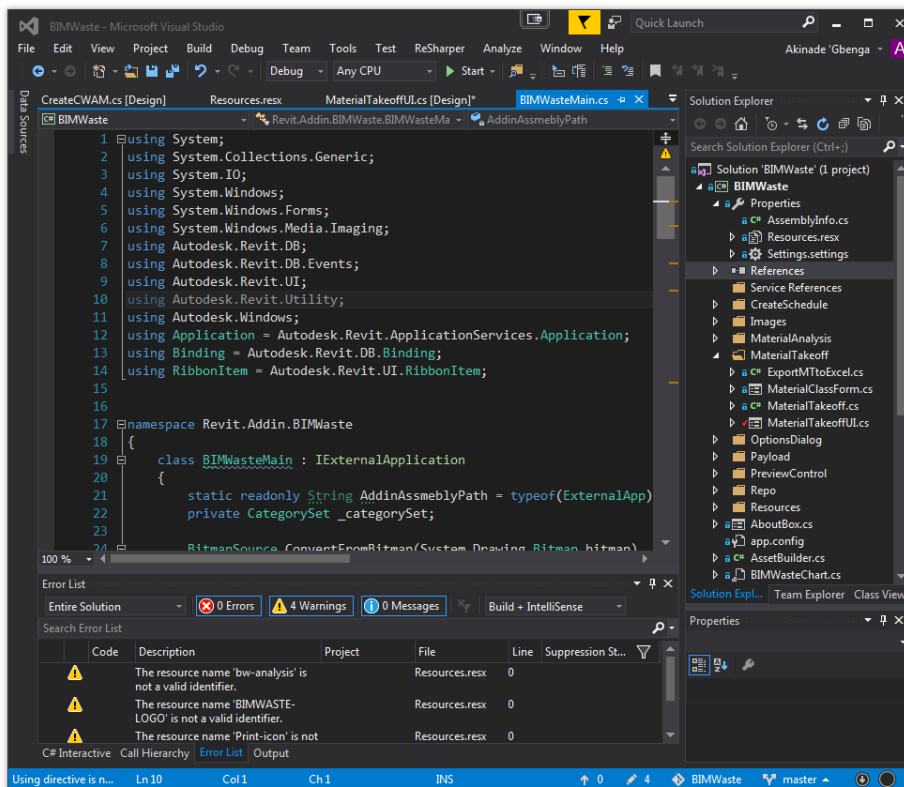


Figure 7.1: Visual Studio Community Integrated Development Environment

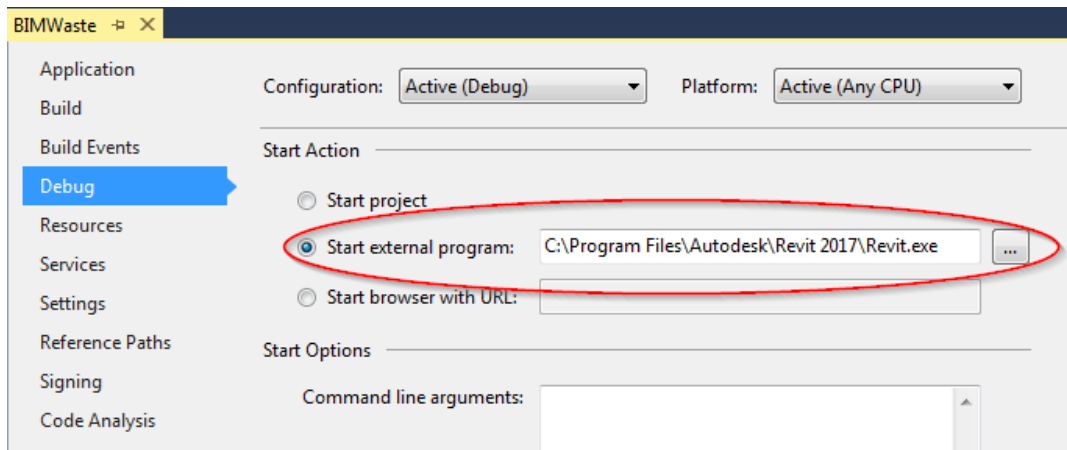


Figure 7.2: Debugging Revit Plugin in Visual Studio

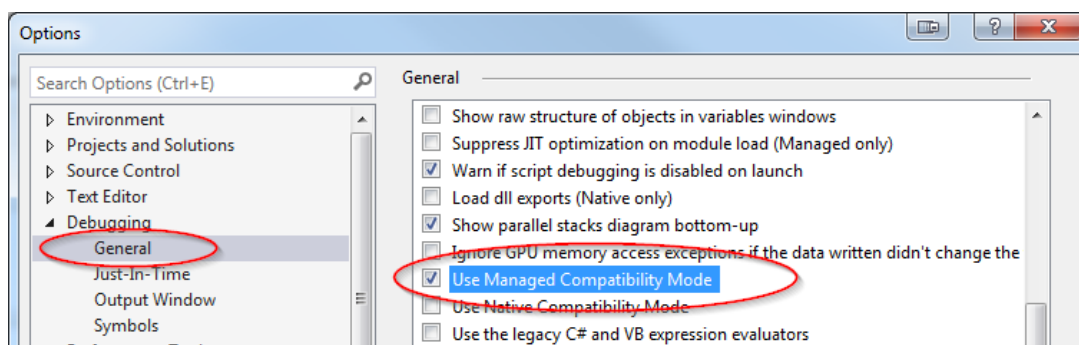
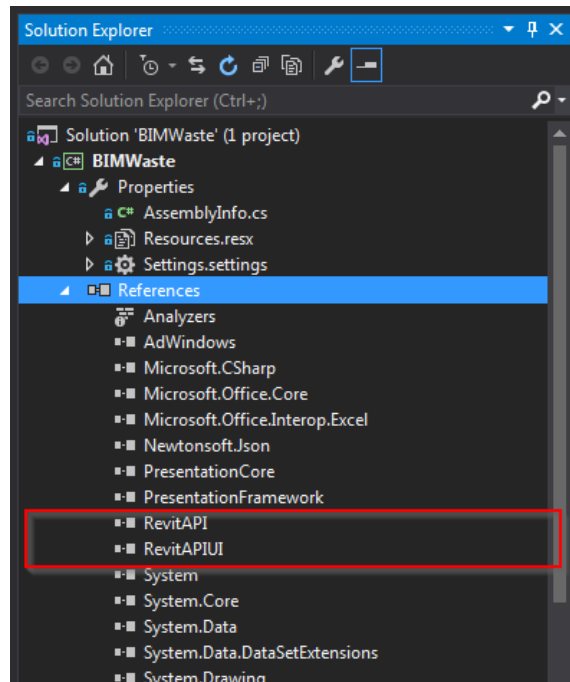


Figure 7.3: Enabling Managed Compatibility Mode in Visual Studio

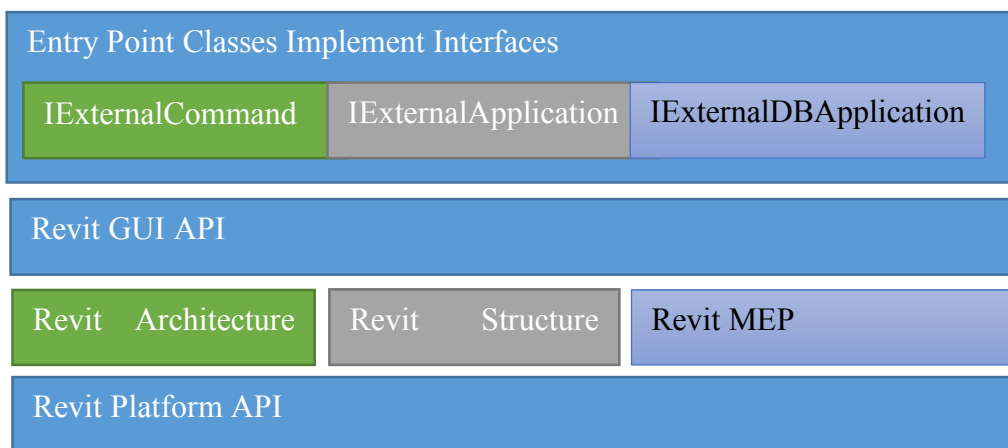
## 7.2.2 Revit 2017 Application Programming Interface (API)

Revit provides a robust API to extend its core functionality in terms of design modelling, visualisation, simulation, construction, and building management. When developing with the Revit API, it is mandatory to reference two DLLs, which are *RevitAPI.dll* and *RevitAPIUI.dll*. These two *.dll* files are in the Autodesk Revit Program directory as shown in Figure 7.4. Revit API provides three types of entry point classes implement interfaces, which are *IExternalCommand*, *IExternalApplication*, and *IExternalDBApplication* as shown in the framework in Figure 7.5. A distinguishing factor among these interfaces is in their usage and the way they are accessed. As their names implies, *IExternalCommand* is required to implement External Commands, *IExternalApplication* is required to implement External

Applications, and *IExternalDBApplication* is required to implement Database-level External Applications. The structure of Revit API framework is shown in Figure 7.5. The framework provides three core APIs, which are Revit Architecture (RAC) API, Revit Structure (RST) API, and Revit MEP (RME) API.



*Figure 7.4: The Two DLL References (RevitAPI.dll and RevitAPIUI.dll) Needed for Add-in Development*



*Figure 7.5: Autodesk Revit API Framework*



External Commands are Revit add-ins that appear on the External Tools menu button by default. When an external command is selected, its *Execute()* method is invoked and executed. The command object is however destroyed when the method returns to Revit environment. The code sample in Figure 7.6 illustrates the structure of an External Command. External Applications are add-ins that provide better UI customisation for Revit using Ribbon tabs and Ribbon Panels. The controls of the tabs or panels are then linked to external commands. *IExternalApplication* interface has two abstract methods that must be implemented. The methods are *OnStartup()*, which is called when the application starts and *OnShutdown()*, which is called when the application closes. The code structure of an External Application class is shown in Figure 7.7. DB-level add-ins are External Applications that do not add anything to the Revit UI. DB-level add-ins are used to assign events and updaters to existing Revit session. The code structure of DB-level External Application is like that of External Application but DB-level External Application implements *IExternalDBApplication*. Revit automatically loads add-ins through a *.addin* manifest file, which is an XML based file. The structure of the manifest file is shown in Figure 7.8.

```
1 public void SampleExternalCommand : IExternalCommand
2 {
3     // Implement the Execute method
4     public Autodesk.Revit.UI.Result Execute(
5         Autodesk.Revit.ExternalCommandData commandData,
6         ref string message,
7         Autodesk.Revit.ElementSet elements)
8     {
9         //body of class goes in here
10        return Autodesk.Revit.UI.Result.Success;
11    }
12 }
```

Figure 7.6: Code Structure for External Command Class

```

1 public class SampleExternalApplication: IExternalApplication
2 {
3     // Implement the OnStartup method
4     public Result OnStartup(
5         UIControlledApplication application)
6     {
7         //body of OnStart goes in here
8         return Result.Succeeded;
9     }
10
11     // Implement this method
12     public Result OnShutdown(
13         UIControlledApplication application)
14     {
15         //body of OnShutdown goes in here
16         return Result.Succeeded;
17     }
18 }

```

Figure 7.7: Code Structure for External Application Class

```

1 <?xml version="1.0" encoding="utf-8"?>
2 <RevitAddIns>
3   <AddIn Type="Application">
4     <Name>BIM Waste App</Name>
5     <Assembly>"D:\BIMWaste\BIM1\bin\Debug\BIM1.dll"</Assembly>
6     <ClientId>cb5c768a-dc24-4289-a803-58ee5afc5788</ClientId>
7     <FullClassName>BIM1.BIMMain</FullClassName>
8     <VendorId>BIMWaste</VendorId>
9     <VendorDescription>Construction waste management</VendorDescription>
10   </AddIn>
11 </RevitAddIns>

```

Figure 7.8: Structure of a .addin manifest file for External Application

To enable Revit to load the addin manifest file, the file must be placed in appropriate folder depending on the access level requirement. If the manifest file will be accessed by all users, it must be placed in the folder: "C:\ProgramData\Autodesk\Revit\Addins\2017\". However, if the file is to be accessed by specific user, it must be placed in the folder: "C:\Users\[username]\AppData\Roaming\Autodesk\Revit\Addins\2017\". By default, all .addin files placed in these folders are loaded and processed by Revit during start-up. The description of the add-in manifest tags is provided below:

- **Name:** The name of an ExternalApplication. Required for ExternalApplication only.
- **Text:** Used for ExternalCommand only to represent the name of the button that triggers the add-in.
- **Description:** A description of an ExternalCommand.

- **Assembly**: The full path to the add-in assembly file (.dll file). Required for both ExternalCommands and ExternalApplications.
- **ClientId**: It is an identifier (GUID) for the ExternalCommand or ExternalApplication.
- **FullClassName**: The path of the main class in the assembly that implements IExternalCommand or IExternalApplication
- **VendorId**: An identifier for the developer of the ExternalCommand or External Application.
- **VendorDescription**: A textual description for the developer of the add-in. This information is useful for error reporting and for add-in support.

### 7.2.3 User Interface (UI) and Presentation Frameworks

Most web applications today use libraries and frameworks that provide means of providing specific functionalities. These frameworks provide a convenient way of providing specialised functionalities on websites. To enable robust report generation and intuitive interaction within the BIMWaste software, an embedded web-based approach was adopted. As such, three main CSS and JavaScript based frameworks were used. The frameworks are Bootstrap, JQuery and ChartJS:

- a) **Bootstrap**: Bootstrap is an open-source HTML, CSS, and JavaScript front-end framework for developing responsive web user interfaces. The strength of Bootstrap includes robust grid system, easy learning curve, extensive list of pre-styled components, among others. Because of these reasons, Bootstrap is the most popular front-end UI framework for mobile first websites. BIMWaste uses Bootstrap to generate responsive report for the CW analytics and prediction results.
- b) **JQuery**: JQuery is a JavaScript framework that simplifies various tasks and it allows web developers to write less code. Important features of JQuery include DOM manipulation, event handling, lightweight, animation support, cross browser support, event handling, among others. All these have encouraged the adoption of JQuery by 72% of all websites. In addition, JQuery has a market share of 96.5% of the JavaScript library market share (W3Techs, 2016).

- c) **ChartJS**: ChartJS is a JavaScript library for drawing different types of interactive charts using SVG. As such, the framework is compatible with all modern and mobile browsers that support SVG. A key strength of ChartJS is that it works well out-of-the-box and it produces highly responsive charts.

### **7.3 System Design for BIMWASTE**

To understand the implementation process of BIMWaste, a block diagram for its process flow was drawn as shown in Figure 7.9. The process starts with the preparation of the BIM design in Revit and the specification of appropriate design parameters. After that, a Construction Waste Analytical (CWA) model is created and the different sections of the CWA models are updated as the analysis progresses. The Revit document is then loaded and analysed to create a material take-off for the design and to calculate the number of levels and Gross Floor Area (GFA) of the design. The asset builder and CWA engine are then invoked to populate the CWA and to prepare the report. In addition to providing basic project information and design parameters, the report also shows the overall waste generation, waste management routes, waste performance analytics, floor level waste distribution, and waste distribution.

### **7.4 BIM-based software for Construction Waste Prediction**

After the review of the prototype of BIMWaste, the software implementation process began using C# within Visual Studio Express IDE. This section therefore discusses the implementation of the modules of BIMWaste and their operations. Based on RAD framework, BIMWaste was divided into five active modules, which include User Interface (UI) module, Custom parameter module, material database module, material take-off calculation module, and report generation module. These modules captured key functionalities of BIMWaste. The modules are explained as follows:

### 7.4.1 User Interface Module

The first activity carried out was the integration of BIMWaste as an add-in within Revit environment. This was implemented as an External Application and added to the Ribbon Panel. The class implementation for one of the buttons is shown in Figure 7.10. The Ribbon Panel for BIMWaste is shown in Figure 7.11. The panel is made-up of six buttons: (i) Welcome Page, (ii) About BIMWaste Button, (iii) Preferences Button, (iv) Create CWA Model Button, (v) Design Advisor Button, and (vi) Reports Button. The functions of the buttons are:

- (i) **Welcome Page Button:** The button displays the welcome page for BIMWaste as shown in Figure 7.12. The welcome page contains a description for BIMWaste and two buttons. The “Start Design” Button disposes the dialog and enables the user to start the design. The “Learn more” Button open the BIMWaste website ([www.bimwaste.org.uk](http://www.bimwaste.org.uk)) to access the user guide and available tutorials on the use of BIMWaste.
- (ii) **About BIMWaste Button:** The button opens the about dialog that provides basic information about the software. The information includes software version, developer details, and description. The about dialog is shown in Figure 7.13.
- (iii) **Preferences Button:** This button opens the preferences dialog as shown in Figure 7.14. The dialog allows the user to customise the parameters and the content of the CWA report. The preferences dialog is made up of three main section, which include: (a) Landfill tax amount: This contains the current amount paid for landfill disposal, (b) CWA Report Sections: This section helps to customise the content of the generated CWA report, and (c) CWA Report Logo: This allows the user to customise the company logo of the CWA report. A preview of the selected logo is also provided within this section. The settings are saved using Application settings, which allows applications to store and retrieve property settings dynamically. The Application Settings page is shown in Figure 7.15.

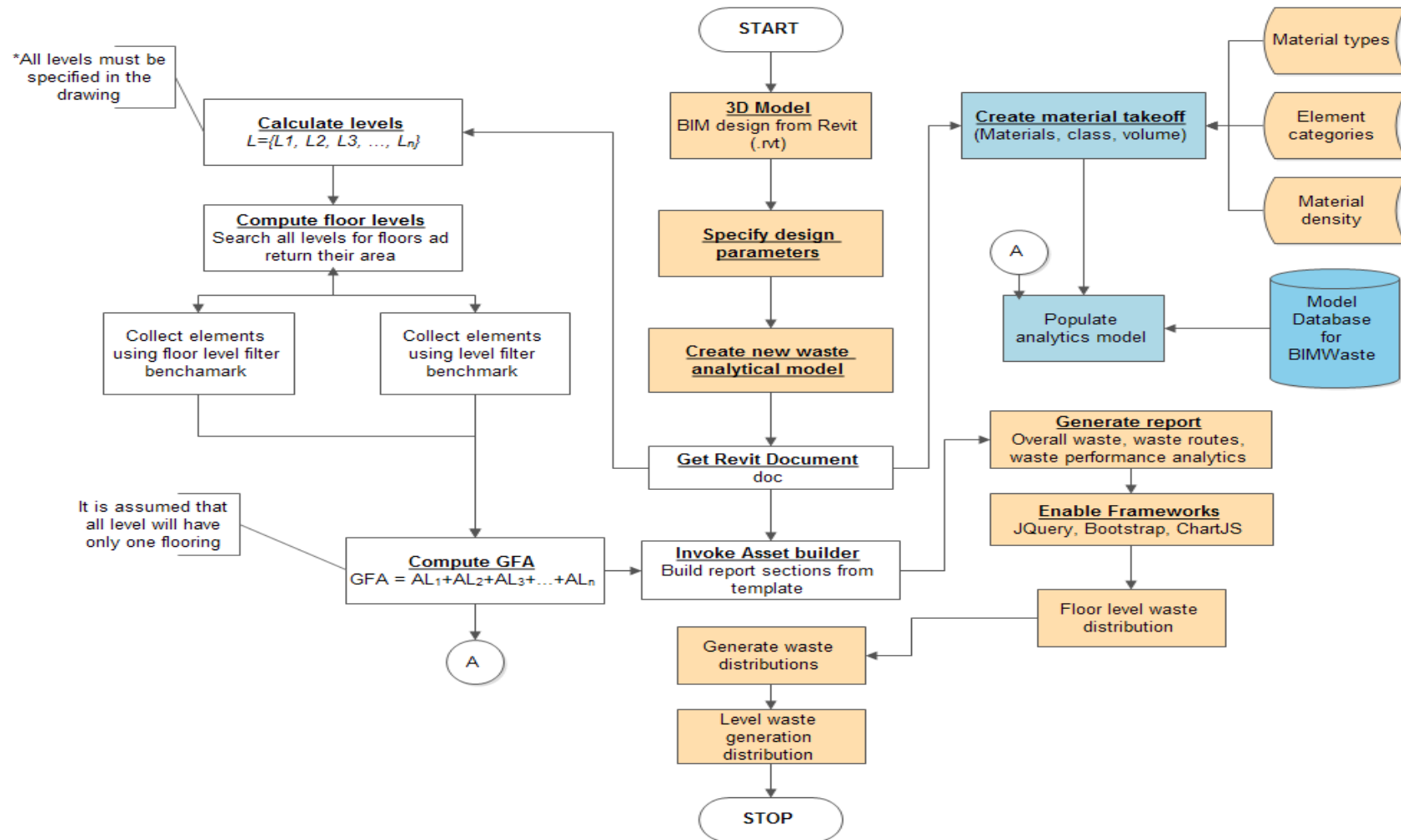


Figure 7.9: Process flow for BIMWaste

```

1 class BIMWasteMain : IExternalApplication
2 {
3     void CreateRibbonButton(UIControlledApplication application)
4     {
5         var BIMWasteRibbon = application.CreateRibbonPanel("BIMWaste");
6         var generateModelButton = new
7         PushButtonData("BIM_Waste_Generate_Model", "Create model", AddinAssmeblyPath,
8             "Revit.Addin.BIMWaste.CWAMHandler")
9         {
10            LargeImage = ConvertFromBitmap(Properties.Resources.Predict),
11            Image = ConvertFromBitmap(Properties.Resources.Predict),
12            ToolTip = "Generate new waste analytical model for current design"
13        };
14        var generateModelPB = BIMWasteRibbon.AddItem(generateModelButton) as
15        PushButton;
16    }
17
18    public Result OnShutdown(UIControlledApplication application)
19    {
20        return Result.Succeeded;
21    }
22
23    public Result OnStartup(UIControlledApplication application)
24    {
25        CreateRibbonButton(application);
26        return Result.Succeeded;
27    }
28 }

```

Figure 7.10: Class Implementation for BIMWaste Ribbon Panel

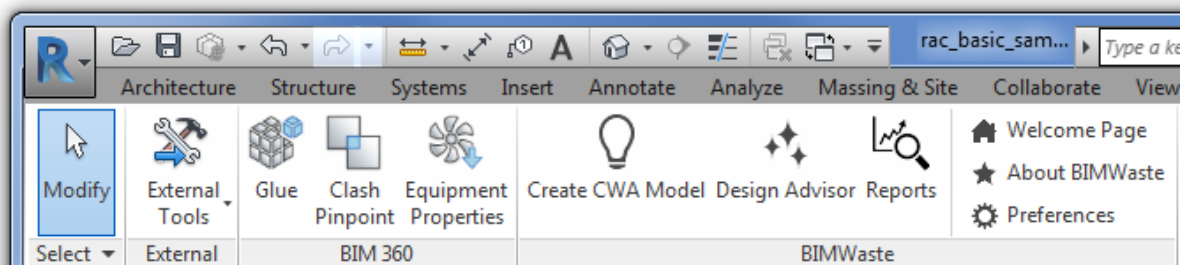


Figure 7.11: BIMWaste Ribbon Panel



*Figure 7.12: Welcome Page for BIMWaste*



*Figure 7.13: BIMWaste About Dialog*





Figure 7.14: BIMWaste Preferences Dialog

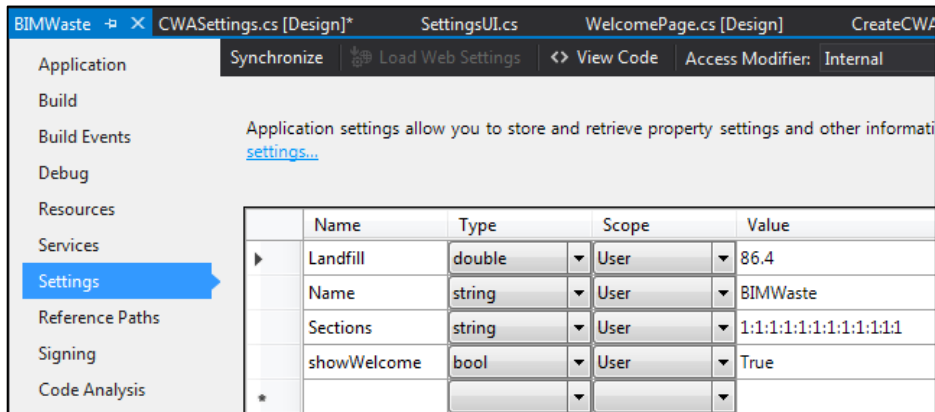
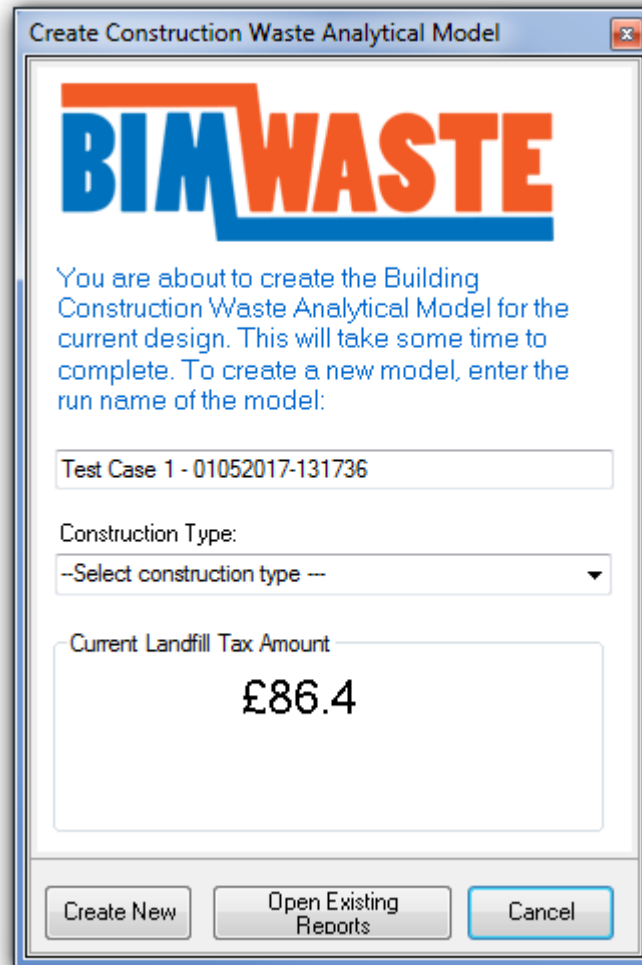


Figure 7.15: BIMWaste Application Settings Page



*Figure 7.16: Create CWA Model Dialog*

- (iv) **Design Advisor Button:** The “Design Advisor” button opens a dialog for supporting users during design-out-waste process. The dialog provides different interactive visualisation of the existing project and exploratory analysis of the Quantity Take-off. In addition, the dialog provides a decision support mechanism CW minimisation through material optimisation.
- (v) **Reports Button:** The Reports Button opens a Window that displays previous CWA reports. The report window is shown in Figure 7.17. The Window is made up of three main panels, which are: (a) **Menubar Panel**, which contains button for commands that allows reports to be compared, exported to PDF, and printed. It also contains the help button that links the user to the user guide, (b) **Report Treeview Panel**, which contains links to previous reports. The reports are identified by their

names. Selecting a project from the Treeview enables specific commands on the Menubar and displays the corresponding report in the Report View Panel, and (c) **Report View Panel**, which contains the report of the selected CWA project selected on the Report Treeview Panel.

The report view panel is a web-based view that contains the following sections: (a) Project information that contains basic information and other details such as GFA, number of levels, and total number of floors; (b) Dashboard that shows the total waste, cost of disposal, predicted CW management route; (c) Levels details that shows the name and elevation of the levels; (d) Overall waste output by element types Table; (e) Overall waste output by material type Table; (f) Waste distribution charts by element type and material type; (g) Element-Material Waste Distribution Histogram; and (h) Stacked Chart and pie chart for Waste distribution by levels. Figure 7.18 to Figure 7.20 show sections of a sample CWA report. In addition, the panel provides a link to download the Bill of Quantity (BoQ) as an Excel file. A sample of the exported BoQ in Excel format is shown in Figure 7.21.

#### **7.4.2 Custom Parameters Module**

An important factor that makes BIM relevant in building design is its ability to capture design parameters automatically for simulating building performances. To leverage upon this, current BIM parametric modelling software allows user-specific design parameters to extend the information about building elements. Revit API provides two types of parameters: shared parameters and project parameters. Shared parameters can be shared among several projects but project parameter is specific to a project. Accordingly, project parameters were created to capture various aspects of CWA from building elements. The custom parameters include Prefabrication attribute, recyclability attribute, reusability attribute, toxicity of element, and packaging attribute. The Project parameters were the attached to a CategorySet that is made up of Walls, Doors, Floors, Roofs, Windows, Columns, Curtain Wall Panels, Structural Foundations, and Structural Columns. Figure 7.2 shows the project parameters for a Basic Wall. The method used to create the project parameters is shown in Figure 7.23.

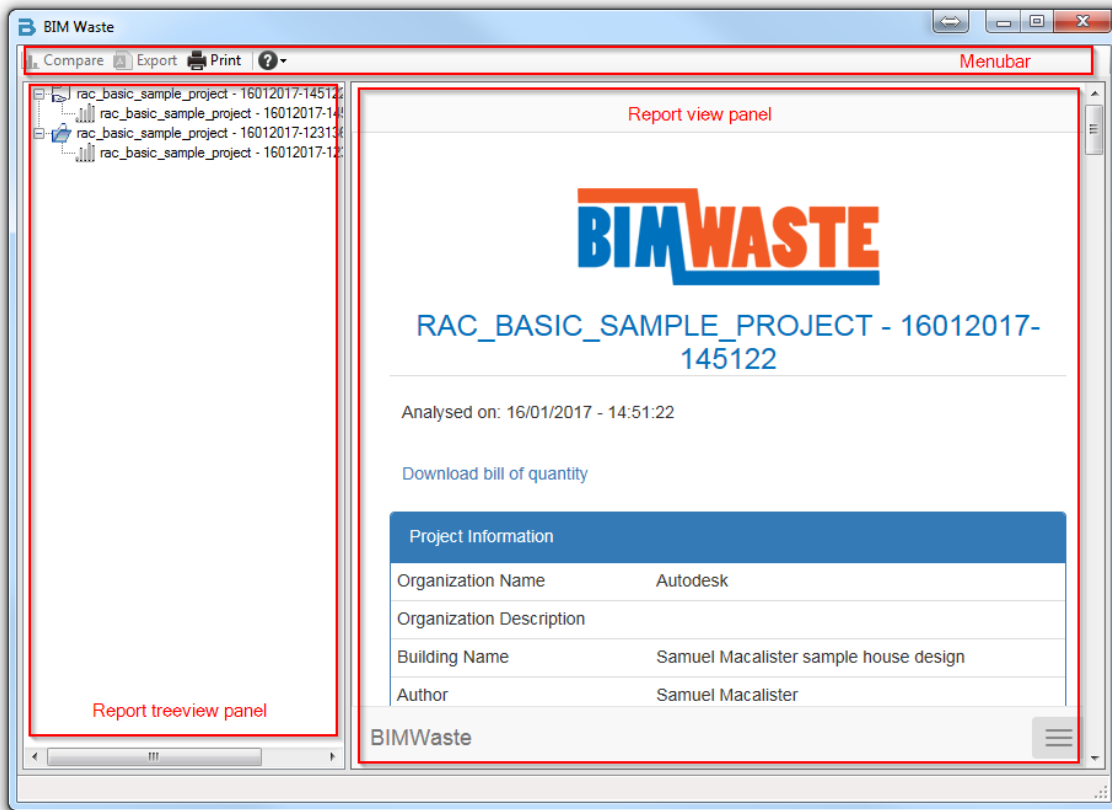


Figure 7.17: BIMWaste Reports Window

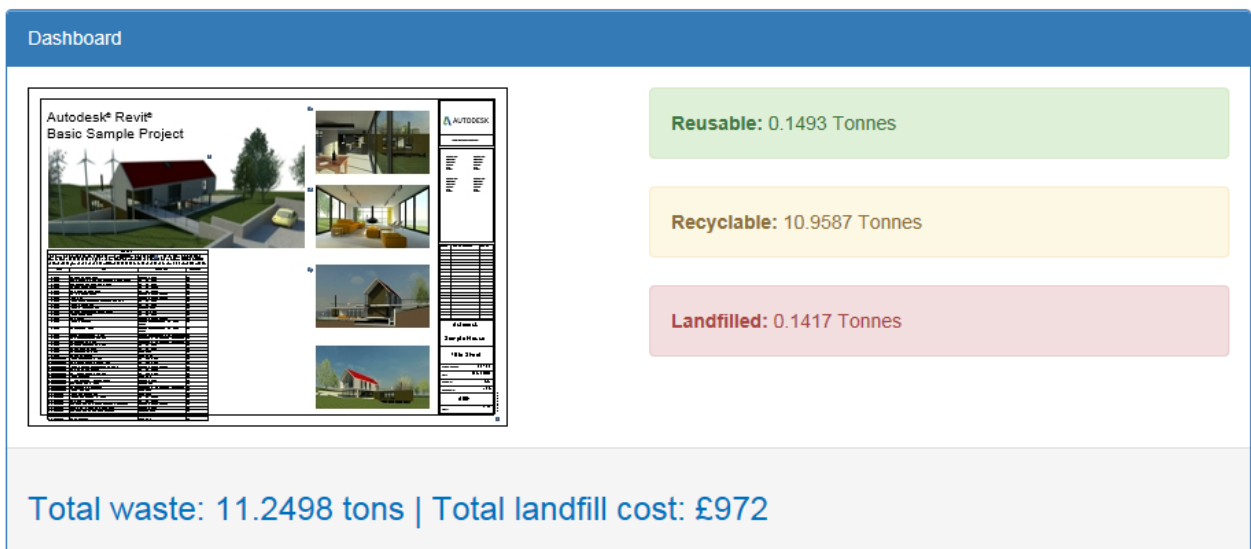


Figure 7.18: Sample Dashboard of a CWA Report

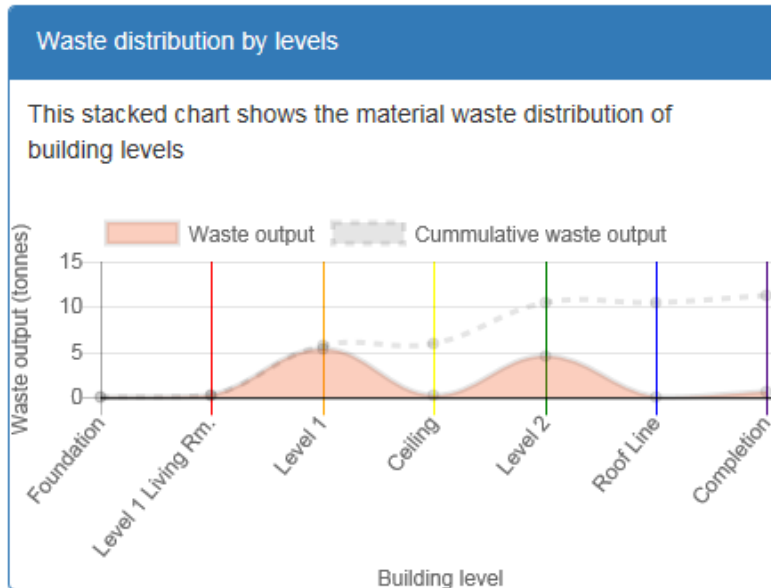


Figure 7.19: Sample Waste Distribution by Levels Stacked Chart

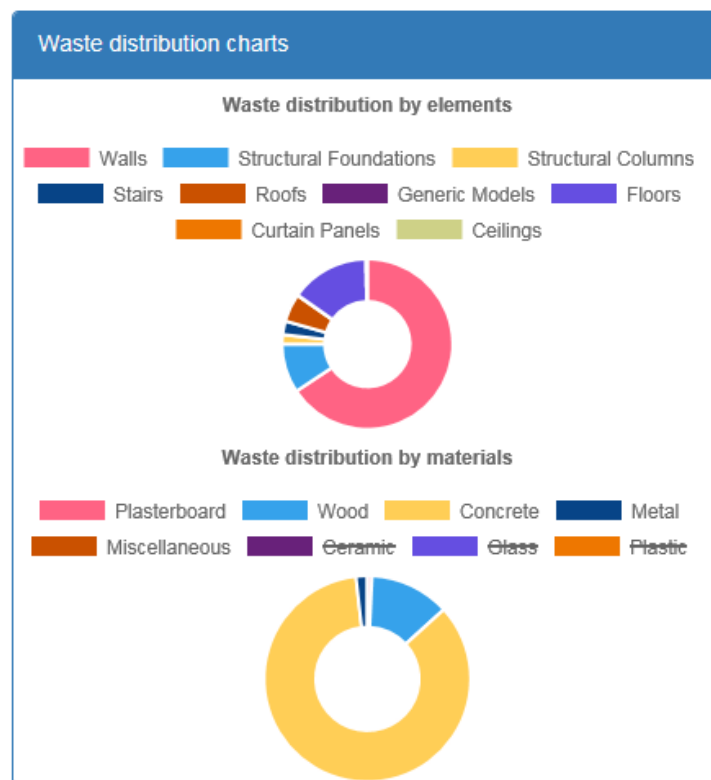


Figure 7.20: Sample Waste Distribution by Element and Material Types

1	Category Name	Element Id	Element Name	Material Name	Material Class	Tonnage	Volume
2	Walls	198694	SIP 202mm Wall - c	Finishes - Interior - Plasterboard	Plasterboard	0.7352544	0.319675826
3	Walls	198694	SIP 202mm Wall - c	Wood - Stud Layer	Wood	0.344266274	0.614761204
4	Walls	198694	SIP 202mm Wall - c	Structure - Timber Insulated Panel -	Wood	1.542312909	2.754130194
5	Walls	198694	SIP 202mm Wall - c	Structure - Timber Insulated Panel -	Wood	0.413119529	0.737713445
6	Walls	198694	SIP 202mm Wall - c	Concrete, Sand/Cement Screed	Concrete	1.081979719	0.54098986
7	Walls	198749	Wall - Timber Clad	Finishes - Interior - Plasterboard	Plasterboard	0.197667514	0.085942397
8	Walls	198749	Wall - Timber Clad	Wood - Stud Layer	Wood	0.092553351	0.165273841
9	Walls	198749	Wall - Timber Clad	Structure - Timber Insulated Panel -	Wood	0.414639013	0.740426809
10	Walls	198749	Wall - Timber Clad	Structure - Timber Insulated Panel -	Wood	0.111064021	0.198328609
11	Walls	198749	Wall - Timber Clad	Finishes - Exterior - Timber Cladding	Wood	0.081446949	0.14544098
12	Walls	234869	Wall - Timber Clad	Finishes - Interior - Plasterboard	Plasterboard	0.706295411	0.307084961
13	Walls	234869	Wall - Timber Clad	Wood - Stud Layer	Wood	0.330706882	0.590548003
14	Walls	234869	Wall - Timber Clad	Structure - Timber Insulated Panel -	Wood	1.481566829	2.645655052
15	Walls	234869	Wall - Timber Clad	Structure - Timber Insulated Panel -	Wood	0.396848258	0.708657603

Figure 7.21: Sample of Exported Bill of Quantity in Excel Format

Properties

Basic Wall  
Wall - Timber Clad

Walls (1) Edit Type

Constraints

Structural

Dimensions

Identity Data

Phasing

General

Prefabricated assembly

Recyclable item

Reusable item

Contains toxic items

Has own packaging

Figure 7.22: Project Parameters for CWA

```

1 public void CreateProjectParameter(
2     Document doc, string name,
3     ParameterType type)
4     {
5         Application app = doc.Application;
6         var oriFile = app.SharedParametersFilename;
7         var tempFile = Path.GetTempFileName() + ".txt";
8         using (File.Create(tempFile))
9             {
10            }
11        app.SharedParametersFilename = tempFile;
12
13        var def = app.OpenSharedParameterFile()
14            .Groups.Create("TemporaryDefintionGroup")
15            .Definitions.Create(new
16 ExternalDefinitionCreationOptions(name, type)) as ExternalDefinition;
17
18        app.SharedParametersFilename = oriFile;
19        File.Delete(tempFile);
20        Binding binding = app.Create.NewTypeBinding(_categorySet);
21        if (true) binding = app.Create.NewInstanceBinding(_categorySet);
22
23        var map = (new
24 UIApplication(app)).ActiveUIDocument.Document.ParameterBindings;
25        map.Insert(def, binding, BuiltInParameterGroup.PG_GENERAL);
26    }

```

*Figure 7.23: Create Project Parameters Function*

### 7.4.3 Material Database for BIMWaste

To facilitate CWA, a material database was created. This was implemented as a class with static global variables. As such, the variables were used to capture the forms of materials available and their classes. The forms include: (a) AllMaterialClass, which is a list of strings that contains the name of all materials; (b) UnknownMaterial, which contains the materials that are not assigned; (c) ExceptionMaterialClass, which contains the materials that are not included in CWA; (d) ExceptionElementClass, which contains the list of element classes that are not included in CWA; and (e) ValidMaterialClass, which contain a total of 13 material classes that were involved in CWA. The Material Database class is shown in Figure 7.24.

```

1  class MaterialDatabase
2  {
3      public static List<string> AllMaterialClass = new List<string>(new[]
4      {
5          "Asphalt", "Bricks", "Concrete", "Earth", "Gas", "Generic", "Glass",
6  "Gypsum", "Inert", "Insulation", "Leather", "Liquid", "Masonry", "Metals",
7          "Mixed", "Paint", "Paint/Coating", "Plasterboard", "Plastic", "Stone",
8  "System", "Textile", "Plant",
9          "Unassigned", "Wood"
10     });
11
12     public static List<string> UnknownMaterial = new List<string>(new[]
13     {
14         "Generic", "Miscellaneous", "Unassigned"
15     });
16
17     public static List<string> ExceptionMaterialClass = new List<string>(new[]
18     {
19         "Asphalt", "Earth", "Gas", "Leather", "Liquid", "Paint",
20 "Paint/Coating", "System", "Textile", "Plant", "Generic"
21     });
22
23     public static List<string> ExceptionElementClass = new List<string>(new []
24     {
25         "Doors", "Windows", "Specialty Equipment", "Site", "Plumbing Fixtures",
26 "Lighting Fixtures", "Furniture Systems",
27         "Furniture", "Electrical Equipment", "Casework"
28     });
29
30     public static List<string> ValidMaterialClass = new List<string>(new[]
31     {
32         "Bricks", "Concrete", "Glass", "Gypsum", "Inert", "Insulation",
33 "Masonry", "Metals", "Mixed", "Plasterboard", "Plastic", "Stone", "Wood"
34     });
35 }

```

*Figure 7.24: Material Database Class*

#### 7.4.4 Material Take-Off Calculation Module

The Material Take-off calculation module was developed based on RICS New Rules of Measurement: Detailed measurement of building works (NRM2). NRM2 contains specific guidelines and good practice on the quantification and description of work at all work stages to produce BoQ and quantified schedule of works. In addition, NRM2 provides guidance on unquantifiable items such as risk transfer, overheads, and profits. NRM2 is particularly important to produce a tender price. In addition, NRM2 provides a consistent framework for preparing bill of quantities and quantified schedule of works and it offers easily comprehensible rules that could be used by stakeholders. This thereby aids effective communication between the project team and the client.



The accuracy to which a building is measured and described has a great influence on the accuracy of the quantities and the reliability of the tender price. To codify and automate construction waste quantification process, the composition, and the structure of the bill of quantities needs to be determined. Bill of quantities provides a list of building components, their description, and quantities for accurate tender preparation. Accordingly, two approaches to the measurement of bill of quantities exist; (a) firm measurement, and (b) approximate measurement. Firm measurement is done on a fully designed building to obtain a BoQ. Accordingly, a firm BQ produces an accurate measurement where there is no design change. Firm BoQs thus provides better control over material quantities and project cost. On the contrast, approximate BoQ is adopted when available information is insufficient for the preparation of firm BQ. As such, a firm measurement was adopted for the preparation of elemental BoQ breakdown structure. The methods for collecting all elements and material are shown in Figure 7.25. Figure 7.26, Figure 7.27, and Figure 7.28 show the functions for identifying all levels, collecting elements according to their levels and for calculating GFA respectively.

#### **7.4.5 Report Generation Module**

CWA reports are generated using an HTML-based Asset builder. The Asset builder employs JQuery, Bootstrap, and ChartJS for the creation of the panels of the report. The UI of the report is Bootstrap-based and ChartJS is used to generate interactive charts. The content of the HTML Head tag is shown in Figure 7.29. Sample code for Element-Material Waste Distribution Panel is shown in Figure 7.30 and the corresponding JavaScript code that creates the chart is shown in Figure 7.31. The corresponding chart is shown in Figure 7.32. To enable easy access to the different parts of the report, a menu bar is provided as shown in Figure 7.33.

```

1 public Dictionary<string, List<Element>>
2   CollectAllEllements(FilteredElementCollector collector)
3   {
4       Dictionary<string, List<Element>> sortedElements =
5       new Dictionary<string, List<Element>>();
6       foreach (Element e in collector)
7       {
8           Category category = e.Category;
9           if (null != category && category.HasMaterialQuantities &&
10              !MaterialDatabase.ExceptionElementClass.Contains(category.Name))
11           {
12               var name = category.Name;// If this category was not yet
13 encountered, add it and create a new container for its elements.
14               if (!sortedElements.ContainsKey(name))
15               {
16                   sortedElements.Add(name, new List<Element>());
17               }
18               sortedElements[name].Add(e);
19           }
20       }
21       return sortedElements; }
22
23 public IEnumerable<Element> GetAllMaterials(
24     Document doc, Dictionary<string, List<Element>> sortedElements,
25     string category)
26 {
27     List<ArrayList> matArrayList = new List<ArrayList>();
28     IEnumerable<Element> elementList =
29     from e in sortedElements[category] where !(e is ElementType) select e;
30     return elementList;}

```

Figure 7.25: Functions for Collecting All Element and Materials

```

1 public List<Level> GetAllLevels()
2 {
3     return new FilteredElementCollector(document)
4         .WherePasses(new ElementClassFilter(typeof(Level),
5         false)).Cast<Level>()
6         .OrderBy(e => e.Elevation).ToList();
7 }
8 public Dictionary<string, double> GetLevelsInfo()
9 {
10     List<Level> levels = GetAllLevels();
11     Dictionary<string, double> levelsInfo =
12     new Dictionary<string, double>();
13     foreach (Level level in levels)
14     {
15         if (null != level)
16         {
17             levelsInfo[level.Name] =
18             Math.Round(level.ProjectElevation * 304.8);
19         } }
20     return levelsInfo;}

```

Figure 7.26: Functions for Getting all Level and Their Elevation

```

1      public Dictionary<Level, List<Element>> GetLevelElements(
2          Dictionary<string, List<Element>> sortedElements)
3      {
4          Dictionary<Level, List<Element>> levelElements =
5              new Dictionary<Level, List<Element>>();
6          var allLevels = GetAllLevels();
7          foreach (var level in allLevels)
8          {
9              ElementFilter f =
10                 new LogicalOrFilter(new ElementIsElementTypeFilter(false),
11                                     new ElementIsElementTypeFilter(true));
12
13                 ElementLevelFilter filterElementsOnLevel =
14                     new ElementLevelFilter(level.LevelId);
15
16                 FilteredElementCollector collector1 =
17                     new FilteredElementCollector(_document).WherePasses(f);
18                 collector1.OfClass(typeof(FamilyInstance)).
19                     WherePasses(filterElementsOnLevel);
20                 List<Element> elements = collector1.ToElements().ToList();
21                 levelElements.Add(level, elements);
22             }
23         return levelElements;
24     }

```

*Figure 7.27: Function for Getting Elements According to Level*

```

1      public double GetGFA(IEnumerable<Element> allFloors)
2      {
3          var area = 0.0;
4          foreach (var element in allFloors)
5          {
6              area =
7                  area + element.get_Parameter(
8                      BuiltInParameter.HOST_AREA_COMPUTED).AsDouble() * 92903;
9          }
10         return area;
11     }
12

```

*Figure 7.28: Function for Calculating Gross Floor Area*

```

1      <head>
2          <meta charset="UTF-8"/>
3          <title>BIMWaste - Construction Waste Analysis</title>
4          <!--Load Frameworks - Bootstrap, ChartJS, and JQuery -->
5          <link rel="stylesheet" type="text/css"
6              href="css/bootstrap/bootstrap.min.css"/>
7          <script src="js/Chart.bundle.min.js"></script>
8          <script src="js/jquery.min.js"></script>
9      </head>

```

*Figure 7.29: HTML Code for Report Head Tag*

```

1      <div class='row' id="wasteelementmaterial">
2          <div class='col-md-12'>
3              <div class='panel panel-primary'>
4                  <div class='panel-heading'>
5                      Element-material waste distribution
6                  </div>
7                  <p>This stacked chart shows the material waste
8                      distribution of building elements</p>
9                  <div style="width: 100%">
10                     <canvas id="ele-mat-dist"></canvas>
11                 </div>
12             </div>
13         </div>
14     </div>

```

*Figure 7.30: HTML Code for Element-Material Waste Distribution Panel*

```

1  window.onload = function() {
2      var ctxstacked = document.getElementById("ele-mat-dist").
3          getContext("2d");
4      window.myBarStacked = new Chart(ctxstacked,
5          {
6              type: 'bar', data: stackedData,
7              options: {
8                  title: {
9                      display: false,
10                     text: "Element-material waste distribution"
11                 },
12                 },
13                 tooltips: { mode: 'label' },
14                 responsive: true,
15                 scales: {
16                     xAxes: [
17                         { stacked: true, }
18                     ], yAxes: [
19                         { stacked: true }
20                     ]
21                 }
22             }
23         });

```

*Figure 7.31: JavaScript Code for Stacked Bar Chart*

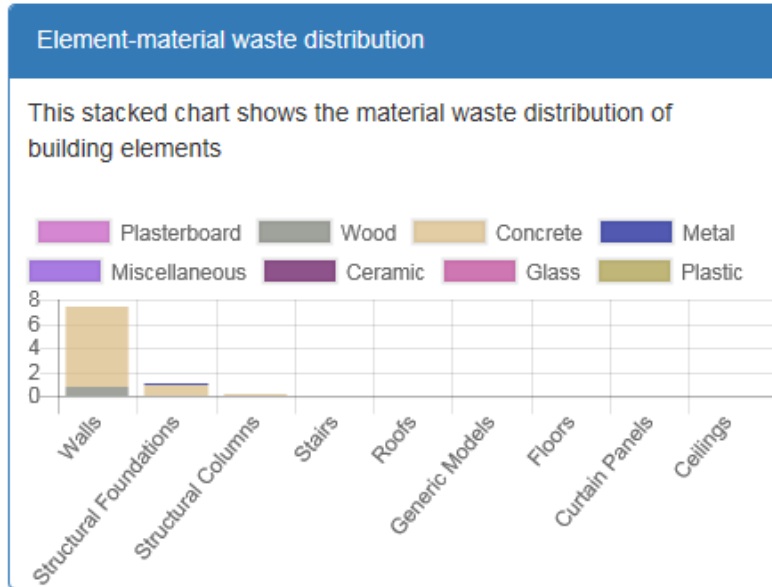


Figure 7.32: Sample Element-Material Waste Distribution Stacked Chart



Figure 7.33: Menu Bar to Access Panels of the Reports

## 7.5 BIM-Based Design Advisor for Material Optimisation

Effective material optimisation system comprises of three main components, which perform the following tasks:

- a) **Quantity Take-off Calculation**: This is to compute the total amount of material required for a building model.
- b) **CW Output Prediction**: This is to estimate the CW potential of a building design model.
- c) **CW Output Minimisation**: This is to optimise material selection towards effective waste minimisation.

The process for achieving Tasks (a) and (b) in BIM environment has been enumerated. What is left is how the predicted CW output for a building design can be minimised. The following focuses on how CW minimisation models were integrated into BIM environment.

The “Design Advisor” button on the BIMWaste Ribbon panel, as shown in Figure 7.34, opens a dialog for supporting users during CW minimisation process. The resulting dialog is shown in Figure 7.35. The dialog provides interactive visualisation and exploratory analysis of the material quantity take-off. It also provides a decision support mechanism for CW minimisation through material optimisation. The design advisor provides alternatives to materials from the BIM design to minimise the overall CW output. The dialog is made up of several panels, which include (a) Report Panel, (b) Waste Output Panel, (c) Document Preview Panel, (d) Material and Element Class Navigator Panel, (e) Properties Panel, (f) Chart Navigator Panel, and (g) Element Details Navigator Panel. The details and functions of these panels are provided as follows.

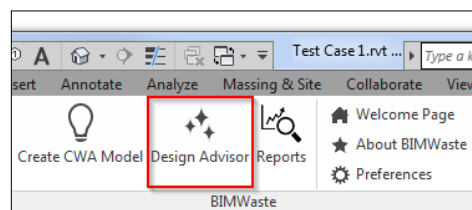


Figure 7.34: Design Advisor Button on BIMWaste Ribbon

- a) **Report Buttons Panel:** The buttons of this panel provide access to new and existing Construction Waste Analytics (CWA) reports. The “New” button creates a new CWA report based on the existing configuration of the design advisor. The “Reports” button opens existing reports for comparison.
- b) **Waste Output Panel:** This panel provides a summary of the waste output and the amount that could be reused, recycled, and landfilled. The panel is automatically updated based on the current configuration of the design advisor.
- c) **Document Preview Panel:** The document preview panel provides a 3D interactive visualisation of the Revit model. The panel is bound with the Revit software such that a change in view in the panel updates the preview of the document. The panel provides a dropdown to determine the layout that would be displayed.
- d) **Material and Element Class Navigator Panel:** This panel provides an exploratory overview of material and element classes from the BIM design. The panel allows users to select material and element class that would be explored. The panel also provides Waste Output in tonnes, Overall Waste Output Percentage (OWOP) and Waste Output Index (WOI) of the class. OWOP measures the percentage contribution of the material and element class with respect to the overall waste output. WOI shows the waste efficiency of the material and element class. This measures the proportion of the material and element class that is contributing to the overall waste output.

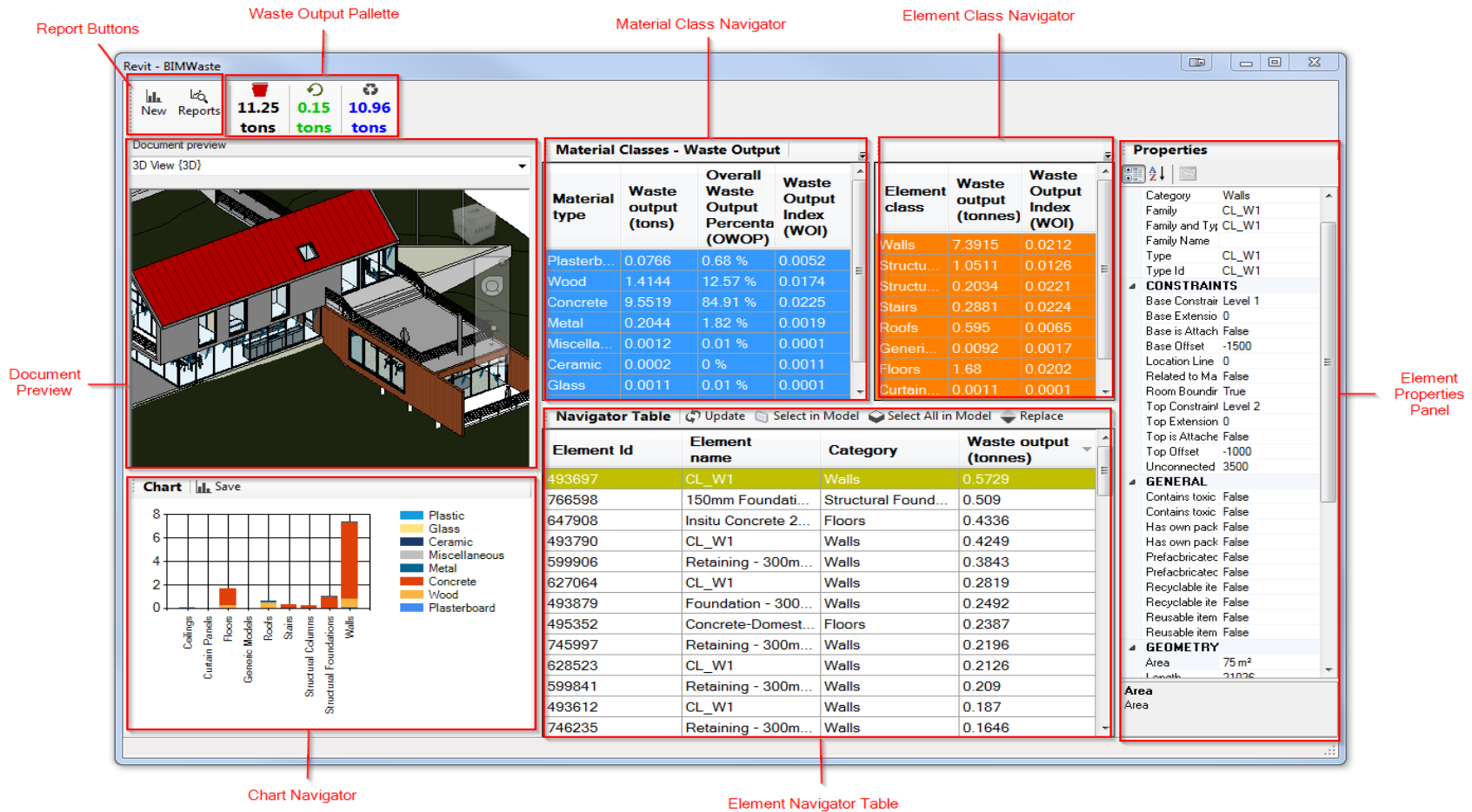


Figure 7.35: Material Optimisation Design Advisor Dialog



```

1 private void selectElement_Click_1(object sender, EventArgs e)
2 {
3     var fg = detailsGridView.SelectedRows[0].Cells[0].Value.ToString();
4     Element selectedElement = _dbDocument.GetElement(new
5 ElementId(int.Parse(fg)));
6     IList<ElementId> idsToSelect = new List<ElementId>();
7     idsToSelect.Add(selectedElement.Id);
8     _uidoc.Selection.SetElementIds(idsToSelect);
9     _uidoc.ShowElements(idsToSelect);
10 }
11
12 private void SelectAllElements_Click(object sender, EventArgs e)
13 {
14     var fg = detailsGridView.SelectedRows[0].Cells[0].Value.ToString();
15     Element selectedElement = _dbDocument.GetElement(new
16 ElementId(int.Parse(fg)));
17     IList<ElementId> idsToSelect = new List<ElementId>();
18     idsToSelect.Add(selectedElement.Id);
19
20     var allElements = _sortedElements[selectedElement.Category.Name];
21     var selectedFamily =
22 selectedElement.get_Parameter(BuiltInParameter.ELEM_FAMILY_PARAM).AsString();
23     var selectedType =
24 selectedElement.get_Parameter(BuiltInParameter.ELEM_TYPE_PARAM).AsString();
25
26     foreach (var ele in allElements)
27     {
28         var currentElementFamily =
29 selectedElement.get_Parameter(BuiltInParameter.ELEM_FAMILY_PARAM).AsString();
30         var currentElementType =
31 selectedElement.get_Parameter(BuiltInParameter.ELEM_TYPE_PARAM).AsString();
32         if (selectedFamily == currentElementFamily && selectedType ==
33 currentElementType)
34             idsToSelect.Add(ele.Id);
35     }
36     MessageBox.Show(idsToSelect.Count + " Elements selected");
37     _uidoc.Selection.SetElementIds(idsToSelect);
38     _uidoc.ShowElements(idsToSelect);
39 }

```

*Figure 7.36: Selecting Single and All Elements in Document Preview*

Selecting an element in the table activates the “Replace” button, which opens a dialog that contains possible replacement elements. The dialog also contains the amount of waste that will be added to or reduced from the current total waste. Figure 7.39 shows replacement elements for “Basic Wall CL\_W1”.

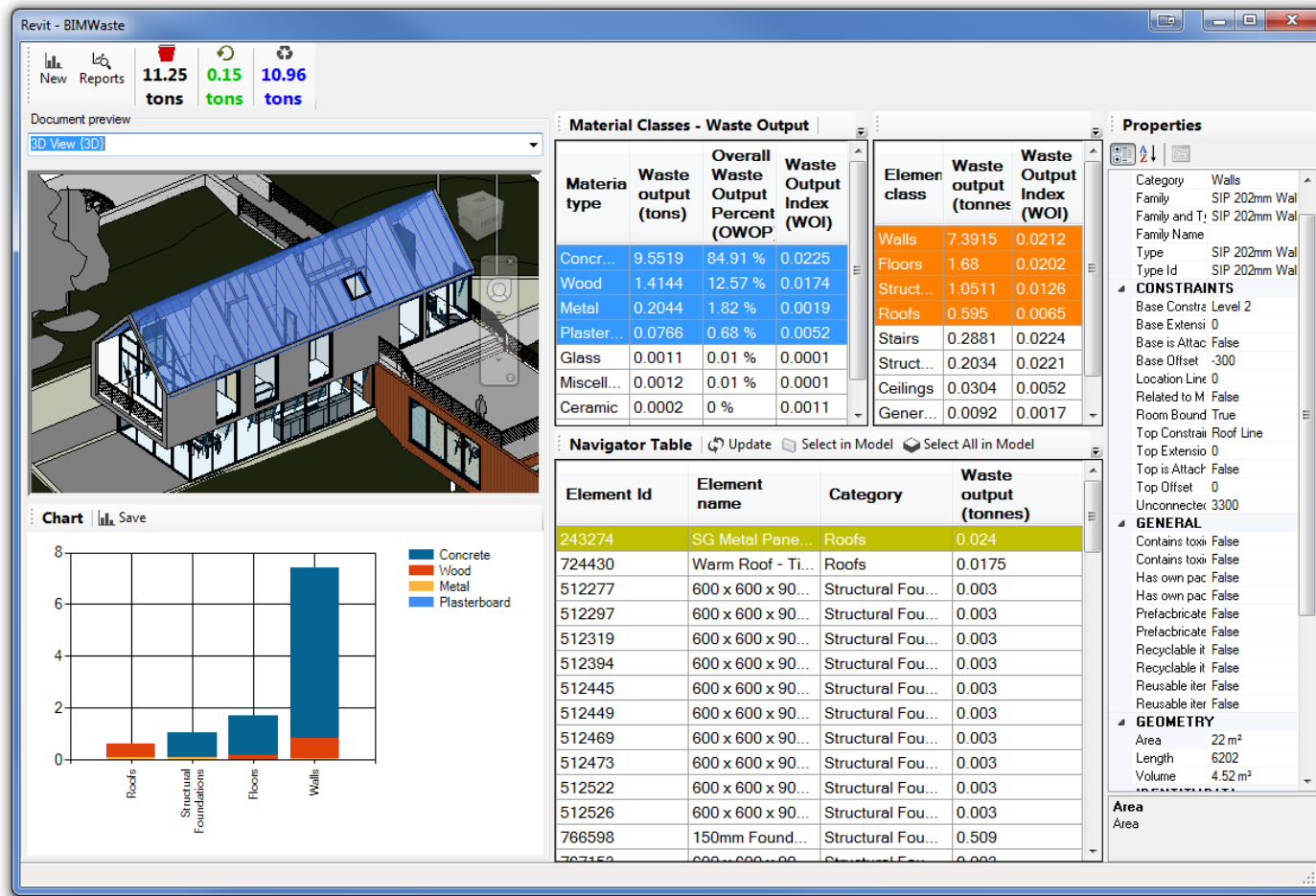


Figure 7.37: Updating Element Details Table and Chart. The selected element is shown in the preview panel

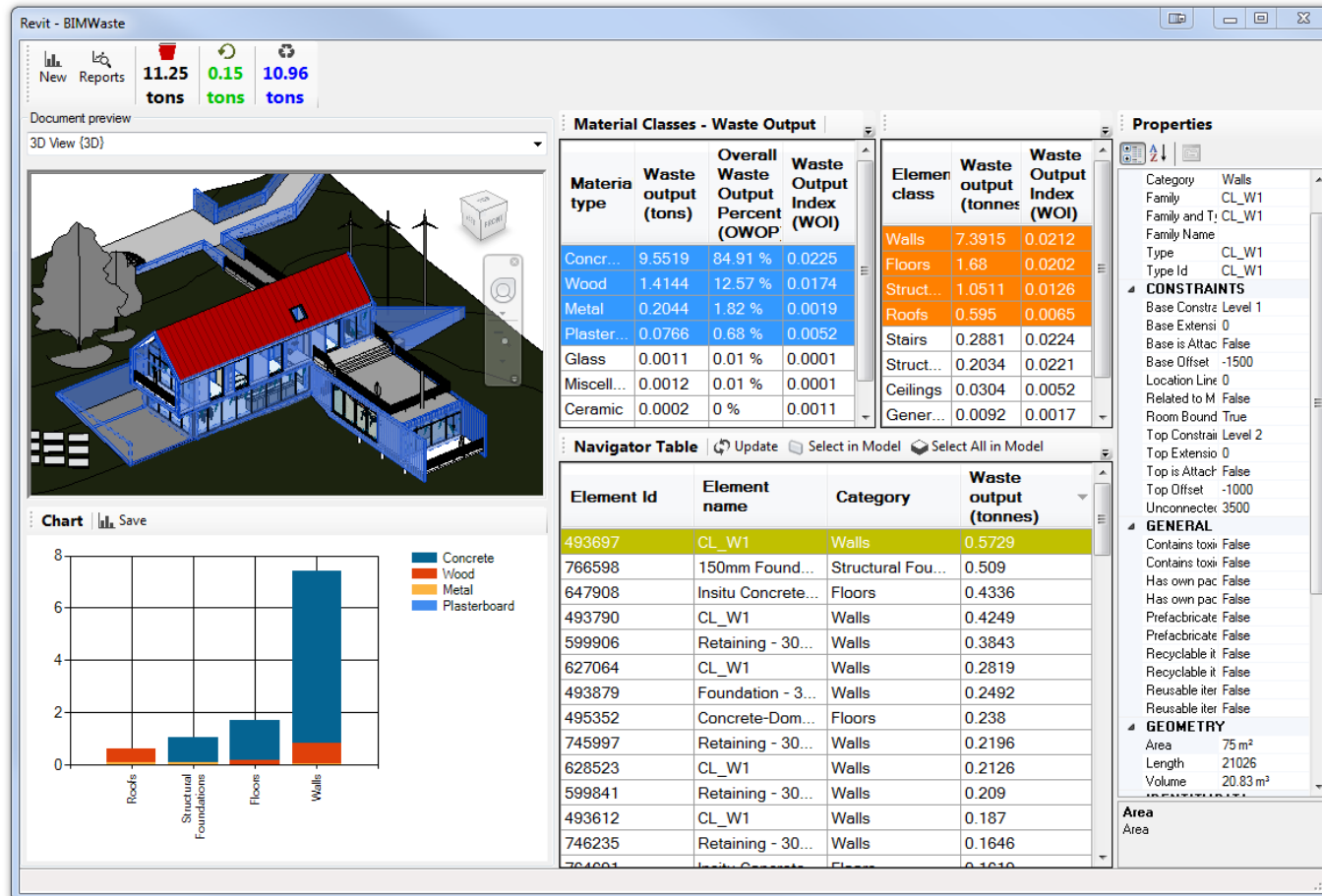


Figure 7.38: Selecting all Elements of Type CL\_W1

Type Id	Family	Type	+/-
397	Basic Wall	Exterior - Brick ...	0.2833
54538	Basic Wall	Exterior - Block ...	0.3824
198367	Basic Wall	Wall - Timber Cl...	0.3718
232754	Basic Wall	Interior - 165 P...	0.2833
232827	Basic Wall	Interior - Partition	0.3642
428955	Basic Wall	SIP 202mm Wal...	0.3718
581500	Basic Wall	Foundation - 30...	0.3718
600634	Basic Wall	CL_W1	0
711906	Basic Wall	Retaining - 300...	0.8498
845480	Basic Wall	Cavity wall_slid...	0.478
458927	Curtain Wall	SH_Curtain wall	0.2833

*Figure 7.39: Possible Replacement Elements for Basic Wall CL\_W1*

- e) **Chart Navigator Panel:** This panel provides a visual comparison of the selected material and element classes. The chart is shown as a stacked histogram and it provides a quick way of compare the contributions of the material and element classes to the overall waste output. The chart in Figure 7.35 shows the contributions of all material and element classes while Figure 7.38 shows a stacked histogram for a subset of {Roofs, Structural Foundations, Floor, Walls} and {Concrete, Wood, Metal, Plasterboards}. Figure 7.38 clearly shows that Walls are contributing the largest proportion of waste and that the largest portion of the waste is concrete. The chart navigator panel also provides a “save” button to export the chart as a PNG image.
- f) **Properties Panel:** The properties panel provides details of the selected element from the element details navigator panel. The panel provides the properties of the selected element.

```

1 private void chartSaveButton_Click(object sender, EventArgs e)
2 {
3     chartSaveDialog.Filter = "PNG Image|.png|Jpeg Image|.jpg";
4     chartSaveDialog.Title = "Save Chart as Image File";
5     chartSaveDialog.FileName = "Chart.png";
6     DialogResult result = chartSaveDialog.ShowDialog();
7     chartSaveDialog.RestoreDirectory = true;
8     if (result == DialogResult.OK && chartSaveDialog.FileName != "")
9     {
10        try
11        {
12            if (chartSaveDialog.CheckPathExists)
13            {
14                if (chartSaveDialog.FilterIndex == 2)
15                {
16                    chartNavigator.SaveImage(chartSaveDialog.FileName,
17 ChartImageFormat.Jpeg);
18                }
19                else if (chartSaveDialog.FilterIndex == 1)
20                {
21                    chartNavigator.SaveImage(chartSaveDialog.FileName,
22 ChartImageFormat.Png);
23                }
24            }
25            else
26            {
27                MessageBox.Show("Given Path does not exist");
28            }
29        }
30        catch (Exception ex)
31        {
32            MessageBox.Show(ex.Message);
33        }
34    }
35 }

```

*Figure 7.40: Save Chart as PNG image*

## 7.6 System Testing for BIMWaste

To test the full BIMWaste tool for its prediction ability, a plan for functional and non-functional testing of BIMWaste was developed. The test plan for BIMWaste is shown in Table 7.1. Two test cases of BIM designs were developed in Autodesk Revit for this purpose. Description of the two test cases is presented in Table 7.2. Estimation of the amount of CW for the two test cases was carried out on BIMWaste and it provides an overview of the waste arising by material types, element categories, and floor levels. BIMWaste accurately computes the Gross Floor Area and the number of floors in the building design. An overview of the test results is shown in Table 7.3.

Table 7.1: Test Plan for BIMWaste

<b>ID</b>	<b>Requirement and Test Component</b>	<b>Functional/Non-Functional</b>	<b>Test Area</b>
1	BIMWaste .addin file successfully loaded by Autodesk Revit Engine	Non-Functional	System
2	Add-in interface successfully integrated into Revit UI. Test all buttons are properly displayed.	Non-Functional	System/Usability
3	Welcome Screen: Display welcome screen for BIMWaste when a project is loaded in Revit	Non-Functional	System
4	Create new CWA dialog: BIMWaste presents a dialog for user to enter project name and to choose construction type.	Functional	Unit/System/Usability
5	Compute GFA of design: Check the accuracy of the computed GFA by BIMWaste	Functional	Unit/System
6	Compute number of floors and levels in design: Check the accuracy of the number of floors and levels computed by BIMWaste	Functional	Unit/System
7	Result of CWA: The system provides CWA results to user	Functional	Unit/System/Usability
8	Responsive report: The system allow user to interact with components of report	Functional	Unit/System/Usability
9	Show previous results: The reports of previous CWA should be accessible through a tree	Functional	Unit/System/Usability
10	Print Report: Allow users to print CWA report to printer and PDF	Functional	Unit/System/Usability
11	Design Advisor: Open dialog for Exploratory analysis	Functional	Unit/System/Usability
12	Communication between CWA and Design Advisor	Functional	Unit/System/Usability

Table 7.2: Test Cases for BIMWaste

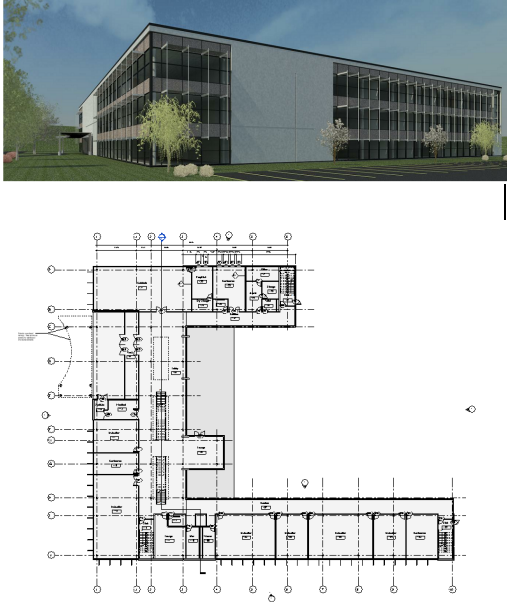
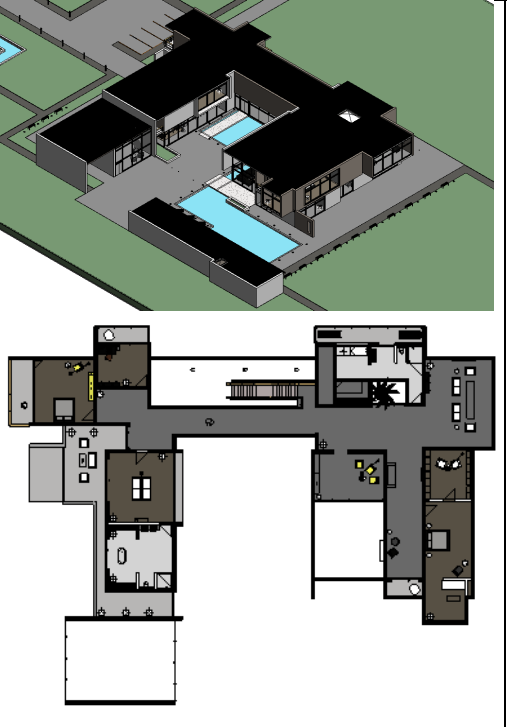
Test Case	Graphics for Test Case	Description of Test Case
<p><i>Test Case 1</i></p>	 <p>The graphics for Test Case 1 consist of two parts. The top part is a 3D architectural rendering of a modern office building with a glass facade and a flat roof, set against a clear blue sky. The bottom part is a detailed 2D floor plan of the building, showing various rooms, corridors, and structural elements with grid lines.</p>	<p>This case is an office building:            No of levels: 5 Levels            No of floors: 3 Floors            GFA: 5,312.04m<sup>2</sup></p>
<p><i>Test Case 2</i></p>	 <p>The graphics for Test Case 2 consist of two parts. The top part is a 3D isometric rendering of a commercial building complex with multiple interconnected volumes, a central courtyard with a pool, and a parking area. The bottom part is a detailed 2D floor plan of the building, showing various rooms, corridors, and structural elements with grid lines.</p>	<p>This is a two-floor commercial building.            No of levels: 5 Levels            No of floors: 2 Floors            GFA: 33,952.41m<sup>2</sup></p>

Table 7.3: Overview of Test Results

	Bricks	Concrete	Gypsum	Inert	Metals	Mixed	Total Waste
Test Case 1	0.04	2.98	0.02	9.21	0.30	8.31	20.86
Test Case 2	0.07	5.63	0.03	17.42	0.57	15.71	39.44

### 7.6.1 Results for Test Case 1

This case is an office building with three floors and a GFA of 5,312.04m<sup>2</sup>. Total waste is 20.86 tonnes. This amount of waste will require a payment of £1,802 if all the total waste is sent to land fill at the current rate of £86.4. The summary of the CWA is shown in Figure 7.41. The results of the CWA revealed that 0.0312 tonnes, 20.7814 tonnes, and 0.0428 tonnes of the total waste could be reused, recycled, and finally sent to landfill respectively. The result also showed that waste output by waste type is as follows: brick (0.04 tonnes), concrete (2.98 tonnes), gypsum (0.02 tonnes), inert (9.21 tonnes), metal (0.30 tonnes), and mixed waste (8.31 tonnes). Thereafter, waste distribution by element types and building levels were computed as shown in Figure 7.42 and Figure 7.43 respectively.



Figure 7.41: CWA Dashboard for Test Case 1



Overall waste by element type			
OWOP - Overall Waste Output Percentage, Waste Output Index (WOI) shows the proportion of element that is waste			
Element class	Waste output by element type (tons)	OWOP (%)	WOI
Walls	4.0837	19.5811%	0.0013
Structural Framing	0.6169	2.958%	0.0052
Structural Columns	0.5267	2.5256%	0.0053
Stairs	0.0751	0.3603%	0.0053
Roofs	3.7586	18.0223%	0.0037
Generic Models	0.0002	0.0009%	0.0001
Floors	11.601	55.6259%	0.0052
Curtain Panels	0.0239	0.1147%	0.0001
Ceilings	0.1692	0.8112%	0.0005

Figure 7.42: Waste Output by Element Type for Test Case 1

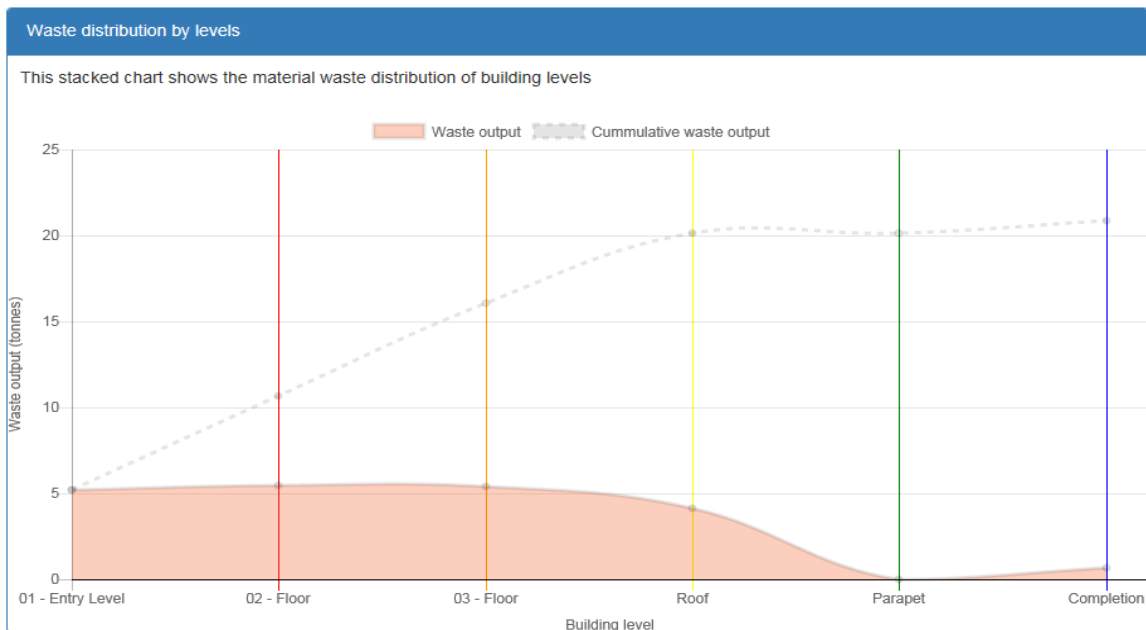


Figure 7.43: Waste Distribution by Building Levels for Test Case 1

## 7.6.2 Results for Test Case 2

This case is an office building with three floors and a GFA of 33,952.41m<sup>2</sup>. Total waste is 39.44 tonnes. This amount of waste will require a payment of £3,408 if all the total waste is sent to land fill at the current rate of £86.4. The summary of the CWA is shown in Figure 7.44. The results of the CWA revealed that 0.0673 tonnes, 39.3048 tonnes, and 0.0693 tonnes of the total waste could be reused, recycled, and finally sent to landfill respectively. The result also showed that waste output by waste type is as follows: brick (0.07 tonnes), concrete (5.63tonnes), gypsum (0.03 tonnes), inert (17.42 tonnes), metal (0.57 tonnes), and mixed waste (15.71 tonnes). Thereafter, waste distribution by element types and building levels were computed as shown in Figure 7.45 and Figure 7.46 respectively.



Figure 7.44: CWA Dashboard for Test Case 2

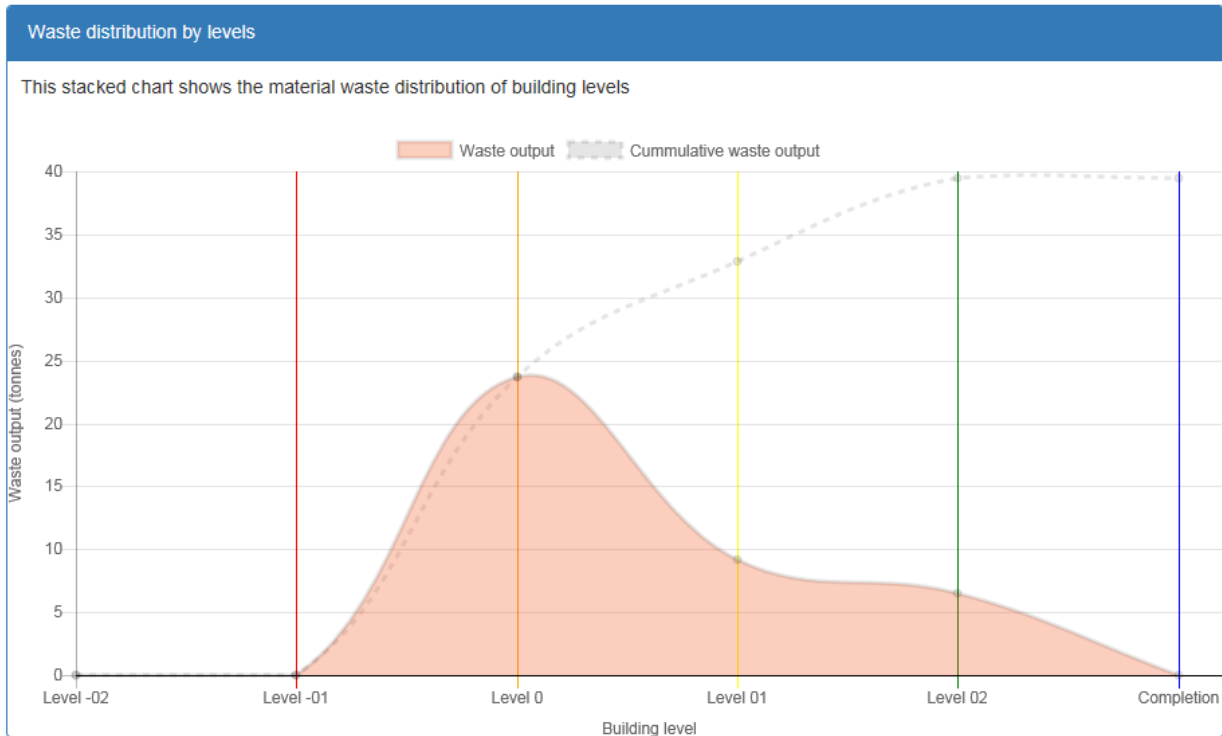
Overall waste by element type			
OWOP - Overall Waste Output Percentage, Waste Output Index (WOI) shows the proportion of element that is waste			
Element class	Waste output by element type (tons)	OWOP (%)	WOI
Walls	10.9844	27.8499%	0.0111
Stairs	0.0265	0.0671%	0.0225
Roofs	7.3382	18.6053%	0.0217
Generic Models	0.0001	0.0003%	0.0033
Floors	21.0877	53.466%	0.0033
Curtain Panels	0.0041	0.0103%	0.0001
Ceilings	0.0004	0.0011%	0.0001

Figure 7.45: Waste Output by Element Type for Test Case 2

## 7.7 Summary

In this chapter, a BIM-based system for CW management (BIMWaste) was developed and tested. The BIM system incorporates AI hybrid and mathematical models that were developed in the previous chapter. This is to allow the system to capture the parameters of the BIM design automatically for CW analytics. Details of the SDE was discussed. The SDE is made up of C# programming environment using Visual Studio Community 2015 IDE, Autodesk Revit 2017 and its API, and UI and presentation frameworks. Thereafter, the prototyping and implementation of BIMWaste began using C# within Visual Studio Express IDE. The key functionalities of BIMWaste were divided into five active modules, which include User Interface (UI) module, Custom parameter module, material database module, material take-off calculation module, and

report generation module. A BIM-Based design advisor for material optimisation was also implemented for BIMWaste. The chapter ends with the evaluation and testing of BIMWaste.



*Figure 7.46: Waste Distribution by Building Levels for Test Case 2*

This next chapter contains the discussion of findings from the study. The discussion starts with the identification of evaluative criteria for CW management tools and BIM strategies for CW management. Concluding section of the chapter contains discussion of findings from ANFIS model development and BIM-based tool development for CW management.

## **8 DISCUSSION OF RESULTS**

### **8.1 Overview**

This chapter contains the discussion of findings from the previous chapters. The discussion starts with the identification of evaluative criteria for CW management tools. Findings revealed a list of 40 criteria that could be used to evaluate the performance of existing CW management tools and this was grouped under six categories. The chapter proceeds with the discussion of BIM strategies for CW management and holistic BIM framework for CW management. Concluding section contains discussion of findings from ANFIS model development and BIM-based tool development for CW management.

### **8.2 Evaluative Criteria for Construction Waste Tools**

The results of the thematic analysis revealed a list of 40 criteria that could be used to evaluate the performance of existing waste management tools, grouped into six categories: (a) waste prediction; (b) waste data; (c) commercial and procurement; (d) BIM; (e) design; and (f) technological. The six evaluation criteria categories are discussed as follows.

#### **8.2.1 Waste Prediction Criteria**

As previously noted, accurate waste quantification and prediction is a prerequisite for the implementation of effective waste minimization strategies (Bossink and Brouwers, 1996; Solís-Guzmán *et al.*, 2009). As such, waste prediction tools must be fully engaged during the design process to identify potential opportunities to reduce waste. However, no such tool exists, as noted by an architect during the FGIs:

*While it is possible to reduce waste during design, there is no tool that can measure waste that is preventable during the design process. (excerpt from FGI-1)*

Although existing tools such as NWT (WRAP, 2011b) and DoWT-B (WRAP, 2011a) require design parameters for waste forecast, they cannot be used until the design plan – or bill of quantity – has been prepared, thus revealing a huge gap in knowledge that an operational waste management tool must provide waste prediction functionality during the model design process. This is carried out with the knowledge that all building materials and strategies have waste potential, which can be aggregated and analysed during design. A waste manager suggested:

*The process could be like analysing design and then predicting the amount of waste it would generate. The calculation would be based on the fact that every material has defined waste potential. Once we know the volume of waste, then to reduce waste we could apply different strategies to design out waste, followed by ways to manage the unavoidable waste. (excerpt from FGI-2)*

This shows that an appraisal of the effectiveness of designing out waste strategies is important. As such, the participants of the FGIs agreed that a waste reduction ratio could be used as a measure of effectiveness of CW management tools, i.e.

$$\text{Waste Reduction Ratio} = \text{Reduced Waste} / \text{Original Waste}$$

The scale runs from 0 to 1, such that a value of 0 depicts that nothing has been reduced, while a value of 1 shows that all waste has been reduced.

Another drawback to the use of waste prediction tools is the non-universality of quantification models. Most of the models depend on location/project-specific data influenced by project type,

project location, project size, and construction methods (Mokhtar *et al.*, 2011). To address this challenge, Llatas (Llatas, 2011) proposed a model, which estimates waste ratio using factors that depend on the construction technology, country, and project type; and a change in technology, country or project type only requires a modification of the corresponding factors. As a result, the model becomes universally applicable for waste quantification, thereby providing an avenue for the evaluation of alternative construction technologies across several project types in different locations.

### **8.2.2 Waste Data Criteria**

A key challenge to the study of construction waste management is waste data deficiency (Mokhtar *et al.*, 2011). To ensure the development of a robust waste prediction and minimization tool, waste data collection and auditing as well as data analysis functionalities must be incorporated. This would ensure transparency and uniformity in data collection. The waste data must be stored in a centrally accessible database for ease of access. Ultimately, the results of the analysis of the data would provide a benchmark for the waste generation analysis of future projects. A major challenge regarding waste data collection is that most of the waste from a project is not segregated, as stated in FGI-2:

*Most waste data recorded are for mixed/general waste, they are hardly segregated due to financial implications, time, and space constraints. The waste is taken off by third-party agents to waste recycling facilities. They may segregate the waste and may reuse or recycle it for their own purposes. (excerpt from FGI-2)*

So, to ensure the accuracy of waste data, construction companies, and third party waste segregation companies must be appropriately engaged during the waste collection process. While discussing the impact of SWMP for transparent waste data collection, it was claimed that companies comply to retain their reputation and to fulfil legislative requirements.

To sum up, waste data collection and auditing activities are primarily aimed at improving waste quantification. For this reason, the quality of the waste data collected must be ensured to guarantee the accuracy of waste quantification (Cochran *et al.*, 2007a). In addition, such waste data must capture the expert knowledge required for waste quantification and designing out waste.

### 8.2.3 BIM Criteria

A common thread runs throughout the transcripts of the FGIs, which is the implicit and explicit references to BIM. Analysis of the transcripts showed that participants believe that BIM offers huge opportunities for construction waste management. Evidence from the interviews clearly showed that the integration of waste management and BIM is the way forward for an effective and economical waste quantification, waste prevention, collaboration amongst stakeholders and supply-chain integration. It was agreed among the designers in FGI-1 that:

*“Gluing together the commercial, design, and procurement processes into a BIM software system to performing optimisation with little effort may provide more opportunities to see that it is economical to reduce waste in all the cases. This software would be a collaborative tool that would be used by all the stakeholders.” (excerpt from FGI-1)*

Ultimately, integrating waste management with BIM would favour the automatic capture of design parameter for analysis. This would help to mitigate errors committed as a result of entering parameters manually as done in existing waste tools, in waste prediction. Integrating waste management with BIM thereby increases the usability of such tools to make appropriate decisions in favour of waste minimisation within BIM software. In addition, such system would offer leverage on existing BIM modelling platforms and materials database to understand and visualise the effects of design decisions. Pointedly, BIM would provide a powerful collaboration platform for all stakeholders towards an effective construction waste management, seamless information sharing, and software interoperability as noted by a design engineer:



*To ensure effective collaboration, the design must be available in pictorial forms [3D] so that other members [non-designers/contractors] would easily understand it and use it for decision-making. (excerpt from FGI-2)*

Although the DoWT-B (WRAP, 2011a) seems to be the most practical of all the existing tools in the sense that it can forecast the impact of design changes on waste output, it does not engage all stakeholders and is external to BIM software, thereby limiting its usefulness. The only BIM-enabled waste management tool is the DRWE tool (Cheng and Ma, 2013), which leverages BIM technology through the Autodesk Revit API. However, the system only estimates waste generation from the demolition and renovation of existing buildings, clearly highlighting the need for the development of a BIM-enabled tool for simulating the different aspects of waste reduction. Integrating waste management into BIM would also provide a powerful synergy, which would favour the simulation of other performance concerns of buildings.

#### **8.2.4 Commercial and Procurement Criteria**

It was agreed that a synergy is required between design, commercial, and procurement for a successful waste management campaign and implementation. The reason for this is that some people/companies make money from waste; so blocking it in all directions may affect the business. As such, there is the need to understand the relationship between design and procurement as well as commercial and sustainability. In fact, it was affirmed that BIM provides the best opportunity to achieve this through improved coordination and communication among teams. One of the project managers suggested that:

*“Currently, design is divorced from commercial and procurement. Synergy has to be ensured between finance department and procurement if any waste management strategy would be successful. And BIM is probably the most appropriate way to do this” (FGI-3)*

This clearly shows that an efficient waste management strategy requires a tight supply-chain engagement (Dainty and Brooke, 2004). This synergy would help to understand the financial implications of waste management and how waste output is influenced by procurement. Despite the ability of some of the existing waste management tools to provide cost-benefit analysis functionalities, none of them is fully engaged during the procurement process. During the FGIs, it was noted that the procurement process contributes significantly to waste output but some procurement options favour waste reduction. A project manager argued that:

*“One of the economic strategy is to procure materials in bulk for the whole project, stock it at one of the project site, and then move it around on-demand. This is called double-handling where more construction waste is generated due to material movement and manhandling, however, it is a cheap option. Contrary to this is just-in-time approach, where only the required materials are procured to generate lesser waste but it is a costly solution.” (FGI-3)*

This clearly shows that it is believed that waste reduction has a cost overhead. Likewise, it was argued that the generation of waste could be cheaper than avoiding waste especially when choosing between standard-sized materials and custom-sized materials. Custom-sized materials produce less waste but are costlier whereas standard-sized materials are cheap but generate construction waste through off-cuts. As a result, companies tend to give preference to lower cost over waste reduction in the procurement process. The mind-set that waste reduction is costlier seems plausible at the procurement stage, however, it is defeated in the end by considering the environmental impacts of waste and the cost of waste disposal. Although some studies have explored the impacts of procurement processes on waste reduction (Gamage, Osmani and Glass, 2009; Poon, Yu and Jaillon, 2004), no study has been carried out to measure the financial impact of procurement in relation to waste reduction.

### 8.2.5 Design Criteria

While discussing the role of design in waste management and the availability of waste design tools, it was acknowledged that industry practitioners recognise the beneficial roles of design tools in waste reduction, however, it was confirmed that such tool does not exist. An architect claimed that:

*“Although we are aware of waste reduction through design, but no software is available to simulate these waste reduction processes. Still, designing out waste is done manually and it requires design expertise knowledge and experience.” (FGI-1)*

This assertion was confirmed in the literature as none of the tools reviewed provide a real-time design-centric approach to waste minimisation. This clearly suggests that architects and design engineers take it upon themselves to identify possible sources of design waste through design optimisation. Three sources of design waste were identified as design changes, lack of dimensional coordination, and non-standardisation of materials. A design engineer argued that:

*“Another way-out could be to optimise the design by keeping in mind the standardisation of materials to avoid off-cuts (often called design optimisation). It therefore means that most of the design waste is due to changes in the design, lack of dimensional coordination, and standardisation of materials.” (FGI-4)*

This affirms the general consensus in the literature that the largest percentage of construction waste could be avoided at planning and design (pre-construction) stages (Bossink and Brouwers, 1996; Faniran and Caban, 1998; Ekanayake and Ofori, 2000; Treloar *et al.*, 2003; Osmani, Glass and Price, 2008; Poon, 2007; Yuan and Shen, 2011; Oyedele *et al.*, 2013). This evidence shows that architects have huge responsibility to ensure that waste is given high priority, compared to project time and cost during design (Greenwood, 2003; Poon, Yu and Jaillon, 2004).

This therefore suggests the need for a design tool to identify possible sources of design waste and to assist in design optimisation. The focus of such design tools would be to capture and codify the

knowledge about designing out waste and better understand the impacts of design strategies on waste output. Therefore, an important step in achieving this would be to create a list of basic parameters for designing out waste. In order to properly implement this, WRAP (WRAP, 2009) identified 5 principles that must be considered. These principles are: (a) design for material optimisation, (b) design for waste efficient procurement, (c) design for reuse and recovery, (d) design for off-site construction, and (e) design for deconstruction and flexibility. Integrating these principles into design tools would foster real-time construction and end-of-life waste analysis and ensuring buildability of designs.

### **8.2.6 Technological Criteria**

Based on the interview, it was pointed out that it is possible to integrate all the waste generation factors into design tools because every building project is unique. Even so, this might be a very complex task as observed by a lean practitioner and BIM specialist:

*“Waste management minimisation is a very complex issue; however, if what causes waste is known, then, they could be factored into waste management tools.” (FGI-3)*

For this reason, it is important for such tools to embrace intelligent technologies such as Decision Support Systems (DSS), big data analytics, machine learning, and pattern recognition. These technologies would empower waste minimisation tools with the ability to assist designers to understand and visualise the impact of design changes in real-time. Thus, supporting decisions by providing recommendations for the choice of strategies and subsequently revealing avenue for significant waste reduction.

In addition, a robust waste management tool must be integrated with location-based technology such as GPS and GIS to provide location-specific services such as material tracking, supply chain management, and locating nearest waste management facilities. To ensure this, application schema such as Geographic Mark-Up Language (GML), cityGML, and IFC for GIS (IFG) must be supported

to scale the hurdle of interoperability between AEC and GIS standards. Certainly, a full integration of GIS and BIM (Xu *et al.*, 2014) into appropriate lifecycle stages of a project would assist in effective waste management (Wang and Chong, 2014).

### **8.3 BIM Strategies for Design-based Construction Waste Management**

Evidence shows that decisions made at the design stage have multiple ripple implications throughout the lifecycle of the building (Faniran and Caban, 1998; Osmani, Glass and Price, 2008; Ekanayake and Ofori, 2004). According to Lopez and Love (2012), this means that design decisions could influence key project performance indicators such as project cost, time, quality, construction waste, and others. In view of this, MacLeamy (2004) highlights that it is cheaper to make changes to projects at the design stage than in subsequent stages. This means that CW could be reduced by ensuring adequate preventive measures at the design stage (Faniran and Caban, 1998; Osmani, Glass and Price, 2008). This is because design based philosophy offers flexible and cost-effective approach to CW management before its occurrence. Accordingly, architects and design engineers have responsibilities to ensure that waste is given high priority in addition to project time and cost during design. Despite the willingness of architects and design engineers to carry out these duties, this study shows that existing CW management tools cannot support them effectively. Besides, none of the existing CW management tools is BIM compatible despite the benefits of BIM at improving building process performances. Keeping in mind the BIM strategies for CW management that were identified in Chapter 6, this section discusses how BIM approach to waste efficient design coordination has been adopted to meet the expectations and to overcome limitations of existing CW management tools.

#### **8.3.1 BIM-based Collaboration for Waste Management**

The traditional product delivery approaches employed within the AEC industry constitute a number of inherent problems, which include design errors, clashes, cost and time uncertainty,

material wastage, increased risks, among others. (Lichtig, 2010). This is mainly as a result of lack of communication and collaboration among the stakeholders within the highly fragmented AEC industry (Ghassemi and Becerik-gerber, 2011). Each stakeholder seems to make decisions in isolation to maximise personal gains. This is so because the knowledge of building construction is developed across numerous fields and the needs of all stakeholders (building owners, architects, MEP engineers, structural engineers, cost managers, contractors, sub-contractors, facility managers, users, and others.) must be met. This suggests that as several stakeholders begins to generate digital data of various forms; adequate mechanism must be put in place to share the data. To therefore mitigate against this unfortunate practice and outcomes, BIM provides a well-structured collaborative process to harness the expertise of all project stakeholders throughout the building lifecycle especially at the early design stages (AIA, 2014). The adoption of BIM ensures early informed decision, waste reduction (in terms of cost, time, material, human resources, among others), improved project quality and greater cost certainty (Azhar, Hein and Sketo, 2007) among other benefits.

The use of BIM for improved collaborative CW management has the highest value among the groups with a total variance of 32.246% and it is made up of seven variables. This being the highest ranked factor is not a surprise because adequate collaboration and effective communicate is critical to the success of projects (Oyedele, 2013). In this regard, BIM plays a major role in ensuring that all stakeholders are actively involved right from the conception of the building project through its entire lifecycle (Eadie *et al.*, 2013a). The major benefit of adopting BIM for waste management is that it enables the creation of a federated model that could be assessed and updated by all the project team. This idea helps to improve the allocation and monitoring of responsibilities and encourages *shared risk and reward*' philosophy. The "*shared risk and reward*" engenders process efficiency, harmony among stakeholders, reduced litigation and prevents the culture of blame-game as well as the transfer of responsibilities (Eadie *et al.*, 2013). The use of BIM also engenders design coordination, task harmonisation, clash detection, and process monitoring of CW management activities.

Despite the evidence from previous studies that BIM has the potential for waste minimisation, no clear instructions have been provided on achieving this. The discussions from the FGIs corroborated this because the participants were aware of the potentials of BIM; however, none of them had adopted BIM for CW management. While deliberating on the opportunities obtainable from the adoption of BIM for CW management, it was argued that incorporating waste management functionalities into BIM would encourage effective participation of all project teams in making waste management related decisions. In addition, the participants of the FGIs posit that BIM based design tools must be developed to ensure that participating teams can collaborate effectively on waste management issues. These tools could be in the form of plugins to existing BIM software to extend their functionalities. To leverage the collaborative feature of BIM, a holistic BIM framework for CW management was developed as described in the following section.

### **8.3.2 Waste-Driven Design Process and Solutions**

This group accounts for 24.385% of the total variance and contains seven variables. After an extensive consideration of the sub-factors brought together under this group, the name “*enhanced performance for waste analysis*” was chosen because all the sub-factors contribute towards automatic analysis of waste performance of building models. Performance analyses of buildings provide a platform for functional evaluation of buildings before the commencement of construction (Eastman *et al.*, 2011). This functionality has aided the wide acceptability of BIM in the AEC industry to improve the performance of the form and functions of buildings right from the design stage (Manning and Messner, 2008). Alternative design options are therefore compared to select the most cost-effective and sustainable solution. At the same time, performance evaluation of design models helps to identify possible design and operational errors issues at a stage where design changes are cheaper; thus, reducing waste.

In keeping with the foregoing facts, the FGI participants agreed that the increasing popularity of BIM in the AEC industry has strengthened the development of various tools for design analyses, such as cost performance, energy consumption, lighting analyses, and acoustic analyses. The

majority of these tools are provided as plugins on existing BIM software to carry out specific design analysis. Despite the benefits of building performance analyses and the environmental/economic impacts of construction waste, none of the existing BIM software has capabilities for waste performance analysis. This gap calls for a rethink of BIM functionalities towards capacity for waste simulation right from early design stages.

In agreement with earlier studies (Eastman et al., 2011), the participants of the FGIs agreed that another benefit of integrating CW management into BIM is automatic capture of design parameters for performance analysis. Accordingly, it was highlighted that employing BIM during design would eliminate human error during data entry. For example, CW management tools such as NWT, DoWT-B and waste estimation models require practitioners to manually transfer design parameters from the bill of quantity. This approach therefore makes these tools susceptible to errors in waste estimation and it requires more effort and time.

While IFC is generally regarded as the industry standard for interoperability (Eastman et al., 2011), its current implementation is not equipped with adequate mechanism to streamline challenges of the AEC industry such as construction waste analytics (Tibaut, Rebolj and Perc, 2014). This is because the current IFC implementation does not incorporate enough information to facilitate waste information analysis. This study therefore took a closer look at how IFC could be extended to support data exchange between CW management tools and BIM software. Accordingly, the requirement and schema for information exchange among CW management processes needs are identified and captured within existing BIM standards. Achieving this enables CW management tools to exploit BIM standards to read and interpret building models and their parameters for waste analytics. Achieving this allows CW analytical process to be integrated into design process and solutions.



### 8.3.3 Lifecycle Waste Analytics

This group produces a total variance of 10.971% and contains two variables. While discussing the role of BIM in life-cycle performance of buildings, the participants of the FGI agreed that the use of BIM encompasses all project work stages from the planning stage to the end-of-life of buildings. Thus, information on building requirements, planning, design, construction, and operations can be amassed and used majorly for making management related decisions on facilities. Accordingly, BIM allows all teams to embed relevant project information into a federated model. For instance, project information such as project schedule, cost, and facility management information. could be incorporated into BIM using COBie format. Preserving information throughout the lifecycle of buildings is important for effective facility management and end-of-life decisions for buildings. The information thus enables a powerful modelling, visualisation and simulation viewpoint that helps to identify design, construction, operation, and end-of-life related problems before they occur. This distinguishing feature makes BIM applicable to all work stages by accumulating building lifecycle information (Eadie et al., 2013). Although many stakeholders in the AEC industry understand the benefits of adding more information into models, which could extend parametric BIM into 4D, 5D, 6D, and nD, no BIM dimension exist for CW management.

It should be borne in mind that the major limitation of existing CW prediction models is insufficient waste data (Mills, Showalter and Jarman, 1999) and that most CW collected from building sites are not segregated (Langdon, 2011). This means that adequate information about waste collected from construction site may not be provided or the waste data may not be properly labelled. Even so, majority of existing CW prediction tools are based on waste indices despite the multi-dimensional nature of waste generation factors. This raises serious concerns because the tools were developed without adequate consideration for detailed material information and building methodology. This is because building properties influencing CW generation are quite diverse and treating them the same way could be misleading. The expectation of a robust waste estimation tool therefore taps into the perceived degree of accuracy from relationship among specific variables determining CW generation.

To therefore ensure accurate waste record data collection and the integration of waste data into a BIM federated model, this study provides an intuitive interface for capturing CW collection activities. The waste collection interface ensures that CW data records are embedded into BIM models and that they could be retrieved as required. This approach encourages data transparency, controlled data access, data portability within a single federated model. In this way, BIM helps to address interdisciplinary inefficiency inherent in current CW management practices. This approach will certainly improve team effectiveness towards effective management of CW and reduce duplication of effort. Since CW is generated at all project work stages, adopting BIM for CW management allows effective capturing of waste related data from design to the end-of -life of buildings.

A BIM feature that aids its wide acceptability is the ability to analyse and simulate buildings' performance (Manning and Messner, 2008) such as cost estimation, energy consumption, and lighting analysis. Building performance analyses provide a platform for functional evaluation of building models before the commencement of construction and it allow comparison of alternative design options(Eastman *et al.*, 2011). At the same time, performance evaluation of design models helps to identify possible design and operational errors. Despite the availability of BIM based tools for the analyses of various building performances such as airflow, energy, and seismic analyses, no tool exist for CDW analysis. The tool developed as part of this study is the first software to provide CW analytics functionality with a BIM platform. The tool provides an intuitive interface to simulate CW generation of BIM design according to specific metrics, which include building materials, building elements, building levels,

#### **8.3.4 Innovative Technologies for Waste Intelligence and Analytics**

The group “*enhanced technological capabilities for waste management*” accounts for 9.989% of the total variance and it contains four variables. The implementation of BIM relies on the appropriate use of technologies and their effective integration into the design process. Synthesising emerging technologies such as Internet of Things (IoT), Global Positioning System (GPS), Big

Data analytics and RFID help to provide real-time building performance monitoring and analyses (Bilal et al., 2016a). An integration of these technologies into BIM could facilitate location based services, tagging and identification of building materials, and remote collection of building data. In terms of CW management, Radio-Frequency Identification (RFID) could be used to tag construction materials with waste information and GPS could be employed to track CW movement. For example, RFID tags could be embedded into building components to collect waste related data arising from projects. This will help to scale the hurdle of waste data deficiency by providing technology-enabled methods of waste data tracking and collection. Achieving this will enable the full automation of waste data collection and analyses of waste performance of buildings.

In addition, technological support such as 3D printing could empower BIM for computer-controlled prefabrication of building components. This approach would improve design flexibility as components could be designed and printed to specification without material waste. Accordingly, synthesising these emerging technologies into BIM computational platform will eventually favour prefabs and modular construction, which will in turn yield significant reduction in the generation of CW.

Although one could argue that the adoption of BIM is on the rise (Arayici *et al.*, 2011), a major challenge confronted by construction companies is the issue interoperability between BIM and these new technologies (Steel, Drogemuller and Toth, 2012). Accordingly, standards such as IFC (ISO 16739:2013) for seamless exchange of information among software, IFD (ISO 12006-3:2007) to harmonise and structure construction terms, and IDM (ISO 29481-1:2010) to unite construction processes for collaborative practices are adopted to scale the hurdle of interoperability. In addition, the communication standards such as oBIX (open Building Information Exchange) and IFG (IFC for GIS) have enabled building systems to communicate with enterprise applications such as cloud based and location based services.

The BIM-enabled tool (BIMWaste) developed as part of this study is IFC compliant to ensure interoperability with existing open communication standards and emerging technologies.

### **8.3.5 Improved Documentation for Waste Management**

This group contributes 6.64% of the total variance and the group is composed of two variables. Due to the increasing sophistication of buildings, the need for more information for construction, operation, maintenance, and end-of-life activities has become vital (Jordani, 2010). This information is important to track building construction process, performances of building elements, isolate operation inefficiencies, and to respond to specific client's requests. Evidence shows that design quality and documentation forms an important requirement for successful building construction and facility management (Andi and Minato, 2003; Gann, Salter and Whyte, 2003). In addition, the quality of design documentation could influence the end of life activities of buildings such as demolition and deconstruction. Albeit, Goedert and Meadati (2008) illustrated that BIM has capabilities to capture building design and construction process documentation to provide full inventory of elements and to sustain the relevant information. This is because the use of BIM and COBie has enabled stakeholders to embed relevant facility maintenance information into building models.

In line with the foregoing, building documentations such as project schedule, cost profile, site waste management, site information sheet, complain/incidence logbook, traffic management plan, and deconstruction plan could be incorporated into BIM models. Accordingly, this capability and the ability to capture design parameters could enable on-demand extraction of the documents from the model of the buildings. Achieving this will therefore improve design coordination, time management and engineering capabilities (Sacks, Radosavljevic and Barak, 2010) to avoid human errors that could lead to the resource wastage. For example, architects may generate design drawings with accuracy and high level of detailing for fabrication. Likewise, the same concept could be adopted for CW management waste reporting and the development of waste management plans.

## **8.4 Holistic BIM Framework for Construction Waste Management**

Taking into consideration the evaluation criteria identified from the literature and during the FGIs, a holistic BIM framework for a robust waste management system was developed. This was done with the intention of integrating the industrial and technological requirements for waste management. The framework aims at achieving a holistic approach to design for waste minimisation by considering five design principles proposed by WRAP (2009). These design principles capture waste minimisation strategies at both the construction stages and end-of-life of the building.

The framework development employs an architecture-based layered approach, where related components are grouped into layers, to ensure hierarchical categorisation of components. This approach also clearly defines boundaries of stakeholders' responsibilities, supports fair and efficient allocation of resources, encourages independent implementation of components, and clearly defines components' interfaces for information exchange. A discussion of these layers is presented in successions with emphasis on how the components in each layer could be harnessed for construction waste management. The following sections discuss the layers of the holistic BIM framework for CW management.

### **8.4.1 Infrastructure Layer**

The infrastructure layer is the first and bottom-most layer, which contains physical and virtual enterprise technologies, i.e., cloud computing, networking, hardware, and GIS technologies. Most importantly, this layer facilitates the transfer of the cost and management burdens from individual companies to the service providers due to the high financial requirement needed for setting up the infrastructure. As a result, this layer does not provide domain specific services as it creates the required platform for numerous specialty areas.

However, major challenges faced by service providers include security, ownership, and management issues. To scale the hurdles posed by these challenges, the infrastructure layer also provides the required security (such as access control, intrusion prevention, and Denial of Service prevention), scalable, and flexible billing and management models, and transparent user licences and agreements.

#### **8.4.2 Data Layer**

The data layer provides the shared knowledge, which uses decision making throughout the building's lifecycle. The layer provides centrally accessible databases, which could be remotely accessed in favour of efficient collaboration among stakeholders. For the purpose of waste management, this layer contains the universally applicable waste list and indices, which must be correctly mapped onto the material database and ontology for the purpose of waste data extraction from design models. In addition, the layer provides a knowledge base that captures design competencies required for efficient waste management. This knowledge base captures and codifies the knowledge about the five design principles proposed by WRAP (WRAP, 2009) to better understand how the knowledge connects to waste output. An important component of this layer is the ontology database that captures the semantic relationship among other resources. This could be represented as a semantic network using Web Ontology Language (OWL), JavaScript Object Notation (JSON) or Resource Description Framework (RDF) schema.

The data layer also ensures the supply chain engagement by providing a database for suppliers and their related activities. As previously noted, the quality of construction waste quantification and prediction largely depends on the quality of data collected (Bossink and Brouwers, 1996; Solís-Guzmán *et al.*, 2009), as well as the quality of data representation and ease of knowledge extraction. As a result, the development of a robust waste prediction and minimisation tool must incorporate Waste Data Collection and Auditing functionality as well as Data Analysis features. This ensures a uniform standard for data collection, representation, and query. Ultimately, the result of the data analysis would provide a benchmark for waste generation for future projects.

### **8.4.3 Presentation Layer**

For an effective implementation of BIM, all the team members must choose appropriate interoperable software tools (Steel, Drogemuller and Toth, 2012). Because of this, software and data interoperability becomes an issue of concern to ensure collaboration among stakeholders. Thus, BIM open standards were developed to represent and openly exchange BIM information. These standards include the IFC (BuildingSMART, 2013), Green Building XML (gbXML, 2013) and the newer Construction Operations Building Information Exchange (CoBie) (East, 2007) for level 2 UK BIM adoption.

Therefore, the presentation layer defines the open BIM standards to ensure system interoperability and transparency in data exchange. This layer also contains spreadsheet formats for various forms of analysis of the performances of buildings, generic component models (such as OBJ, Material Library File – MTL, and Polygon File Format – PLY), and software specific models (such as .rvt, .pln, .dng, and others.). Therefore, for a successful integration of waste management tools into BIM, such tools must incorporate exchange of data using these standard formats. However, there is a need to extend these standards to accommodate the concepts required for construction waste analysis.

### **8.4.4 BIM Business Domain Layer**

The BIM business domain layer defines the core features of BIM as a set of concepts on top of the presentation, data, and infrastructure layers. This layer provides a platform for collaboration among stakeholders, document management, and seamless information sharing. This layer also provides a tight integration with CAD software for model visualisation and parametric modelling. In addition, the BIM business domain layer enables intelligent modelling by extending parametric properties of objects to capture numerous areas of the performances of buildings such as cost, scheduling, visibility, and energy rating.

The BIM business domain layer also helps to integrate the framework into the project's lifecycle. Admittedly, construction waste is produced at all stages of a building's lifecycle (Esin and Cosgun, 2007) especially at the construction and demolition stages (Dolan, Lampo and Dearborn, 1999). Therefore, construction waste management tools must emphasise the integration of the entire lifecycle of a building (Ekanayake and Ofori, 2004; Osmani, Glass and Price, 2008) in favour of BIM adoption. BIM integration would enable waste management tools to consider waste from preparation stage to the end of life of the facility. However, conscious effort should be made to focus more on the pre-construction stages (0 - 4) where design changes are easier and cheaper.

#### **8.4.5 Service Domain Layer**

The service domain layer defines specific concepts and functionalities built on the BIM business domain layer to analyse and simulate various performances of a building project, particularly construction waste analysis and management. The waste management service domain contains the operational and supports technical requirements for designing out waste through BIM such as waste quantification, design model analysis, waste hierarchy consideration, waste prediction, reporting and visualisation functionalities.

Equally important, an effective design-based waste management system must provide recommendations for the choice of strategies and subsequently revealing avenue for significant waste reduction. These design-out-waste strategies include dimensional coordination, modular coordination, and standardisation in favour of off-site construction, deconstruction, and material recovery. Accordingly, the waste management service domain could be used with various BIM analysis software applications in other service domains to simulate a wide range of performance purposes. This software include Ecotect (thermal efficiency, lighting, visibility, solar shading, and exposure), Green Building Studio (CO<sub>2</sub> emission and energy consumption), and IES (airflow, sound, and acoustic quality).



#### **8.4.6 Application Layer**

The application layer is the sixth and topmost layer through which the various stakeholders access the specific domain services. This layer contains BIM software, which provides intelligent parametric modelling and n-D visualisation, web applications which provide access to the service domain through web interfaces, and mobile application, which provides access to the service domain on handheld devices like smart phones and tablets.

Since most BIM software, web, and mobile application provide Application Programming Interface (API) to extend their functionalities, it becomes important to harness this strength for rapid application development. API serves as building blocks for software applications thereby providing developers with the ability to customise application by leveraging on functionality of existing platforms. Available APIs include Revit .NET API, Vectorworks scripting language, ArchiCAD Geometric Description Language (GDL), among others. Several studies (Goedert and Meadati, 2008; Schlueter and Thesseling, 2009; Nepal *et al.*, 2012; Cheng and Ma, 2013; Kota *et al.*, 2014) have used the leverage of the Revit API (Autodesk, 2014) to simulate and analyse several aspects of BIM. Thus, this reveals the need to harness the strength of APIs for the development of waste management software.

### **8.5 BIM-Based Construction Waste Prediction using Hybrid Models**

Waste Data Records (WDR) from 117 construction projects was collected and subjected to exploratory data analysis to understand the distribution and structure of the data. The results of the exploratory data analysis of the WDR revealed that 45% of CW arises as mixed waste, this is followed by inert (37.8%), Concrete (9.6%) and Bricks (3.11%). This supports the general practice in the industry that most CW is not segregated and that it is recorded under mixed or general waste. This general practice could be attributed to the extra cost required for onsite segregation. As such, contractors send the mixed waste to third party waste treatment plants, where they are segregated into appropriate waste stream and processed for reuse, recycling, and safe disposal. It was revealed

from the exploratory data analysis that 22,513 tonnes, which represents 91.61% of the entire waste, was sent to transfer station for sorting, or energy recovery, composting or soil remediation. Adopting this approach is cost effective as the waste from several contractors are aggregated and processed in large scale. This challenge constitutes a great hindrance to CW prediction because the data are not adequately recorded. Overcoming this requires taking an integrated approach to CW data collection and record keeping. As such, BIM strategies for CW record keeping and auditing is timely. This will require the integration of CW data with BIM federated models. Achieving this will ensure that future CW prediction models are able to access CW data right from the building model vis-à-vis BIM design parameters.

This study proposes a design based CW prediction method using ANFIS. ANFIS integrates the advantages of fuzzy inference system the learning ability of ANN into a single hybrid system. Evidence from literature revealed that combining fuzzy logic and neural network could overcome the challenges that are inherent in both systems (Jang, 1996). The main challenge with fuzzy systems is that its membership function and rules are determined by trial and error. As such, fuzzy logic requires significant time and effort to compute correct membership and rule in a complex system. In addition, fuzzy logic is not particularly efficient in its generalisation capability because it uses heuristic algorithms for defuzzification and rule evolution. In the same way, neural networks also have their limitations. Chief among the limitations is how to determine the optimal structure of the network. These limitations led to the combination of ANN and FL into a single system to produce system with better prediction capability.

Prior to the training of the ANFIS model, input selection was carried out to select the best input parameters for predicting CW. Input selection process for ANFIS model employs an efficient hybrid learning algorithm that combines least square methods and gradient descent algorithm in a two-way pass system. Identification of the best combination of input parameters largely depends on the strength of least square methods to quickly train models. The least square method was used to train the model quickly while gradient descent was used to update the MF that generated functions for the least square method. Accordingly, six ANFIS models were constructed and

trained. The RMSE of the models were then compared to select the model that best predicts CW. The results revealed that two inputs, i.e., “*Gross Floor Area*” and “*Construction Type* (GFA-Ct model with RMSE of 7.56), are the best predictors for CW. An explanation for the exclusion of project cost and building usage could be that project cost exceeds the value of the building materials. The total project cost includes other cost such as cost of plant and fleets, transportation cost, consultancy cost, and design cost. This means that it is difficult to correlate project cost to CW output of a building design because a breakdown of the costs is not provided. Also, the cost of building project could be influenced by the building usage intentions. This is because building usage will determine the amount of equipment and amenities that will be provided within the building.

The selected model was then trained using a hybrid algorithm with grid partitioning. As such, hybrid algorithm was applied to optimize and adjust the Membership Function (MF) parameters and coefficients of the output linear equations (Fijani *et al.*, 2013). The RMSE of the model using various MFs was compared to select the best MF for the ANFIS model. The ANFIS with Gaussian MF produced the best results, achieving up to 91.4% improvement in error with a maximum residual error of  $\pm 2.1094$  tons.

The final ANFIS model provided an efficient way of predicting the total waste of a building given its total gross floor area and construction type. However, a more challenging task is computing the waste output by construction waste type. A practicable way of achieving this would have been to develop AI models for all the waste types, however, the nature and quality of waste data record obtained could not allow this. To achieve this task, standard Waste Distribution Percentage (WDP) for all waste types based on construction type was developed to estimate the parentage that a material type contributes to the total waste. Distribution of waste management route for each waste type is computed using the same approach. Although this is not an accurate measure of waste output by waste types and waste management routes, this approach provided a good reference point for computing these values. In addition to the ANFIS model, a mathematical model was developed for dimensional coordination of brickworks. Mathematical equations were formulated

for calculating the amount of brick required for the construction of walls and the corresponding waste output. The Equations were then employed in the selection of appropriate brick dimensions to minimise offcuts. This enables appropriate design for material optimisation by appropriate material substitution.

The developed models were then integrated into Autodesk Revit as an Add-in. Integrating CW management into BIM platforms addresses two main limitations of existing CW management tools. These limitations are: (i) existing CW tools are completely detached from the design process, and (ii) existing CW management tools lack interoperability capabilities. The final software (BIMWaste) was implemented using C# and Revit API based on a RAD software development framework. As such, BIMWaste was implemented using five active modules, which include UI module, Custom parameter module, material database module, material take-off calculation module, and report generation module. To test the performance of BIMWaste, a test plan and two test cases were developed. The testing process showed that BIMWaste passed all functional and non-functional tests. The results also showed that the tool predicted CW according to waste types, element types, and building levels. It was also revealed that BIMWaste accurately computed Gross Floor Area and the number of floors in building designs.

## **8.6 Summary**

This chapter presents the discussion of findings from the study. A list of 40 criteria used to evaluate the performance of existing CW management tools was presented. The evaluative criteria were grouped under six categories, which are: (a) waste prediction; (b) waste data; (c) commercial and procurement; (d) BIM; (e) design; and (f) technological. The chapter also contains discussion of BIM strategies for CW management that were identified from the exploratory sequential mixed methods process. The strategies are presented in five groups, which are: (a) Group 1 denoted by improved collaboration for waste management, (b) Group2 denoted by waste-driven design process and solutions, (c) Group 3 denoted by lifecycle waste analytics, (d) Group 4 denoted by Innovative technologies for waste intelligence and analytics, and (e) Group 5 denoted by improved

documentation for waste management. These strategies are required to enable BIM approach to waste efficient design coordination. Thereafter, a holistic BIM framework for CW management was discussed. The last section discusses key findings from ANFIS model development and BIM-based tool development for CW management.

This next chapter concludes the study. The chapter gives a summary of the study by discussing the research objectives, research design, data collection and analysis techniques, model development process and software development approach adopted for the study. The chapter also presents key findings vis-à-vis the specific objectives of the study.

## **9 CONCLUSION, RECOMMENDATIONS, AND FUTURE WORKS**

### **9.1 Overview**

This chapter provides the conclusion to the study. The chapter starts with a summary of the study by discussing the research objectives, research design, data collection and analysis techniques, model development process and software development approach adopted for the study. The key findings of the study are presented vis-à-vis the specific objectives of the study. As such, the key findings are presented in three sections, which are: (i) the first section focusses on the identification of limitations of existing CW management tools and a list of evaluative criteria. In addition, the section also discusses key BIM features that are relevant to the development of CW management tools and the development of a holistic BIM framework for CW management, (ii) the second section is on the development of an ANFIS model for CW prediction using historical waste record data, (iii) while the third section focusses on the development of a BIM-based tool as an add-in for Autodesk Revit, and the evaluation of the developed BIM tool. The chapter also provides implications of the study by discussing implications for practice and theoretical implications, the limitations of the study, and areas of future research.

### **9.2 Summary of the Study**

Evidence showed that about 30% of the total waste generated in the UK originated from construction related activities (Osmani, Glass and Price, 2008). Considering high landfill cost, severe ecological damage (Yuan *et al.*, 2011), shortage of land (Gavilan and Bernold, 1994), and increased transportation and project costs (Yuan, 2012), there is the need to reduce waste generated from construction activities. Despite the consensus in the literature that the best approach to mitigating causes of CW is designing out waste (Faniran and Caban, 1998; Poon, Yu and Jaillon,

2004; Osmani, Glass and Price, 2008; Liu *et al.*, 2011), existing CW management tools are not robust enough to support architects and design engineers during the design stage. Key limitations of existing CW management tools are that they are completely detached from the design process and that they lack interoperability capabilities. Overcoming these limitations require tight integration of BIM-based approach to CW management into design tools used by architects and design engineers. Achieving this will offer huge opportunities for an effective and economical waste quantification and minimisation. BIM capability for CW management tools would offer a powerful synergy for simulating performances of buildings with respect to CW.

It based on the foregoing that this study addresses how design-based CW prediction and minimisation capabilities could be incorporated into existing BIM platforms. The study is targeted towards the development of a BIM-based tool, which could be used by architects and design engineers to estimate CW output of buildings and to minimise CW at the design stage. The specific objectives of the study are: (a) to investigate strategies for enabling BIM-based prediction and minimisation at the design stage, (b) to formalise strategies for CW prediction and minimisation into computational systems, (c) to integrate the computational systems for CW management into BIM platforms, and (d) to test the performance of the BIM-based CW management tool in terms of its CW prediction and minimisation capabilities.

The study adopted several techniques to achieve the specific objectives. Based on a critical realism paradigm, the study adopted exploratory sequential mixed methods, which combines both qualitative and quantitative methods in a single study. The study started with a review of extant literature and FGIs with industry practitioners to assess the limitations of existing CW management tools and to understand the expectations of industry stakeholders. The transcripts of the FGIs were subjected to thematic analysis to identify prevalent themes from the quotations. The factors from literature review and FGIs were then combined and put together in a questionnaire survey. The questionnaires were then distributed to industry practitioners.

To identify the BIM strategies for CW management based on the experience and opinion of industry practitioners, the questionnaire responses were subjected to rigorous statistical processes. These include reliability analysis and factor analysis. Reliability analysis helps to statistically check if the factors in the questionnaire consistently reflect the construct it is meant to measure, while exploratory factor analysis helps to identify clusters of factors that measure aspects of the same underlying dimension. Factor analysis revealed key strategies for BIM-based approach to waste efficient design coordination. Thereafter, the key strategies were developed into a holistic BIM framework for CW management. This framework served as a guide to the development of AI hybrid models and BIM based tool for CW management.

An ANFIS model was developed for CW prediction and mathematical models were developed for CW minimisation. Based on historical CWR from 117 projects, the model development revealed that two key predictors of CW are “*GFA*” and “*Construction Type*”. The final models were then incorporated into Autodesk Revit to enable the prediction of CW from building designs. The performance of the final tool was tested using a test plan and two test cases. The results showed that the tool performed well and that it predicted CW according to waste types, element types, and building levels.

### **9.3 Main Findings of the Study**

Main findings of the study are discussed vis-à-vis the research objectives that the study was set out to achieve. The first section was based on the first objective of the study, which is to investigate strategies for enabling BIM-based construction waste prediction and minimisation at the design stage. After the extant review of literature on existing CW management tools and key BIM features for CW management, an exploratory sequential mixed methods strategy was used. A combination of FGIs and questionnaire survey were used to assess the expectations of industry practitioners in terms of BIM strategies for CW management. A combination of thematic and statistical analyses was employed to obtain the results. The first section ends with the development of a holistic BIM-based framework for CW management. The second part focuses on the second objective, which is



to formalise strategies for construction prediction and minimisation into computational systems. After an exploratory analysis of the collected waste record data, a hybrid model based on ANFIS was developed to predict CW from a set of features. In addition, a Dimensional Coordination Model (DCM) was developed for CW minimisation using mathematical modelling. The last section provides key findings in line with the third and fourth objectives, which are to integrate computational systems for construction waste management with BIM platforms and to test the BIM-based CW management tool.

### **9.3.1 Strategies for BIM-Based Construction Waste Management**

Evidence from literature reveals most CW arises from the design stage and appropriate design decisions could be employed to mitigate waste (Faniran and Caban, 1998; Osmani, Glass and Price, 2008; Ekanayake and Ofori, 2004; Poon, 2007; Yuan and Shen, 2011). Potential design-based causes of CW include design changes during the construction stages (Faniran and Caban, 1998; Yuan and Shen, 2011), lack of knowledge about standard size of available materials and dimensional coordination (Ekanayake and Ofori, 2004), unfamiliarity with materials alternatives (Ekanayake and Ofori, 2000), complex detailing (Oyedele et al., 2013), and building complexity (Baldwin *et al.*, 2009). Despite the opportunity to manage CW at the design stage, it was revealed that existing CW management tools are not robust enough to tackle CW at the source. As a result, 32 existing CW management tools were identified and reviewed to identify inefficiencies of the tools. After a careful assessment of the primary functions of these tools, five broad classifications of tools emerged: (a) waste management plan templates and guides, (b) waste data collection and audit tools (c) waste quantification models, (d) waste prediction tools, and (e) Geographic Information System (GIS)-enabled waste tools. An in-depth performance assessment of these tools was carried out to identify their limitations. It was revealed that five main limitations impede the effectiveness and usability of existing tools. These limitations are: (a) existing CW tools are completely detached from the design process, (b) existing CW management tools lack interoperability capabilities, (c) CW data are not sufficient, (d) CW management responsibilities are not clear, and (vi) lifecycle analysis of CW performance is not available.

Accordingly, FGIs were conducted to identify evaluative criteria for existing CW management tools and to explore BIM features for addressing the limitations of the tools. The results of the thematic analysis of the transcripts from the FGI revealed a list of 40 evaluative criteria that could be used to appraise the performance of existing waste management tools. These evaluative criteria were grouped into six categories. The first group is waste prediction related criteria which assessed how the tool could accurately estimate waste potentials of buildings. It contains evaluative criteria that are related to identifying potential waste origins and causes. The next group is waste data related criteria, which contains evaluative criteria that are related to waste data collection and provisioning of waste data in a format that is usable for decision making. The third group is commercial and procurement related criteria, which contains evaluative criteria that are related to early supply chain engagement, procurement process coordination, provision of robust suppliers' database, and material standardisation. The fourth is BIM related criteria, which measures the level of compliance of the tool with basic BIM features such as visualisation, project lifecycle management, collaboration, and interoperability. The fifth group is design related criteria, which assessed the usability of the tool for designing out CW. This group contains evaluative criteria such as design out waste principles consideration, automatic capture of design parameters, design optimisation, buildability consideration, real-time waste analytics, and dimensional coordination. The last group technological support related criteria, which measures the readiness of the tool to integrate with existing technology. Relevant technology includes decision support mechanism, location based services, cloud computing support, APIs, and RFID support.

Twenty-two (22) variables that relate to the use of BIM for CW management were identified after the review of extant of literature and FGIs. The variables were put together in a questionnaire survey and distributed to 130 respondents. Fifty-nine (59) completed questionnaires were used, which represents a response rate of 45.4%, were subjected to rigorous statistical analyses using Statistical Package for Social Sciences (SPSS) software. Results of factor analysis revealed five groups of BIM strategies for CW management. Group 1 denoted by improved collaboration for waste management, which is required to enable effective communication among teams. This group is made up of seven variables, which include improved waste information sharing among

stakeholders using BIM, task harmonisation among stakeholders to reduce duplication of effort, improved waste minimisation commitment among stakeholders, transparency of responsibilities during design process, early supply-chain integration for waste management decisions, development of BIM federated model for use by all teams, and use of BIM as a co-ordination tool for designing out waste.

Group 2 denoted by waste-driven design process and solutions contains variables that contribute to automatic analysis of waste performance of building models. Performance analyses of buildings allows for functional evaluation of buildings before the commencement of construction to identify possible design and operational errors issues at a stage where design changes are cheaper. The group contains seven variables, which are embedding waste-related information into building model, improved clash detection in building models to reduce waste, improved materials classification methods, automatic capture of design parameters for waste analysis, decision-making on waste reduction during design, improved cost-benefit analysis of construction waste management, and computer aided simulation scenario and visualisation of waste performance. Group 3 denoted by lifecycle waste analytics with two variables, which are support for whole-life waste analysis and preservation of deconstruction information in COBie. These variables bother on how information on building requirements, planning, design, construction, and operations can be amassed and used majorly for making management related decisions on facilities. It was revealed that preserving information throughout the lifecycle of buildings is important for effective facility management and end-of-life decisions.

Group 4 denoted by Innovative technologies for waste intelligence and analytics, which represents appropriate use of technologies in design out waste process. It was revealed that synthesising emerging technologies such as Internet of Things (IoT), GPS, Big Data analytics and RFID would provide real-time building performance monitoring and analyses. In addition, an integration of these technologies into BIM would facilitates location based services, tagging and identification of building materials, and remote collection of building data. Group 5 denoted by improved documentation for waste management contains variables related to on-demand extraction of the

design documents from the building models. It was revealed that building documentation such as project schedule, cost profile, site waste management, site information sheet, complain/incidence logbook, traffic management plan, and deconstruction plan needs to be tightly integrated into BIM models for effective CW management.

Based on the identified evaluative criteria for CW management tools and BIM strategies for CW management, a holistic BIM framework for CW management was developed using an architecture-based layered approach. The architecture-based layered approach allows related components to be grouped into layers and to ensure hierarchical categorisation of components. The framework helps to identify key knowledge units towards the enhancement of existing tools and to enable the implementation of BIM compliant CW management tools. The framework consists of six layers, which are: infrastructure layer, which contains physical and virtual enterprise technologies, data layer, which provides the shared knowledge, presentation Layer, which defines open BIM standards to ensure system interoperability, BIM Business Domain Layer that defines the core features of BIM, Service Domain Layer that defines specific concepts and functionalities built on the BIM business domain layer to analyse and simulate waste performances, and Application Layer, to allow various stakeholders access to specific domain services.

### **9.3.2 Development of AI Hybrid Models for CW Prediction**

An ANFIS model was developed for CW prediction. A major strength of ANFIS is that it integrates advantages of fuzzy inference system and learning ability of ANN into a single hybrid system. A hybrid training algorithm with grid partitioning was used to optimize and adjust MF parameters and coefficients of the ANFIS model. The Root Mean Square Error (RMSE) of the model using various Membership Functions (MFs) was then compared to select the best MF for CW prediction. The results showed that Gaussian MF produced the best results, achieving up to 91.4% improvement in error with a maximum RMSE of  $\pm 2.1094$  tons. The training process of the ANFIS model also revealed that that two key predictors of CW are “*Gross Floor Area*” and “*Construction Type*”.

To compute waste output by construction waste type, standard Waste Distribution Percentage (WDP) for all waste types based on construction type was developed. WDP helps to estimate the percentage that a material type contributes to the total waste. Distribution of waste management route for each waste type is computed using the same approach. Although this is not an accurate measure of waste output by waste types and waste management routes, this approach provides a good reference point for computing these values. In addition to the ANFIS model, a mathematical model was developed for dimensional coordination of brickworks. Mathematical equations were formulated for calculating the amount of brick required for the construction of walls and the corresponding waste output. The Equations were then employed in the selection of appropriate brick dimensions that will minimise offcuts to enable appropriate design for material optimisation.

### **9.3.3 Development and Testing of BIM-Based Tool for CW Management**

The developed AI hybrid and mathematical models were integrated into Autodesk Revit as an Add-in. Integrating CW management into BIM platforms addressed two main limitations of existing CW management tools. These limitations are: (i) existing CW tools are completely detached from the design process, and (ii) existing CW management tools lack interoperability capabilities. The final software (BIMWaste) was implemented using C# and Revit API based on a RAD software development framework. As such, BIMWaste was implemented using five active modules, which include UI module, Custom parameter module, material database module, material take-off calculation module, and report generation module. To test the performance of BIMWaste, a test plan and two test cases were developed. The testing process showed that BIMWaste passed all functional and non-functional tests. The results also showed that the tool predicts CW according to waste types, element types, and building levels. It was also revealed that BIMWaste accurately computes Gross Floor Area and the number of floors in building designs.

## **9.4 Implications of the Study**

This research has huge implications to CW management at the design stages in several ways, which include implications for practice and theoretical implications. This study has generated several implications that would be of interest to BIM professionals, sustainability experts, material suppliers, architects, design engineers, software developers, and academics. These implications are discussed in subsequent subsections. It is worthy of note that the implications presented are by no means exhaustive. They are, however, intended to stimulate thinking on how the insights from this study might impact current practices.

### **9.4.1 Implications for practice**

Findings from this study showed that integrating CW management into BIM is key for efficient waste prediction and minimisation at the design stage. This study therefore offers significant implications for industrial practice and various industry stakeholders.

#### ***9.4.1.1 Architects and Design Engineers***

This study has significant implications for practice especially at the design stage. The design stage is crucial for CW management because it is cheaper to make changes at this stage. The study creates awareness on the roles of design in CW management and it broadens the understanding of how design-related factors influence CW generation. Although architects and design engineers are becoming more interested in designing out waste, existing tools are not robust enough to support them. Software (BIMWaste) developed as part of this study is therefore useful for architects and design engineers by providing them with insights into identifying sources of CW during design. BIMWaste predicts the potential CW output of a building design and it provides suggestion on how CW could be minimised through dimensional coordination and material optimisation. BIMWaste also provides a basis for comparative analysis of building design for selecting the one with the least CW potential among options without affecting building forms or function.

#### ***9.4.1.2 BIM professional***

This research makes a huge contribution to CW management at the design stages in several ways. The study identified the limitations of existing CW management tools. The two key limitations are: (i) the tools are completely detached from the design process, and (ii) existing tools lack interoperability capability. Accordingly, the study employs BIM to address the key limitations identified. Although there are several studies that have provided evidence that BIM is required for efficient CW management, the use of BIM for CW management is often neglected. Due to the steep rise in BIM adoption and the importance of environmental sustainability, BIM professionals are becoming interested in ways of integrating sustainable practices in BIM platform. This study therefore provides clear direction on how BIM could be used for this purpose. The study also significantly to BIM by developing a system to streamline the estimation and minimisation of CW in BIM environment.

#### ***9.4.1.3 Circular Economy and Sustainability Management***

Construction activities have major impacts on social, environmental, and economic aspects of sustainability. Although, construction industry contributes to Gross Domestic Product (GDP) of a nation, it consumes the largest percentage of resources and it generates huge waste. As such, the circular economy ensures that the added value of building materials is kept within an economic circle to avoid waste generation and demand for virgin resources. The circular economy therefore maximises material usage through recycling and reuse. This study therefore has huge implications for circular economy and sustainability because it offers an effective way for measuring the environmental impact (in terms of CW generation) of building design. It also offers an objective means of measuring which of the predicted waste could be recycled and reused. This is important for effective material economic circle, resource allocation, and resource utilization.

#### **9.4.1.4 Material Manufacturers**

Although, waste in LEAN philosophy include non-material waste such as waste associated with time loss, transportation, under-utilisation, and waiting. (Koskela, 2004), material waste constitutes the largest proportion of waste and it has the highest environmental impact (Osmani *et al.* 2008; Oyedele *et al.* 2013). Although materials suppliers are usually considered as external stakeholders in building projects, this study suggests that adequate waste management requires active involvement of materials suppliers. This means that early supply chain involvement is more beneficial rather than the fragmented approach in traditional procurement. BIM is therefore required to ensure communication among stakeholders and design coordination. Early involvement of material suppliers will allow them to engage in decision making for driving waste minimization. In addition, it is important for material manufacturers to ensure that their products have minimal impact on the environment. BIMWaste will therefore assist material manufacturers to test the potential impact their products on waste potentials of buildings.

#### **9.4.1.5 Software Developers**

The recent advancement in ICT and BIM technologies reveals that any promising innovation within the Architectural, Engineering, and Construction (AEC) industry requires BIM compliance. It is also important that complex and repetitive construction related tasks are automated to achieve the required flexibility, reliability, and efficiency. The foregoing thus revealed the importance of software development for BIM and construction activities. This study therefore has three key implications for software developers. First, the holistic framework developed as part of this study provides a methodological basis for developing BIM-enabled software for CW management. The framework details components that must be considered when developing tools for CW prediction and minimisation. Second, ANFIS and mathematical models developed could be adapted by software developers to extend their tools for CW management. Lastly, the development process of BIMWaste detailed in this study provides a blueprint for the integration of construction related tasks into BIM. As such, software developer could adopt the procedures enumerated in this study



to achieve tasks such as extracting BoQ from building design, calculating GFA, and calculating number of floors.

#### **9.4.2 Theoretical Implications**

A major theoretical implication that this study provides is that CW management process could be described into a computational system such that it could be simulated. This confirms the relevance of theory of Artificial Intelligence to the study. This study satisfies epistemological and heuristic adequacy that is required to formalise existing design-out-waste strategies into a computational tool. Key objectives of the tool are to ensure that building designs have minimal impact on the environment and that finite natural resources are preserved through material recycling and reuse. This reveals the relevance of Tragedy of the commons, which informs the understanding of how construction materials, as finite common resources, could be optimised for maximum sustainability and productivity. This is needed to ensure that more proactive strategies rather than remedial measures to waste management are put in place in the construction industry. As such, the BIM based tool contributes towards the sustenance of finite virgin resources and help to maintain a close material flow loop.

A key requirement of this study is to identify evaluative criteria for existing CW management tools. The exercise was based on Scriven's logic of evaluation, which details steps that must be followed during evaluation. The evaluation started by identifying a list of 32 CW management tools and proceeds to establish criteria for merit for the tools. Thereafter, the performance of the objects in relation to the criteria of merit was determined before drawing valid conclusions. Based on the tenets of theories of evaluative practices, a constructivist evaluation and qualitative methodology was adopted to understand stakeholders' views and needs in a valid evaluation. The results reveal a list of 40 evaluative criteria that could be used to evaluate the performance of existing CW management tools. The six groups of evaluative criteria are: (a) Group 1 denoted by waste prediction related criteria; (b) Group 2 denoted by waste data related criteria; (c) Group 3

denoted by commercial and procurement; (d) Group 4 denoted by BIM related criteria; (e) Group 5 denoted by design related criteria; and (f) Group 6 denoted by technological related criteria.

It has been shown that a major challenge to the development of intelligent system is how plausible decisions are made using both quantitative and qualitative information that have a level of uncertainty and imprecision. It is therefore important to adopt evidential reasoning mechanism to draw out plausible course of actions. This allows the collection and combination of evidence in support or against some hypotheses. The study adopted Fuzzy set theory to represent and process imprecise information by using linguistic variables. Concepts in fuzzy set theory were integrated with ANN to obtain a more powerful hybrid system.

## **9.5 Limitations of the Study**

Despite the contributions of this study, it has some limitations in terms of its scope and data availability. A major limitation of this study is that the study was undertaken in the context of the UK so the findings have a UK bias. Effort has been made to enhance generalisability of findings using survey research and probabilistic sampling, however, findings of the study should not be generalised beyond the UK. Although projects in construction industry falls under three broad sectors, which are building, infrastructure, and industrial, data collection for the study was focused only on building project. This means that infrastructure projects (such as highway, bridges, and dams) and industrial projects (such as refineries, manufacturing plants, and process plants) were not considered in the study.

Although, LEAN include non-material waste such as waste associated with transportation, time loss, under-utilisation, inadequate training, and waiting. (Koskela, 2004), only material waste was considered in this study. This is because materials contribute the largest proportion of waste compared with other sources. As such, waste considered in this study is limited to building material waste and the definition of waste used in the study does not cover non-material waste. In addition, this study only considered environmental dimension of sustainability. The impact of waste was

not assessed along other two sustainability dimensions, which are economic, and social. In terms of the scope of the building lifecycle stage, this study focused on the prediction of CW at the design stages, which include Stage 2 (Concept Design) to Stage 4 (Technical Design). Software developed in this study is useful to architects and design engineers at these stages to predict and minimise CW. However, the study did not consider excavation waste and demolition waste. Other limitation of the study is in terms of data used for the model development. The data lacks information about the bill of quantity for the designs. In addition, the data did not provide information about the building methodology employed. The availability of information such as data on prefabrication, procurement route, material procurement, material delivery, recycling rate, material reuse, and waste transportation would enable more accurate prediction of CW along other dimensions.

## **9.6 Areas of Future Research**

Since this study was carried out within the UK, future research could investigate generalisability of findings from this study to other countries. Future research could also extend the scope of this study beyond material waste. Based on LEAN philosophy, non-material sources of CW could be investigated and integrated into BIM. In the same way, the scope of future studies could be extended to cover civil engineering and infrastructure projects. Future research could also go beyond just construction waste to consider prediction of excavation, operational, and demolition waste.

As earlier stated that the data used for model development are limited in some areas, future research could develop BIM-based waste collection tools. This is to integrate waste data record into federated BIM models. In addition, IFC standard could be extended for a more robust waste analysis and simulation. This will offer IFC based framework to streamline the performance analysis of waste within BIM software. Accordingly, waste information generation could be stored appropriately within the scope of material management routes, element prefabrication, procurement route, material procurement details, material delivery schedule, recycling rate, material reuse, and waste transportation. Achieving this would enable more accurate prediction of

CW along other dimensions other than GFA and construction type. Integrating waste related data into IFC schema would provide huge opportunities for developing a structured knowledge base for waste management and would enable a standard schema for construction waste analytics.

Another area of future research could be integration of BIM-based waste management capability with immersive technologies such as Augmented Reality (AR) and Virtual Reality (VR). Achieving this would help to visualise virtual building material in real world, and how these materials and building practices could influence waste generation. AR particularly overlays digital information over the real-world environment using a piece of head-mounted display like Google Glass and Microsoft HoloLens. As such, these technologies could help to visualise and simulate waste management activities during building construction, site planning, building maintenance, transportation route planning, and hazardous waste management. In addition, other learning algorithms, particularly those with distributed representation such as convolutional deep neural networks, deep belief networks, and deep Boltzmann machines could be explored for CW prediction.

The Autodesk plugin developed in this study could lead to the development of a complementary plugin for Autodesk Navisworks. This will enable CW generation to be visualised vis-à-vis building project timeline and construction sequence. Achieving this will enable building operators to simulate CW generation and to plan for waste collection activities effectively.

## REFERENCES

- Abraham, A. (2003) Intelligent systems: Architectures and perspectives. In: *Recent advances in intelligent paradigms and applications*. (no place) Springer. pp. 1–35.
- Abraham, A. (2004) Meta learning evolutionary artificial neural networks *Neurocomputing* 56 (1–4) p.pp. 1–38. doi:10.1016/S0925-2312(03)00369-2.
- Abraham, a (2005) Hybrid intelligent systems: evolving intelligence in hierarchical layers. *Do Smart Adaptive Systems Exist?* [online]. 179 pp. 159–179. Available from: [http://link.springer.com/content/pdf/10.1007/3-540-32374-0\\_8.pdf](http://link.springer.com/content/pdf/10.1007/3-540-32374-0_8.pdf).
- Abrahamsson, P., Salo, O., Ronkainen, J. and Warsta, J. (2002) Agile software development methods: Review and analysis *VTT Publications* (478) p.pp. 3–107. doi:10.1076/csed.12.3.167.8613.
- Abrishami, S., Goulding, J.S., Rahimian, F.P. and Ganah, A. (2014) Integration of BIM and generative design to exploit AEC conceptual design innovation. *Journal of Information Technology in Construction*. 19 (1), pp. 350–359.
- Adachi, Y. (2003) Overview of partial model query language. In: *Proc. ISPE Conf. Concurrent Engineering*. 2003 pp. 549–555.
- Addis, B. (2008) Briefing: Design for deconstruction. *Proceedings of the ICE - Waste and Resource Management*. 161 (1), pp. 9–12. doi:10.1680/warm.2008.161.1.9.
- Afshar, A., Massoumi, F., Afshar, A. and Mariño, M.A. (2015) State of the art review of ant colony optimization applications in water resource management. *Water Resources Management*. 29 (11), pp. 3891–3904.
- Agarwal, R., Prasad, J., Tanniru, M. and Lynch, J. (2000) Risks of rapid application development. *Communications of the ACM*. 43 (1), pp. 177–188. doi:10.1145/352515.352516.
- Agrawal, R., Mannila, H., Srikant, R., Toivonen, H. and Verkamo, a I. (1996) *Fast discovery of association rules* [online].
- Ahadzie, D.K., Proverbs, D.G. and Sarkodie-Poku, I. (2014) Competencies required of project managers at the design phase of mass house building projects. *International Journal of Project Management*. 32 (6), pp. 958–969. doi:10.1016/j.ijproman.2013.10.015.
- Ahern, T., Leavy, B. and Byrne, P.J. (2014) Knowledge formation and learning in the management of projects: A problem solving perspective. *International Journal of Project Management*. 32 (8), pp. 1423–1431. doi:10.1016/j.ijproman.2014.02.004.

- AIA (2014) Integrated Project Delivery: An Updated Working Definition *AIA California Council, Sacramento, CA* [online]. Available from: [http://www.aiacc.org/wp-content/uploads/2014/07/AIACC\\_IPD.pdf](http://www.aiacc.org/wp-content/uploads/2014/07/AIACC_IPD.pdf).
- Ajayi, S.O., Oyedele, L.O., Akinade, O.O., Bilal, M., Owolabi, H.A., Alaka, H.A. and Kadiri, K.O. (2016) Reducing waste to landfill: A need for cultural change in the UK construction industry. *Journal of Building Engineering* [online]. 5 pp. 185–193. Available from: <http://www.sciencedirect.com/science/article/pii/S2352710215300590>doi:10.1016/j.jobbe.2015.12.007 [Accessed 6 February 2016].
- Ajayi, S.O., Oyedele, L.O., Bilal, M., Akinade, O.O., Alaka, H.A., Owolabi, H.A. and Kadiri, K.O. (2015a) Waste effectiveness of the construction industry: Understanding the impediments and requisites for improvements. *Resources, Conservation and Recycling* [online]. 102 pp. 101–112. Available from: <http://www.sciencedirect.com/science/article/pii/S0921344915300203>doi:10.1016/j.resconrec.2015.06.001 [Accessed 10 March 2016].
- Ajayi, S.O., Oyedele, L.O., Ceranic, B., Gallanagh, M. and Kadiri, K.O. (2015b) Life cycle environmental performance of material specification: a BIM-enhanced comparative assessment. *International Journal of Sustainable Building Technology and Urban Development* [online]. 6 (1), pp. 14–24. Available from: <http://www.tandfonline.com/doi/full/10.1080/2093761X.2015.1006708#.Vk94qXbhDcsdoi:10.1080/2093761X.2015.1006708> [Accessed 20 November 2015].
- Akbarnezhad, A., Ong, K.C.G. and Chandra, L.R. (2014) Economic and environmental assessment of deconstruction strategies using building information modeling. *Automation in Construction*. 37 pp. 131–144. doi:10.1016/j.autcon.2013.10.017.
- Akerkar, R. and Sajja, P. (2010) *Knowledge-Based Systems* [online]. (no place) Jones and Bartlett.
- Akinade, O.O., Oyedele, L.O., Bilal, M., Ajayi, S.O., Owolabi, H.A., Alaka, H.A. and Bello, S.A. (2015) Waste minimisation through deconstruction: A BIM based Deconstructability Assessment Score (BIM-DAS). *Resources, Conservation and Recycling* [online]. 105 pp. 167–176. Available from: <http://www.sciencedirect.com/science/article/pii/S0921344915301166>doi:10.1016/j.resconrec.2015.10.018 [Accessed 20 November 2015].
- Akinade, O.O., Oyedele, L.O., Munir, K., Bilal, M., Ajayi, S.O., Owolabi, H.A., Alaka, H.A. and Bello, S.A. (2016) Evaluation criteria for construction waste management tools: towards a holistic BIM framework (in press). *International journal of building technology and urban development*. pp. 1–19.
- Al-Hajj, A. and Hamani, K. (2011) Material Waste in the UAE Construction Industry: Main Causes and Minimization Practices. *Architectural Engineering and Design Management*

[online]. 7 (4), pp. 221–235. Available from: [http://ucd.summon.serialssolutions.com/2.0.0/link/0/eLvHCXMw3V1La9wwEBZtTqUlpC\\_iPECX9hLcypItyYUelpISCnsomyW5CdmSwKVrCnGgPz8aPXbdbaD33nbtXdtoPms0o5nvQ4jRD6TcmxN4pXllvavUXFbMeEfhJKFauNaKloSm12\\_f-WLZ3q7Yaic-ujv2Pxb-qadw8Ysb7S2Y6xjXi8sgzppnYi-SZkcgfFpq6P3T93](http://ucd.summon.serialssolutions.com/2.0.0/link/0/eLvHCXMw3V1La9wwEBZtTqUlpC_iPECX9hLcypItyYUelpISCnsomyW5CdmSwKVrCnGgPz8aPXbdbaD33nbtXdtoPms0o5nvQ4jRD6TcmxN4pXllvavUXFbMeEfhJKFauNaKloSm12_f-WLZ3q7Yaic-ujv2Pxb-qadw8Ysb7S2Y6xjXi8sgzppnYi-SZkcgfFpq6P3T93)doi:10.1080/17452007.2011.594576.

- Alaka, H.A., Oyedele, L.O., Owolabi, H.A., Oyedele, A.A., Akinade, O.O., Bilal, M. and Ajayi, S.O. (2016) Critical factors for insolvency prediction: towards a theoretical model for the construction industry. *International Journal of Construction Management*. doi:10.1080/15623599.2016.1166546.
- An, S.-H., Park, U.-Y., Kang, K.-I., Cho, M.-Y. and Cho, H.-H. (2007) Application of support vector machines in assessing conceptual cost estimates. *Journal of Computing in Civil Engineering*. 21 (4), pp. 259–264.
- Anderson, J. and Shiers, D. (2009) *Green guide to specification*. 4th edition. Oxford: John Wiley & Sons.
- Andi and Minato, T. (2003) Design documents quality in the Japanese construction industry: factors influencing and impacts on construction process. *International Journal of Project Management* [online]. 21 (7), pp. 537–546. Available from: <http://www.sciencedirect.com/science/article/pii/S0263786302000832>doi:10.1016/S0263-7863(02)00083-2 [Accessed 21 June 2015].
- Arayici, Y., Coates, P., Koskela, L., Kagioglou, M., Usher, C. and O'Reilly, K. (2011) BIM adoption and implementation for architectural practices. *Structural survey*. 29 (1), pp. 7–25.
- Arayici, Y., Egbu, C. and Coates, P. (2012) Building information modelling (Bim) implementation and remote construction projects: Issues, challenges, and critiques *Electronic Journal of Information Technology in Construction* 17 p.pp. 75–92. doi:ISSN 1874-4753.
- Arnott, D. and Pervan, G. (2005) A critical analysis of decision support systems research. *Journal of Information Technology*. 20 pp. 67–87. doi:10.1057/palgrave.jit.2000035.
- Asadi, E., da Silva, M.G., Antunes, C.H., Dias, L. and Glicksman, L. (2014) Multi-objective optimization for building retrofit: A model using genetic algorithm and artificial neural network and an application. *Energy and Buildings*. 81 pp. 444–456.
- Atanassov, K. (1986) Intuitionistic Fuzzy Sets.pdf. *Fuzzy Sets and Systems*. 20 (1), pp. 87–96.
- Aubry, M., Richer, M.-C. and Lavoie-Tremblay, M. (2014) Governance performance in complex environment: The case of a major transformation in a university hospital. *International Journal of Project Management*. 32 (8), pp. 1333–1345. doi:10.1016/j.ijproman.2013.07.008.

- Augusto, T., Mounir, K. and Melo, A.M.C. (2012) A cost optimization-based design of precast concrete floors using genetic algorithms. *Automation in Construction*. 22 pp. 348–356.
- Autodesk (2014) *Revit 2009 API Developer's Guide*.
- Azhar, S. (2011) Building information modeling (BIM): Trends, benefits, risks, and challenges for the AEC industry. *Leadership and Management in Engineering*. 11 (3), pp. 241–252.
- Azhar, S., Hein, M. and Sketo, B. (2007) Building Information Modeling ( BIM ): Benefits , Risks and Challenges. *Leadership and Management in Engineering*. 11 (3), pp. 241–252.
- Baldwin, A., Poon, C.-S., Shen, L.-Y., Austin, S. and Wong, I. (2009) Designing out waste in high-rise residential buildings: Analysis of precasting methods and traditional construction. *Renewable Energy*. 34 (9), pp. 2067–2073. doi:10.1016/j.renene.2009.02.008.
- Banias, G., Achillas, C., Vlachokostas, C., Moussiopoulos, N. and Papaioannou, I. (2011) A web-based Decision Support System for the optimal management of construction and demolition waste. *Waste management (New York, N.Y.)*. 31 (12), pp. 2497–2502. doi:10.1016/j.wasman.2011.07.018.
- Banzhaf, W. (2013) Evolutionary Computation and Genetic Programming. In: *Engineered Biomimicry*. pp. 429–447. doi:10.1016/B978-0-12-415995-2.00017-9.
- Beck, K. (1999) *Extreme Programming Explained: Embrace Change*.
- Beetz, J. and Berlo, L. Van (2010) *BIMSERVER . ORG – AN OPEN SOURCE IFC MODEL SERVER*. (Weise 2006), pp. 16–18.
- Begum, R.A., Satari, S.K. and Pereira, J.J. (2010) Waste generation and recycling: Comparison of conventional and industrialized building systems. *American Journal of Environmental Sciences*. 6 pp. 383–388. doi:10.3844/ajessp.2010.383.388.
- Bergsdal, H., Bohne, R.A. and Brattebø, H. (2007) Projection of construction and demolition waste in Norway. *Journal of Industrial Ecology*. 11 (3), pp. 27–39.
- Bernroider, E.W.N., Wong, C.W.Y. and Lai, K. (2014) From dynamic capabilities to ERP enabled business improvements: The mediating effect of the implementation project. *International Journal of Project Management*. 32 (2), pp. 350–362. doi:10.1016/j.ijproman.2013.05.006.
- Beynon-Davies, P., Carne, C., Mackay, H. and Tudhope, D. (1999) Rapid application development (RAD): an empirical review. *European Journal of Information Systems*. 8 (3), pp. 211–223.
- Bilal, M., Oyedele, L.O., Akinade, O.O., Ajayi, S.O., Alaka, H.A., Owolabi, H.A., Qadir, J., Pasha, M. and Bello, S.A. (2016a) Big data architecture for construction waste analytics (CWA): A conceptual framework. *Journal of Building Engineering* [online]. Available from:



<http://www.sciencedirect.com/science/article/pii/S2352710216300262>doi:10.1016/j.jobe.2016.03.002 [Accessed 15 March 2016].

- Bilal, M., Oyedele, L.O., Qadir, J., Munir, K., Akinade, O.O., Ajayi, S., Alaka, H.A. and Owolabi, H.A. (2016b) Analysis of critical features and evaluation of BIM software: towards a plug-in for construction waste minimization using big data. *International Journal of Sustainable Building Technology and Urban Development*. pp. 1–18.
- BIM-Industry-Working-Group (2011) Strategy Paper for the Government Construction Client Group. *Her majesty's Government, UK2011*.
- Bishop, C.M. (1995) *Neural networks for pattern recognition*. (no place) Oxford university press.
- Blaikie, N. (2007) *Approaches to social enquiry: Advancing knowledge*. (no place) Polity.
- BlueWise (2010) ConstructCLEAR. Available from: <http://www.constructclear.co.uk> [online]. Available from: <http://www.constructclear.co.uk>.
- Blum, C. and Roli, A. (2003) Metaheuristics in combinatorial optimization: Overview and conceptual comparison. *ACM Computing Surveys (CSUR)*. 35 (3), pp. 268–308.
- Boehm, B. (2000) Spiral Development: Experience, Principles, and Refinements. *Spiral Development Workshop February 9, 2000*. (July), pp. 49. doi:CMU/SEI-2000-SR-008.
- Boehm, B.W. (1988) SPIRAL MODEL OF SOFTWARE DEVELOPMENT AND ENHANCEMENT. *Computer*. 21 (5), pp. 61–72. doi:10.1109/2.59.
- Bogdan, R.C. and Biklen, S.K. (1998) *Qualitative research in education. An introduction to theory and methods*. Boston: Allyn and Bacon.
- Boose, J.H. (1989) A survey of knowledge acquisition techniques and tools *Knowledge Acquisition* 1 p.pp. 3–37. doi:10.1016/S1042-8143(89)80003-2.
- Borrmann, A., Van Treeck, C. and Rank, E. (2006) Towards a 3D spatial query language for building information models. In: *Proc. Joint Int. Conf. of Computing and Decision Making in Civil and Building Engineering (ICCCBE-XI)*. 2006
- Bossink, B.A.G. and Brouwers, H.J.H. (1996) Construction waste: quantification and source evaluation. *Journal of Construction Engineering and Management*. 122 (1), pp. 55–60.
- Braglia, M. and Frosolini, M. (2014) An integrated approach to implement Project Management Information Systems within the Extended Enterprise. *International Journal of Project Management*. 32 (1), pp. 18–29. doi:10.1016/j.ijproman.2012.12.003.
- Brannen, J. (2005) Mixing Methods: The Entry of Qualitative and Quantitative Approaches into

the Research Process. *International Journal of Social Research Methodology*. 8 (3), pp. 173–184. doi:10.1080/13645570500154642.

BRE (2009) BreMap. Available from: <http://www.bremap.co.uk/Default.aspx> [online]. Available from: <http://www.bremap.co.uk/Default.aspx> (23rd O [Accessed 23 July 2014]).

BRE (2008a) SMARTAudit. Available from: <http://www.smartwaste.co.uk/smartaudit/about.jsp> [online]. Available from: <http://www.smartwaste.co.uk/smartaudit/about.jsp> [Accessed 23 July 2014].

BRE (2007) SMARTStart. Available from: <http://www.smartwaste.co.uk/smartstart/about.jsp> [online]. Available from: <http://www.smartwaste.co.uk/smartstart/about.jsp> [Accessed 23 July 2014].

BRE (2008b) SMARTWASTE. Available from: <http://www.smartwaste.co.uk/index.jsp> [Accessed 25 April 2016].

BRE (2010) True cost of waste calculator. Available from: <http://www.wastecalculator.co.uk/login.jsp> [online]. Available from: <http://www.wastecalculator.co.uk/login.jsp> [Accessed 23 July 2014].

Bredillet, C. (2004) Beyond the positivist mirror: Towards a project management 'gnosis'. *International Research Network for Organizing by Projects-IRNOP VI*.

Brunner, P.H. (2011) Urban Mining - A Contribution to Reindustrializing the City. *Journal of Industrial Ecology*. 15 (3), pp. S-339.

Brunnermeier, S.B. and Martin, S.A. (2002) Interoperability costs in the US automotive supply chain. *Supply Chain Management: An International Journal* [online]. 7 (2), pp. 71–82. Available from: <http://www.emeraldinsight.com/doi/10.1108/13598540210425821> doi:10.1108/13598540210425821 [Accessed 22 April 2017].

Bryson, J.M., Patton, M.Q. and Bowman, R.A. (2011) Working with evaluation stakeholders: A rationale, step-wise approach and toolkit. *Evaluation and program planning* [online]. 34 (1), pp. 1–12. Available from: <http://www.sciencedirect.com/science/article/pii/S0149718910000637> doi:10.1016/j.evalproplan.2010.07.001 [Accessed 7 September 2015].

Buchan, R.D., Fleming, F.W. and Kelly, J.R. (1991) *Estimating for builders and quantity surveyors*. Oxford: Newnes.

BuildingSMART (2013) Industry Foundation Classes IFC4 Official Release, buildingSMART. Available from: <http://www.buildingsmart-tech.org> [online]. Available from: <http://www.buildingsmart-tech.org> [Accessed 23 August 2014].

- Burguet, R., Ganuza, J.-J. and Hauk, E. (2012) Limited liability and mechanism design in procurement. *Games and Economic Behavior* [online]. 76 (1), pp. 15–25. Available from: <http://www.sciencedirect.com/science/article/pii/S0899825612000723>doi:10.1016/j.geb.2012.04.004 [Accessed 12 April 2017].
- Burkingham, A. and Saunders, P. (2004) *The Survey Methods Workbook: From Design To Analysis*.
- Burrell, G. and Morgan, G. (1979) *Sociological paradigms and organisational analysis*. London: Heinemann Educational.
- CabinetOffice (2011) Government Construction Strategy. Available from: [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/61152/Government-Construction-Strategy\\_0.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/61152/Government-Construction-Strategy_0.pdf). [online]. Available from: [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/61152/Government-Construction-Strategy\\_0.pdf](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/61152/Government-Construction-Strategy_0.pdf).
- Çaydaş, U., Hasçalık, A. and Ekici, S. (2009) An adaptive neuro-fuzzy inference system (ANFIS) model for wire-EDM. *Expert Systems with Applications*. 36 (3), pp. 6135–6139. doi:10.1016/j.eswa.2008.07.019.
- Cerovsek, T. (2011) A review and outlook for a ‘Building Information Model’ (BIM): A multi-standpoint framework for technological development. *Advanced Engineering Informatics*. 25 (2), pp. 224–244. doi:10.1016/j.aei.2010.06.003.
- Charlson, A. (2008) Recycling and reuse of waste in the construction industry. *The Structural Engineer*. 86 (4), pp. 32–37.
- Chen, Z., Li, H., Kong, S.C.W., Hong, J. and Xu, Q. (2006) E-commerce system simulation for construction and demolition waste exchange. *Automation in Construction*. 15 (6), pp. 706–718. doi:10.1016/j.autcon.2005.09.003.
- Chen, Z., Li, H. and Wong, C.T.C. (2002) *An application of bar-code system for reducing construction wastes*. 11 pp. 521–533.
- Chen, Z., Li, H. and Wong, C.T.C. (2003) Webfill before landfill: an e-commerce model for waste exchange in Hong Kong. *Construction Innovation*. 3 (1), pp. 27–43.
- Cheng, J.C.P. and Ma, L.Y.H. (2013) A BIM-based system for demolition and renovation waste estimation and planning. *Waste management (New York, N.Y.)*. 33 (6), pp. 1539–1551. doi:10.1016/j.wasman.2013.01.001.
- Cheng, J.C.P. and Ma, L.Y.H. (2011) A BIM-based System for Demolition and Renovation Waste Quantification and Planning. In: *14th International Conference on Computing in Civil Engineering*. 2011

- Cheng, M.-Y. and Hoang, N.-D. (2014) Interval estimation of construction cost at completion using least squares support vector machine. *Journal of Civil Engineering and Management*. 20 (2), pp. 223–236.
- Cheng, M.-Y., Tsai, H.-C. and Hsieh, W.-S. (2009) Web-based conceptual cost estimates for construction projects using Evolutionary Fuzzy Neural Inference Model. *Automation in Construction*. 18 (2), pp. 164–172.
- Cheng, Y.-M. (2014) An exploration into cost-influencing factors on construction projects. *International Journal of Project Management*. 32 (5), pp. 850–860. doi:10.1016/j.ijproman.2013.10.003.
- Chini, A.R. and Acquaye, L. (2001) Grading and mechanical properties of salvaged lumber. In: *Proceedings of the CIB Task Group 39-Deconstruction Meeting*. 2001 pp. 138–162.
- Chini, A.R. and Balachandran, S. (2002) Anticipating and responding to deconstruction through building design. *Design for Deconstruction and Materials Reuse, CIB Publication*. 272 .
- Chipman, T., Liebich, T. and Weise, M. (2012) mvdXML: Specification of a standardized format to define and exchange Model View Definitions with Exchange Requirements and Validation Rules. *buildingSMART International*.
- Choi, J.W., Kim, S.A., Lertlakkhanakul, J. and Yeom, J.H. (2008) Developing ubiquitous space information model for indoor gis service in ubicomp environment. In: *Networked Computing and Advanced Information Management, 2008. NCM'08. Fourth International Conference on*. 2008 (no place) IEEE. pp. 381–388.
- Choi, S., Kim, D.Y., Han, S.H. and Kwak, Y.H. (2013) Conceptual cost-prediction model for public road planning via rough set theory and case-based reasoning. *Journal of Construction Engineering and Management*. 140 (1), pp. 4013026.
- Chrysostomou, V. (2000) CALIBRE-the uk's construction industry added value toolkit. In: *International Conference on the Use of Automatic Data Collection in Construction*. 2000
- Chua, D.K.H., Li, D.Z. and Chan, W.T. (2001) Case-based reasoning approach in bid decision making. *Journal of construction engineering and management*. 127 (1), pp. 35–45.
- CMS (2005) *Selecting a Development Approach*. Available from: <https://sms.unikom.ac.id/taryana/download/jad/SelectingDevelopmentApproach.pdf> [Accessed 2 April 2017].
- Cochran, K., Townsend, T., Reinhart, D. and Heck, H. (2007a) Estimation of regional building-related C&D debris generation and composition: case study for Florida, US. *Waste management (New York, N.Y.)*. 27 (7), pp. 921–931. doi:10.1016/j.wasman.2006.03.023.

- Cochran, K., Townsend, T., Reinhart, D. and Heck, H. (2007b) Estimation of regional building-related C&D debris generation and composition: case study for Florida, US. *Waste management (New York, N.Y.)* [online]. 27 (7), pp. 921–931. Available from: <http://www.sciencedirect.com/science/article/pii/S09566053X06001449>doi:10.1016/j.wasman.2006.03.023 [Accessed 19 February 2015].
- Cochran, K.M. and Townsend, T.G. (2010) Estimating construction and demolition debris generation using a materials flow analysis approach. *Waste management (New York, N.Y.)*. 30 (11), pp. 2247–2254. doi:10.1016/j.wasman.2010.04.008.
- Coleman, G. and Verbruggen, R. (1998) A quality software process for rapid application development. *Software Quality Journal* [online]. 7 (2), pp. 107–122. Available from: <http://dx.doi.org/10.1023/A:1008856624790>doi:10.1023/A:1008856624790.
- Constructing-Excellence (2006) *AVANTI - Constructing Excellence*. Available from: <http://constructingexcellence.org.uk/resources/avanti/> [Accessed 12 March 2017].
- Constructivity (2016) *Constructivity Model Server*. Available from: <http://www.constructivity.com/about.htm> [Accessed 24 April 2016].
- Corcho, O., Fernández-López, M. and Gómez-Pérez, A. (2003) Methodologies, tools and languages for building ontologies. Where is their meeting point? *Data & Knowledge Engineering* [online]. 46 (1), pp. 41–64. Available from: <http://linkinghub.elsevier.com/retrieve/pii/S0169023X02001957>doi:10.1016/S0169-023X(02)00195-7 [Accessed 18 December 2014].
- Craven, D.J., Okraglik, H.M. and Eilenberg, I.M. (1994) Construction waste and a new design methodology. In: *Proceedings of the First Conference of CIB TG*. 1994 pp. 89–98.
- Crawford, L. and Pollack, J. (2004) Hard and soft projects: a framework for analysis. *International Journal of Project Management*. 22 (8), pp. 645–653. doi:10.1016/j.ijproman.2004.04.004.
- Creswell, J.W. (2013) *Qualitative inquiry and research design: Choosing among five approaches*. 3rd edition. London: Sage Publications.
- Creswell, J.W. (2014) *Research design: Qualitative, quantitative, and mixed methods approaches*. London: Sage Publications.
- Creswell, J.W. and Clark, V.L.P. (2007) *Designing and conducting mixed methods research*.
- Crotty, M. (1998) *The foundations of social research: meaning and perspective in the research process*. London: Sage publications.
- Crowther, P. (2005) Design for disassembly - themes and principles *RAIA/BDP Environment Design Guide* [online] p.pp. 1–9. Available from: <http://eprints.qut.edu.au/2888/1/Crowther->

RAIA-2005.PDFdoi:10.1115/1.2991134.

Cyon (2009) *Cyon Research 2009 Survey of Engineering Software Users*. Available from: [http://cyonresearch.com/Portals/0/files/whitepapers/Cyon Research 2009 User Survey.pdf](http://cyonresearch.com/Portals/0/files/whitepapers/Cyon%20Research%202009%20User%20Survey.pdf) [Accessed 12 May 2016].

Dainty, A.R.J. and Brooke, R.J. (2004) Towards improved construction waste minimisation: a need for improved supply chain integration? *Structural Survey*. 22 (1), pp. 20–29. doi:10.1108/02630800410533285.

Daniel Forgues D and Lauri Koskela (2008) Can Procurement affect Design Performance. *Journal of Construction Procurement* [online]. 14 (2), pp. 130–141. Available from: [http://usir.salford.ac.uk/9363/1/2008\\_Can\\_procurement\\_affect\\_design\\_performance.PDF](http://usir.salford.ac.uk/9363/1/2008_Can_procurement_affect_design_performance.PDF) [Accessed 12 April 2017].

Davidson, E.J. (2005) *Evaluation methodology basics: The nuts and bolts of sound evaluation*. (no place) Sage.

Davies, A. and Mackenzie, I. (2014) Project complexity and systems integration: Constructing the London 2012 Olympics and Paralympics Games. *International Journal of Project Management*. 32 (5), pp. 773–790. doi:10.1016/j.ijproman.2013.10.004.

Davis, R., Shrobe, H. and Szolovits, P. (1993) What Is a Knowledge Representation ? *AI magazine*. 14 (1), pp. 17–33.

Davison, B. and Tingley, D.D. (2011) Design for deconstruction and material reuse. *Proceedings of the ICE - Energy*. 164 pp. 195–204. doi:10.1680/ener.2011.164.4.195.

DEFRA (2012) Construction, Demolition and Excavation waste generation estimate: England, 2008 to 2010. Available from: [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/142006/CDE-generation-estimates.xls](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/142006/CDE-generation-estimates.xls) [online]. Available from: [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/400534/CDE-generation-estimates.xls](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/400534/CDE-generation-estimates.xls) [Accessed 16 June 2014].

DEFRA (2011) Total UK Waste Generation by Sector 2004 to 2008. Available from: [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/141980/wrfg01\\_gensec.xls](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/141980/wrfg01_gensec.xls) [online]. Available from: [https://www.gov.uk/government/uploads/system/uploads/attachment\\_data/file/141980/wrfg01\\_gensec.xls](https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/141980/wrfg01_gensec.xls) [Accessed 16 June 2014].

Denscombe, M. (2014) *The Good Research Guide: For Small-Scale Social Research Projects: For small-scale social research projects*. (no place) McGraw-Hill International.

Denzin, N. (1970) Strategies of multiple triangulation. *The research act in sociology: A theoretical*

*introduction to sociological method*. pp. 297–313.

- Denzin, N.K. and Lincoln, Y.S. (2000) The discipline and practice of qualitative research. *Handbook of qualitative research*. pp. 1–28.
- Ding, Z., Ng, F. and Li, J. (2014) A parallel multiple mediator model of knowledge sharing in architectural design project teams. *International Journal of Project Management*. 32 (1), pp. 54–65. doi:10.1016/j.ijproman.2013.04.004.
- Dolan, P.J., Lampo, R.G. and Dearborn, J.C. (1999) *Concepts for reuse and recycling of construction and demolition waste*.
- Dong, B., Lam, K.P., Huang, Y.C. and Dobbs, G.M. (2007) A comparative study of the IFC and gbXML informational infrastructures for data exchange in computational design support environments. In: *Tenth International IBPSA Conference*. 2007 pp. 1530–1537.
- Eadie, R., Browne, M., Odeyinka, H., McKeown, C. and McNiff, S. (2013a) BIM implementation throughout the UK construction project lifecycle: An analysis. *Automation in Construction*. 36 pp. 145–151. doi:10.1016/j.autcon.2013.09.001.
- Eadie, R., Browne, M., Odeyinka, H., McKeown, C. and McNiff, S. (2013b) BIM implementation throughout the UK construction project lifecycle: An analysis. *Automation in Construction*. 36 pp. 145–151. doi:10.1016/j.autcon.2013.09.001.
- East, E.W. (2007) Construction Operations Building Information Exchange (COBIE): Requirements Definition and Pilot Implementation Standard *Construction Engineering Research Laboratory ERDC/CERL TR-07-30*.
- Eastman, C., Lee, J., Jeong, Y. and Lee, J. (2009) Automatic rule-based checking of building designs. *Automation in Construction* [online]. 18 (8), pp. 1011–1033. Available from: <http://www.sciencedirect.com/science/article/pii/S0926580509001198>doi:10.1016/j.autcon.2009.07.002 [Accessed 18 January 2016].
- Eastman, C., Teicholz, P., Sacks, R. and Liston, K. (2011) *BIM handbook: A guide to building information modeling for owners, managers, designers, engineers and contractors*. (no place) John Wiley & Sons.
- Egan, J. (1998) Rethinking construction *Department of the Environment, Transport and the Regions, London* [online]. Available from: <http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Rethinking+Construction+0%5Cnhttp://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Rethinking+Construction.#0>.
- Eiben, A.E. and Smith, J. (2015) From evolutionary computation to the evolution of things. *Nature* [online]. 521 (7553), pp. 476–482. Available from:

<http://www.nature.com/nature/journal/v521/n7553/full/nature14544.html>  
<http://www.nature.com/nature/journal/v521/n7553/pdf/nature14544.pdf>doi:10.1038/nature14544.

- Ekanayake, L.L. and Ofori, G. (2004) Building waste assessment score: design-based tool. *Building and Environment*. 39 (7), pp. 851–861.
- Ekanayake, L.L. and Ofori, G. (2000) Construction material waste source evaluation. *Proceedings of Strategies for a Sustainable Built Environment, Pretoria*. pp. 23–25.
- Ekvall, T., Assefa, G., Björklund, A., Eriksson, O. and Finnveden, G. (2007) What life-cycle assessment does and does not do in assessments of waste management. *Waste management (New York, N.Y.)* [online]. 27 (8), pp. 989–996. Available from: <http://www.sciencedirect.com/science/article/pii/S0956053X07000724>doi:10.1016/j.wasman.2007.02.015 [Accessed 1 August 2015].
- Elbeltagi, E. and Dawood, M. (2011) Integrated visualized time control system for repetitive construction projects. *Automation in Construction*. 20 (7), pp. 940–953.
- van den Ende, L. and van Marrewijk, A. (2014) The ritualization of transitions in the project life cycle: A study of transition rituals in construction projects. *International Journal of Project Management*. 32 (7), pp. 1134–1145. doi:10.1016/j.ijproman.2014.02.007.
- Esin, T. and Cosgun, N. (2007) A study conducted to reduce construction waste generation in Turkey. *Building and Environment*. 42 (4), pp. 1667–1674.
- Faniran, O. and Caban, G. (1998) Minimizing waste on construction project sites. *Engineering, Construction and ...* 5 (2), pp. 182–188.
- Fatta, D., Papadopoulos, A., Avramikos, E., Sgourou, E., Moustakas, K., Kourmoussis, F., Mentzis, A. and Loizidou, M. (2003) Generation and management of construction and demolition waste in Greece—an existing challenge. *Resources, Conservation and Recycling* [online]. 40 (1), pp. 81–91. Available from: <http://www.sciencedirect.com/science/article/pii/S0921344903000351>doi:10.1016/S0921-3449(03)00035-1 [Accessed 25 February 2015].
- Feng, Y., Teo, E.A.L., Ling, F.Y.Y. and Low, S.P. (2014) Exploring the interactive effects of safety investments, safety culture and project hazard on safety performance: An empirical analysis. *International Journal of Project Management*. 32 (6), pp. 932–943. doi:10.1016/j.ijproman.2013.10.016.
- Field, A. (2005) *Discovering Statistics using SPSS*. 3rd edition. London: Sage Publications.
- Fijani, E., Nadiri, A.A., Asghari Moghaddam, A., Tsai, F.T.-C. and Dixon, B. (2013) Optimization of DRASTIC method by supervised committee machine artificial intelligence to assess groundwater vulnerability for Maragheh–Bonab plain aquifer, Iran. *Journal of Hydrology*



[online]. 503 pp. 89–100. Available from: <http://linkinghub.elsevier.com/retrieve/pii/S0022169413006252>doi:10.1016/j.jhydrol.2013.08.038 [Accessed 21 July 2017].

Fogel, D.B. (2006) *Evolutionary computation: toward a new philosophy of machine intelligence*. (no place) John Wiley & Sons.

Foote, K.E. and Lynch, M. (1996) Geographic Information Systems as an integrating technology: context, concepts, and definitions. *Austin, University of Texas*.

Ford, N.F. (1985) Decision support systems and expert systems: A comparison. *Information & Management* [online]. 8 (1), pp. 21–26. Available from: <http://linkinghub.elsevier.com/retrieve/pii/0378720685900667>doi:10.1016/0378-7206(85)90066-7 [Accessed 17 April 2017].

Formoso, C.T., Isatto, E.L. and Hirota, E.H. (1999) Method for Waste Control in the Building Industry. In: *Proceedings IGLC-7 - 7th Conference of the International Group for Lean Construction*. 1999 Berkeley, California: . pp. 325–334.

Formoso, C.T., Soibelman, L., De Cesare, C. and Isatto, E.L. (2002) Material Waste in Building Industry: Main Causes and Prevention. *Journal of Construction Engineering and Management*. 128 (4), pp. 316–325. doi:10.1061/(ASCE)0733-9364(2002)128:4(316).

Fowler, M. and Highsmith, J. (2001) The agile manifesto. *Software Development* [online]. 9 (August), pp. 28–35. Available from: <http://www.pmp-projects.org/Agile-Manifesto.pdf><sup>f</sup>%5Cn[http://andrey.hristov.com/fht-stuttgart/The\\_Agile\\_Manifesto\\_SDMagazine.pdf](http://andrey.hristov.com/fht-stuttgart/The_Agile_Manifesto_SDMagazine.pdf)<sup>f</sup>%5Cn<http://www.pmp-projects.org/Agile-Manifesto.pdf>doi:10.1177/004057368303900411.

Freire, J. and Alarcón, L.F. (2002) Achieving lean design process: Improvement methodology. *Journal of Construction Engineering and management*. 128 (3), pp. 248–256.

Fulford, R. and Standing, C. (2014) Construction industry productivity and the potential for collaborative practice. *International Journal of Project Management*. 32 (2), pp. 315–326. doi:10.1016/j.ijproman.2013.05.007.

Galiers, R. (1992) *Information System Research: Issues, Methods and Practical Guidelines*. Oxford: Blackwell Scientific.

Gamage, I.S.W., Osmani, M. and Glass, J. (2009) An investigation into the impact of procurement systems on waste generation: The contractors' perspective. *Proceedings of the Association of Researchers in Construction Management (ARCOM), Nottingham, UK*. pp. 103–104.

Gann, D., Salter, A. and Whyte, J. (2003) Design Quality Indicator as a tool for thinking. *Building Research & Information* [online]. 31 (5), pp. 318–333. Available from:

<http://www.tandfonline.com/doi/abs/10.1080/0961321032000107564>doi:10.1080/0961321032000107564 [Accessed 25 June 2015].

- Garlan, D., Allen, R. and Ockerbloom, J. (1995) Architectural mismatch: Why reuse is so hard. *IEEE software*. 12 (6), pp. 17.
- Garlan, D. and Shaw, M. (1993) An introduction to software architecture. *Advances in software engineering and knowledge engineering*. 1 (3.4), .
- Gavilan, R.M. and Bernold, L.E. (1994) Source evaluation of solid waste in building construction. *Journal of Construction Engineering and Management*. 120 (3), pp. 536–552.
- Gay, L.R., Mills, G.E. and Airasian, P. (2006) *Education research: Competencies for analysis and applications* Columbus, OH: Pearson Education.
- gbXML (2013) *The Green Building XML (gbXML) open schema* [online]. Available from: <http://www.gbxml.org/> [Accessed 14 April 2014].
- Geambaşu, C.V., Jianu, I., Jianu, I. and Gavrilă, A. (2011) Influence factors for the choice of a software development methodology. *Accounting and Management Information Systems*. 10 (4), pp. 479–494.
- Geddes, S. (1996) *Estimating for building and civil engineering works*. Oxford: Butterworth-Heinemann.
- Ghapanchi, A.H., Wohlin, C. and Aurum, A. (2014) Resources contributing to gaining competitive advantage for open source software projects: An application of resource-based theory. *International Journal of Project Management*. 32 (1), pp. 139–152. doi:10.1016/j.ijproman.2013.03.002.
- Ghassemi, R. and Becerik-gerber, B. (2011) *Transitioning to Integrated Project Delivery: Potential barriers and lessons learned Differences between ipd and traditional delivery methods*. pp. 32–52.
- Ghoddousi, P., Eshtehardian, E., Jooybanpour, S. and Javanmardi, A. (2013) Multi-mode resource-constrained discrete time–cost–resource optimization in project scheduling using non-dominated sorting genetic algorithm. *Automation in Construction*. 30 pp. 216–227.
- Gibbs, G. (2007) *Analysing Qualitative Data - The Sage Qualitative Research Kit* [online].
- Goedert, J.D. and Meadati, P. (2008) Integrating construction process documentation into building information modeling. *Journal of construction engineering and management*. 134 (7), pp. 509–516.
- Gordon, O., Herrera, F., Hoffmann, F. and Luis, M. (2001) Genetic fuzzy systems: Fuzzy

- Knowledge Extraction by Evolutionary Algorithms. *Scientific Publishing Co. Pte. Ltd, UK* [online]. Available from: <http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.48.9985&rep=rep1&type=pdfdoi:10.1142/4177>.
- Gorgolewski, M. (2006) The implications of reuse and recycling for the design of steel buildings. *Canadian Journal of Civil Engineering*. 33 (4), pp. 489–496.
- Gray, D.E. (2009) *Doing Research in the Real World*. London: Sage Publications Ltd.
- Greenwood, R. (2003) *Construction Waste Minimisation: Good Practice Guide*. United Kingdom: Cardiff University, Centre for Research in the Built Environment (CRiBE).
- Grilo, A. and Jardim-Goncalves, R. (2010) Value proposition on interoperability of BIM and collaborative working environments. *Automation in Construction* [online]. 19 (5), pp. 522–530. Available from: <http://www.sciencedirect.com/science/article/pii/S0926580509001733doi:10.1016/j.autcon.2009.11.003> [Accessed 13 October 2014].
- Grosan, C. and Abraham, A. (2011) Hybrid Intelligent Systems. In: *Intelligent Systems* [online]. pp. 423–450. Available from: [http://link.springer.com/10.1007/978-3-642-21004-4\\_17doi:10.1007/978-3-642-21004-4\\_17](http://link.springer.com/10.1007/978-3-642-21004-4_17doi:10.1007/978-3-642-21004-4_17).
- Gruber, T.R. (1993) Toward Principles for the Design of Ontologies Used for Knowledge Sharing. *International journal of human-computer studies*.
- Guba, E. and Lincoln, Y. (1994) Competing paradigms in qualitative research. *Handbook of qualitative research*. pp. 105–117.
- Guba, E.G. and Lincoln, Y.S. (2001) Guidelines and checklist for constructivist (aka fourth generation) evaluation. Design, monitoring and evaluation for peacebuilding. Available online: <http://www.wmich.edu/evalctr/checklists/constructivisteval.htm>, Accessed 23 September 2016 [online]. Available from: <http://www.wmich.edu/evalctr/checklists/constructivisteval.htm> [Accessed 23 September 2015].
- Guy, B. and Ciarimboli, N. (2008) *DfD: Design for Disassembly in the Built Environment: a Guide to Closed-loop Design and Building*. (no place) Hamer Center.
- Guy, B., Shell, S. and Esherick, H. (2006) Design for Deconstruction and Materials Reuse. In: *Proceedings of the CIB Task Group 39*. 2006 pp. 189–209.
- Hancock, B., Ockleford, E. and Windridge, K. (1998) *An introduction to qualitative research*. Nottingham: Trent focus group.

- Hartono, B., Sulistyono, S.R., Praftiwi, P.P. and Hasmore, D. (2014) Project risk: Theoretical concepts and stakeholders' perspectives. *International Journal of Project Management*. 32 (3), pp. 400–411. doi:10.1016/j.ijproman.2013.05.011.
- Healy, M. and Perry, C. (2000) Comprehensive criteria to judge validity and reliability of qualitative research within the realism paradigm. *Qualitative Market Research: An International Journal*. 3 (3), pp. 118–126.
- Heemels, W.P.M., Lehmann, D., Lunze, J. and De Schutter, B. (2009) Introduction to Hybrid Systems. In: *Handbook of Hybrid Systems Control: Theory, Tools, Applications*. pp. 3–30. doi:10.1007/0-8176-4404-0\_5.
- Hegazy, T., Fazio, P. and Moselhi, O. (1994) Developing Practical Neural Network Applications Using Back-Propagation *Computer-Aided Civil and Infrastructure Engineering* 9 (2) p.pp. 145–159. doi:10.1111/j.1467-8667.1994.tb00369.x.
- van den Helm, P., Böhm, M. and van Berlo, L. (2010) IFC-based clash detection for the open-source BIMserver. In: *Computing in civil and building engineering, proceedings of the international conference*. Nottingham University Press, Nottingham, UK. 2010 pp. 181.
- Hijazi, I., Ehlers, M. and Zlatanova, S. (2010) BIM for geo-analysis (BIM4GEOA): set up of 3D information system with open source software and open specification (OS). In: *5th International 3D Geoinfo Conference, Berlin, November 3-2, 2010. International archives of photogrammetry, remote sensing and spatial information sciences, vol. 38-4/W15*. 2010 (no place) ISPRS.
- HM-Government (2012) *Industrial Strategy: Government and Industry in partnership* [online] Vol.1. Available from: <http://hdl.handle.net/10204/3364>doi:10.1016/j.aei.2007.03.001.
- Hobbs, G., Blackwell, M. and Adams, K. (2011) *Understanding and predicting construction waste*. 164 pp. 239–245.
- Hobbs, G. and Hurley, J. (2001) Deconstruction and the reuse of construction materials. *Deconstruction and Materials Reuse: Technology, Economic, and Policy*. pp. 98.
- Hola, B. and Schabowicz, K. (2010) Estimation of earthworks execution time cost by means of artificial neural networks. *Automation in Construction*. 19 (5), pp. 570–579.
- Hong, T., Cho, K., Hyun, C. and Han, S. (2011) Simulation-Based Schedule Estimation Model for ACS-Based Core Wall Construction of High-Rise Building. *Journal of Construction Engineering and Management*. 137 (6), pp. 393–402. doi:10.1061/(ASCE)CO.1943-7862.0000300.
- Hu, Z.-Z., Zhang, X.-Y., Wang, H.-W. and Kassem, M. (2016) Improving interoperability between architectural and structural design models: An industry foundation classes-based approach

- with web-based tools. *Automation in Construction* [online]. Available from: <http://www.sciencedirect.com/science/article/pii/S0926580516300152>doi:10.1016/j.autcon.2016.02.001 [Accessed 18 March 2016].
- Huovila, P., Koskela, L. and Lautanala, M. (1997) Fast or concurrent: the art of getting construction improved. *Lean construction*. 20 (2), pp. 143–159.
- ICE (2008) Institution of Civil Engineers (ICE) Demolition Protocol. Available from: <http://www.ice.org.uk/Information-resources/Document-Library/Demolition-Protocol-2008> [online]. Available from: <http://www.ice.org.uk/Information-resources/Document-Library/Demolition-Protocol-2008> [Accessed 23 August 2014].
- IFC (2008) *Industry Foundation Classes (IFC) data model* [online]. Available from: <http://www.buildingsmart.org/standards/ifc> [Accessed 14 April 2014].
- IFChub (2017) *IFC server for construction and built environment*. Available from: <http://ifchub.com/> [Accessed 24 January 2017].
- IFCWebServer (2016) *IFC Web Server | Your BIM data model server and online viewer*. Available from: <http://ifcwebserver.org/> [Accessed 24 April 2016].
- Ilozor, B.D. and Kelly, D.J. (2012) Building Information Modeling and Integrated Project Delivery in the Commercial Construction Industry : A Conceptual Study. *Journal of Engineering, Project, and Production Management*. 2 pp. 23–36.
- Iorio, J. and Taylor, J.E. (2014) Boundary object efficacy: The mediating role of boundary objects on task conflict in global virtual project networks. *International Journal of Project Management*. 32 (1), pp. 7–17. doi:10.1016/j.ijproman.2013.04.001.
- Irani, Z. and Kamal, M.M. (2014) Intelligent Systems Research in the Construction Industry. *Expert Systems with Applications*. 41 (4), pp. 934–950. doi:10.1016/j.eswa.2013.06.061.
- Irizarry, J., Karan, E.P. and Jalaei, F. (2013) Integrating BIM and GIS to improve the visual monitoring of construction supply chain management. *Automation in Construction*. 31 pp. 241–254. doi:10.1016/j.autcon.2012.12.005.
- Ishii, N., Takano, Y. and Muraki, M. (2014) An order acceptance strategy under limited engineering man-hours for cost estimation in Engineering–Procurement–Construction projects. *International Journal of Project Management*. 32 (3), pp. 519–528. doi:10.1016/j.ijproman.2013.07.009.
- Isikdag, U., Underwood, J. and 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*. 22 (4), pp. 504–519.

- Ison, R.L. (2008) Systems Thinking and Practice for Action Research. In: Peter W. Reason and Hilary Bradbury (eds.). *The Sage Handbook of Action Research Participative Inquiry and Practice* 2nd edition. London: SAGE publications. pp. 139–158.
- Jackson, C. and Prawel, D. (2013) *The 2013 State of 3D Collaboration and Interoperability Report*. Available from: [http://www.plm.automation.siemens.com/en\\_us/Images/Lifecycle-Insights-2013-Collaboration-Interoperability\\_tcm1023-210162.pdf](http://www.plm.automation.siemens.com/en_us/Images/Lifecycle-Insights-2013-Collaboration-Interoperability_tcm1023-210162.pdf) [Accessed 24 May 2016].
- Jackson, R.H.G. and Wood, A. (2013) The performance of insolvency prediction and credit risk models in the UK: A comparative study. *British Accounting Review*. 45 (3), pp. 183–202. doi:10.1016/j.bar.2013.06.009.
- Jafarzadeh, R., Ingham, J.M. and Wilkinson, S. (2014) A seismic retrofit cost database for buildings with a framed structure. *Earthquake Spectra*. 30 (2), pp. 625–637.
- Jaillon, L. and Poon, C.S. (2014a) Life cycle design and prefabrication in buildings: A review and case studies in Hong Kong. *Automation in Construction*. 39 pp. 195–202. doi:10.1016/j.autcon.2013.09.006.
- Jaillon, L. and Poon, C.S. (2014b) Life cycle design and prefabrication in buildings: A review and case studies in Hong Kong. *Automation in Construction* [online]. 39 pp. 195–202. Available from: <http://linkinghub.elsevier.com/retrieve/pii/S0926580513001556>doi:10.1016/j.autcon.2013.09.006 [Accessed 23 December 2014].
- Jaillon, L., Poon, C.S. and Chiang, Y.H. (2009) Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong. *Waste management (New York, N.Y.)*. 29 (1), pp. 309–320. doi:10.1016/j.wasman.2008.02.015.
- Jalali, S. (2007) Quantification of Construction Waste Amount. In: *6th International Technical Conference of Waste*. 2007
- Jang, J.-S.R. (1993) ANFIS: Adaptive-Network-Based Fuzzy Inference System. *IEEE TRANSACTIONS ON SYSTEMS, MAN, AND CYBERNETICS*. 23 (3), .
- Jang, J.-S.R. (1996) Input selection for ANFIS learning. *Proceedings of IEEE 5th International Fuzzy Systems*. 2 pp. 1493–1499. doi:10.1109/FUZZY.1996.552396.
- Ji, S.-H., Park, M. and Lee, H.-S. (2011) Case adaptation method of case-based reasoning for construction cost estimation in Korea. *Journal of Construction Engineering and Management*. 138 (1), pp. 43–52.
- Jiao, Y., Zhang, S., Li, Y., Wang, Y. and Yang, B. (2013) Towards cloud Augmented Reality for construction application by BIM and SNS integration. *Automation in Construction*. 33 pp.

37–47. doi:10.1016/j.autcon.2012.09.018.

- Jordani, D.A. (2010) BIM and FM: The portal to lifecycle facility management. *Journal of Building Information Modeling*. 6 pp. 13–16.
- Juan, D. and Zheng, Q. (2014) Cloud and Open BIM-Based Building Information Interoperability Research. *Journal of Service Science and Management*. 7 (2), pp. 47–56.
- Jun, L., Qiuzhen, W. and Qingguo, M. (2011) The effects of project uncertainty and risk management on IS development project performance: A vendor perspective. *International Journal of Project Management* [online]. 29 (7), pp. 923–933. Available from: <http://www.sciencedirect.com/science/article/pii/S0263786310001468>doi:10.1016/j.ijproman.2010.11.002 [Accessed 13 December 2014].
- Jung, Y. and Joo, M. (2011) Building information modelling (BIM) framework for practical implementation. *Automation in Construction*. 20 (2), pp. 126–133. doi:10.1016/j.autcon.2010.09.010.
- Kabak, M., Köse, E., Kırılmaz, O. and Burmaoğlu, S. (2014) A fuzzy multi-criteria decision making approach to assess building energy performance. *Energy and Buildings*. 72 pp. 382–389.
- Keys, A., Baldwin, A. and Austin, S. (2000) DESIGNING TO ENCOURAGE WASTE MINIMISATION IN THE CONSTRUCTION INDUSTRY. *Proceedings of CIBSE National Conference, Dublin, September*.
- Khanh, H.D. and Kim, S.Y. (2014) Identifying causes for waste factors in high-rise building projects: A survey in Vietnam. *KSCE Journal of Civil Engineering* [online]. 18 (4), pp. 865–874. Available from: <http://link.springer.com/10.1007/s12205-014-1327-z>doi:10.1007/s12205-014-1327-z.
- Khoramshahi, F. (2007) Waste Management Practices in Construction Sites. *International Project Management Conference*. pp. 1–13.
- Kibert, C.J. (2003) Deconstruction: the start of a sustainable materials strategy for the built environment. *Industry and environment*. 26 (2–3), pp. 84–88.
- Kibert, C.J. (2008) *Sustainable Construction: Green Building Design and Delivery: Green Building Design and Delivery*. (no place) John Wiley & Sons.
- Kim, G., Shin, J., Kim, S. and Shin, Y. (2013) Comparison of school building construction costs estimation methods using regression analysis, neural network, and support vector machine. *Journal of Building Construction and ...* [online]. 1 (March), pp. 1–7. Available from: <http://www.scirp.org/journal/PaperInformation.aspx?paperID=29576>.

- Kim, G.H., Seo, D.S. and Kang, K.I. (2005) Hybrid models of neural networks and genetic algorithms for predicting preliminary cost estimates. *Journal of Computing in Civil Engineering*. 19 (2), pp. 208–211.
- Kim, K.J. and Kim, K. (2010) Preliminary cost estimation model using case-based reasoning and genetic algorithms. *Journal of Computing in Civil Engineering*. 24 (6), pp. 499–505.
- Kim, S. (2013) Hybrid forecasting system based on case-based reasoning and analytic hierarchy process for cost estimation. *Journal of Civil Engineering and Management*. 19 (1), pp. 86–96.
- Kircher, M., Jain, P., Corsaro, A. and Levine, D. (2001) Distributed extreme programming. *Extreme Programming and Flexible Processes in Software Engineering* [online]. (September 2013), pp. 66–71. Available from: <http://cf.agilealliance.org/articles/system/article/file/1057/file.pdf>.
- Klöpffer, W. (2006) The role of SETAC in the development of LCA. *The International Journal of Life Cycle Assessment*. 11 (1), pp. 116–122.
- Koonce, D., Huang, L. and Judd, R. (1998) EQL an express query language. *Computers & industrial engineering*. 35 (1), pp. 271–274.
- Koskela, L. (2007) Foundations of concurrent engineering. *Concurrent Engineering in construction projects*. 1 pp. 12–29.
- Koskela, L. and Howell, G. (2008) The underlying theory of project management is obsolete. *IEEE Engineering Management Review*. 36 (2), pp. 22–34. doi:10.1109/EMR.2008.4534317.
- Koskela, L.J. (2004) Moving on-beyond lean thinking. *Lean Construction Journal*. 1 (1), pp. 24–37.
- Kota, S., Haberl, J.S., Clayton, M.J. and Yan, W. (2014) Building Information Modeling (BIM)-based daylighting simulation and analysis. *Energy and Buildings*. 81 pp. 391–403. doi:10.1016/j.enbuild.2014.06.043.
- Kozlovská, M. and Spišáková, M. (2013) *Construction waste generation across construction project life-cycle*. pp. 687–695. doi:10.5592/otmcj.2013.1.5.
- Krauss, S.E. and Putra, U. (2005) *Research Paradigms and Meaning Making : A Primer*. 10 (4), pp. 758–770.
- Kuhn, T. (1970) *The Structure of Scientific Revolutions*. 2nd edition. Chicago, IL: University of Chicago Press.
- Kumar, B., Cheng, J.C.P. and McGibbney, L. (2010) Cloud Computing and its Implications for



- Construction IT. In: *Computing in Civil and Building Engineering, Proceedings of the International Conference*. 2010 (no place) Nottingham University press. pp. 312.
- Kwak, Y.H., Walewski, J., Sleeper, D. and Sadatsafavi, H. (2014) What can we learn from the Hoover Dam project that influenced modern project management? *International Journal of Project Management*. 32 (2), pp. 256–264. doi:10.1016/j.ijproman.2013.04.002.
- de la Fraga, L., Coello Coello, C., Fraga, L. de la and Coello, C. (2011) A Review of Applications of Evolutionary Algorithms in Pattern Recognition. *Pattern Recognition, Machine Intelligence and Biometrics* [online]. pp. 3–28. Available from: [http://link.springer.com/chapter/10.1007/978-3-642-22407-2\\_1](http://link.springer.com/chapter/10.1007/978-3-642-22407-2_1) doi:10.1007/978-3-642-22407-2\_1.
- Laakso, M. and Kiviniemi, A. (2012) The IFC standard - A review of history, development, and standardization *Electronic Journal of Information Technology in Construction* 17 p.pp. 134–161.
- Laakso, M., Student, D., Science, I.S. and Kiviniemi, A. (2012) *THE IFC STANDARD - A REVIEW OF HISTORY, DEVELOPMENT, AND STANDARDIZATION*. 17 (May), pp. 134–161.
- de Laat, R. and van Berlo, L. (2011) Integration of BIM and GIS: The development of the CityGML GeoBIM extension. In: *Advances in 3D geo-information sciences*. (no place) Springer. pp. 211–225.
- Langdon, D. (2011) Designing out Waste : a design team guide for buildings *Waste and Resource Action Plan (WRAP)* 462.
- Lanzola, G., Quaglini, S. and Stefanelli, M. (1995) Knowledge-acquisition tools for medical knowledge-based systems. In: *Methods of Information in Medicine*. 1995 pp. 25–39.
- Lassandro, P. (2003) Deconstruction case study in Southern Italy: economic and environmental assessment. In: *CIB Publication*. 2003
- Latham, M. (1994) Constructing the team: joint review of procurement and contractual arrangements in the United Kingdom construction industry: final report. Available from: <http://www.cewales.org.uk/cew/wp-content/uploads/Constructing-the-team-The-Latham-Report.pdf> [online]. Available from: <http://www.cewales.org.uk/cew/wp-content/uploads/Constructing-the-team-The-Latham-Report.pdf>.
- Leandri, S.J. (2001) Measures that matter: How to fine-tune your performance measures. *Journal for Quality & Participation*. 24 (1), pp. 39.
- Lee, D., Kim, S. and Kim, S. (2016) Development of Hybrid Model for Estimating Construction

- Waste for Multifamily Residential Buildings Using Artificial Neural Networks and Ant Colony Optimization. *Sustainability*. 8 (9), pp. 870.
- Lee, J.K. (2011) *Building Environment Rule and Analysis (BERA) Language*. (no place) PhD Thesis: Georgia Institute of Technology.
- Lee, S.-K., Kim, K.-R. and Yu, J.-H. (2014) BIM and ontology-based approach for building cost estimation. *Automation in construction*. 41 pp. 96–105.
- Lenfle, S. (2014) Toward a genealogy of project management: Sidewinder and the management of exploratory projects. *International Journal of Project Management*. 32 (6), pp. 921–931. doi:10.1016/j.ijproman.2013.10.017.
- Li, H., Chen, Z., Yong, L. and Kong, S.C.W. (2005) Application of integrated GPS and GIS technology for reducing construction waste and improving construction efficiency. *Automation in Construction*. 14 (3), pp. 323–331. doi:10.1016/j.autcon.2004.08.007.
- Li, H.M. and Wang, Z.F. (2009) Applying self-adaptive ant colony optimization for construction time-cost optimization. In: *2009 International Conference on Management Science and Engineering - 16th Annual Conference Proceedings, ICMSE 2009*. 2009 pp. 283–289. doi:10.1109/ICMSE.2009.5317463.
- Li, J., Ding, Z., Mi, X. and Wang, J. (2013) A model for estimating construction waste generation index for building project in China. *Resources, Conservation and Recycling*. 74 pp. 20–26. doi:10.1016/j.resconrec.2013.02.015.
- Li, Y. and Zhang, X. (2013) Web-based construction waste estimation system for building construction projects. *Automation in Construction*. 35 (1), pp. 142–156. doi:10.1016/j.autcon.2013.05.002.
- Liang, T. (1987) User interface design for decision support systems: A self-adaptive approach. *Information & Management* [online]. 12 (4), pp. 181–193. Available from: <http://www.sciencedirect.com/science/article/pii/0378720687900413>doi:10.1016/0378-7206(87)90041-3 [Accessed 10 January 2015].
- Lichtig, W.A. (2010) The Integrated Agreement for Lean Project Delivery. In: *Improving Healthcare through Built Environment Infrastructure*. pp. 85–101. doi:10.1002/9781444319675.ch6.
- Lindstrom, L. and Jeffries, R. (2004) Extreme Programming and Agile Software Development Methodologies. *Information Systems Management* [online]. 21 (3), pp. 41–52. Available from: <http://www.tandfonline.com/doi/pdf/10.1201/1078/44432.21.3.20040601/82476.7%5Cnhttp://www.tandfonline.com/doi/abs/10.1201/1078/44432.21.3.20040601/82476.7>doi:10.1201/1078/44432.21.3.20040601/82476.7.

- Liu, S., Duffy, A.H.B., Whitfield, R.I. and Boyle, I.M. (2009) Integration of decision support systems to improve decision support performance. *Knowledge and Information Systems* [online]. 22 (3), pp. 261–286. Available from: <http://link.springer.com/10.1007/s10115-009-0192-4> [Accessed 29 December 2014].
- Liu, S. and Wang, L. (2014) Understanding the impact of risks on performance in internal and outsourced information technology projects: The role of strategic importance. *International Journal of Project Management*. 32 (8), pp. 1494–1510. doi:10.1016/j.ijproman.2014.01.012.
- Liu, T. and Wilkinson, S. (2014) Large-scale public venue development and the application of Public–Private Partnerships (PPPs). *International Journal of Project Management*. 32 (1), pp. 88–100. doi:10.1016/j.ijproman.2013.01.003.
- Liu, Z., Osmani, M., Demian, P. and Baldwin, A. (2011) The potential use of BIM to aid construction waste minimalisation. In: *Proceedings of the CIB W78-W102 2011: International Conference*. 2011 Sophia Antipolis, France: .
- Livermore, J. (2007) Factors that impact implementing an agile software development methodology. *Proceedings 2007 IEEE SoutheastCon* [online]. pp. 82–86. Available from: [http://apps.webofknowledge.com.db.ub.oru.se/full\\_record.do?product=WOS&search\\_mode=GeneralSearch&qid=3&SID=P2awwaI4gR5EcT2yRvu&page=6&doc=56](http://apps.webofknowledge.com.db.ub.oru.se/full_record.do?product=WOS&search_mode=GeneralSearch&qid=3&SID=P2awwaI4gR5EcT2yRvu&page=6&doc=56)doi:10.1109/SECON.2007.342860.
- Llatas, C. (2011) A model for quantifying construction waste in projects according to the European waste list. *Waste management (New York, N.Y.)*. 31 (6), pp. 1261–1276. doi:10.1016/j.wasman.2011.01.023.
- Long, T., Yoon, I., Porter, A., Sussman, A. and Memon, A. (2012) Overlap and Synergy in Testing Software Components across Loosely Coupled Communities. In: *Software Reliability Engineering (ISSRE), 2012 IEEE 23rd International Symposium on*. 2012 (no place) IEEE. pp. 171–180.
- Lopez, R. and Love, P.E.D. (2012) Design Error Costs in Construction Projects *Journal of Construction Engineering and Management* 138 p.pp. 585–593. doi:10.1061/(ASCE)CO.1943-7862.0000454.
- Lu, W., Yuan, H., Li, J., Hao, J.J.L., Mi, X. and Ding, Z. (2011) An empirical investigation of construction and demolition waste generation rates in Shenzhen city, South China. *Waste management*. 31 (4), pp. 680–687.
- MacLeamy, P. (2004) MacLeamy Curve. *Collaboration, Integrated Information, and the Project Lifecycle in Building Design and Construction and Operation (WP-1202)*.
- Magnaye, R., Sauser, B., Patanakul, P., Nowicki, D. and Randall, W. (2014) Earned readiness

- management for scheduling, monitoring and evaluating the development of complex product systems. *International Journal of Project Management*. 32 (7), pp. 1246–1259. doi:10.1016/j.ijproman.2014.01.009.
- Maier, E.R. and Branzei, O. (2014) ‘On time and on budget’: Harnessing creativity in large scale projects. *International Journal of Project Management*. 32 (7), pp. 1123–1133. doi:10.1016/j.ijproman.2014.02.009.
- Maliene, V., Grigonis, V., Palevičius, V. and Griffiths, S. (2011) Geographic information system: Old principles with new capabilities. *Urban Design International*. 16 (1), pp. 1–6.
- Manning, R. and Messner, J. (2008) Case studies in BIM implementation for programming of healthcare facilities. In: *ITcon - IT in Construction, 13 (Special Issue - Case studies of BIM use)*. 2008 (no place) ITcon.
- Masudi, A.F., Rosmani, C., Hassan, C., Mahmood, N.Z. and Mokhtar, S.N. (2011) *Construction Waste Quantification and Benchmarking: A Study in Klang Valley, Malaysia*. 5 pp. 909–916.
- Matsueda, N. and Nagase, Y. (2012) An economic analysis of the packaging waste recovery note system in the UK. *Resource and Energy Economics*. 34 (4), pp. 669–679.
- Mazairac, W. and Beetz, J. (2013) BIMQL—An open query language for building information models. *Advanced Engineering Informatics*. 27 (4), pp. 444–456.
- McDonald, B. and Smithers, M. (1998) Implementing a waste management plan during the construction phase of a project: a case study. *Construction Management and Economics*. 16 (1), pp. 71–78. doi:10.1080/014461998372600.
- McDonough, W. and Braungart, M. (2002) *Remaking the way we make things: Cradle to cradle*. New York: North Point Press.
- Mcgrath, C. (2001) Waste minimisation in practice. *Resources, Conservation and Recycling*. 32 (1), pp. 227–238.
- McKechnie, E. and Brown, E. (2007) Achieving effective waste minimisation through design. *Waste & Resources Action Programme (WRAP), Oxen*.
- Melin, P., Castillo, O., Kacprzyk, J. and Pedrycz, W. (2007) *Design of Hybrid Intelligent Systems* [online].
- Mihic, M., Sertic, J. and Zavrski, I. (2014) Integrated Project Delivery as Integration between Solution Development and Solution Implementation. *Procedia - Social and Behavioral Sciences* [online]. 119 pp. 557–565. Available from: <http://www.sciencedirect.com/science/article/pii/S1877042814021533>doi:10.1016/j.sbspro.

2014.03.062 [Accessed 27 December 2014].

- Mills, T.H., Showalter, E. and Jarman, D. (1999) A cost effective waste management plan. *Cost Engineering*. 41 (3), pp. 35–43.
- Minsky, N. (1975) A framework for representing knowledge in the psychology of computer vision (Winston O., ed) McGraw-Hill. *New York*.
- Mohanty, R., Ravi, V. and Patra, M.R. (2013) Hybrid intelligent systems for predicting software reliability. *Applied Soft Computing Journal*. 13 (1), pp. 189–200. doi:10.1016/j.asoc.2012.08.015.
- Mokhtar, S.N., Mahmood, N.Z., Che Hassan, C.R., Masudi, A.F. and Sulaiman, N.M. (2011) Factors that contribute to the generation of construction waste at sites. *Advanced Materials Research*. 163 pp. 4501–4507.
- Morgan, D.L. (2007) Paradigms Lost and Pragmatism Regained: Methodological Implications of Combining Qualitative and Quantitative Methods. *Journal of Mixed Methods Research*. 1 (1), pp. 48–76. doi:10.1177/2345678906292462.
- Morrissey, a J. and Browne, J. (2004) Waste management models and their application to sustainable waste management. *Waste management (New York, N.Y.)*. 24 (3), pp. 297–308. doi:10.1016/j.wasman.2003.09.005.
- Mosa, A.M., Taha, M.R., Ismail, A. and Rahmat, R.A.O.K. (2013) A diagnostic expert system to overcome construction problems in rigid highway pavement. *Journal of Civil Engineering and Management*. 19 (6), pp. 846–861.
- Moustakas, C. (1994) *Phenomenological research methods*. (no place) Sage Publications.
- Munakata, T., Jani, Y. and Engineering, S. (1994) Fuzzy systems: An overview. *Communications of the ACM* [online]. 37 (3), pp. 69–77. Available from: <http://doc.utwente.nl/72926/1/Top91qualitative.pdf>.
- Musca, G.N., Mellet, C., Simoni, G., Sitri, F. and de Vogüé, S. (2014) ‘Drop your boat!’: The discursive co-construction of project renewal. The case of the Darwin mountaineering expedition in Patagonia. *International Journal of Project Management*. 32 (7), pp. 1157–1169. doi:10.1016/j.ijproman.2014.02.006.
- Nagapan, S., Rahman, I.A., Asmi, A., Hameed, A. and Zin, R.M. (2012a) Identifying Causes of Construction Waste - Case of Central Region of Peninsula Malaysia. *International Journal of Integrated Engineering, Vol. 4 No. 2 (2012) p. 22-28*. 4 (2), pp. 22–28.
- Nagapan, S., Rahman, I.A., Asmi, A., Memon, A.H. and Latif, I. (2012b) *Issues on Construction Waste : The Need for Sustainable Waste Management*. (Chuser), pp. 329–334.

- Nepal, M.P., Staub-French, S., Pottinger, R. and Webster, A. (2012) Querying a building information model for construction-specific spatial information. In: *Advanced Engineering Informatics*. 2012 pp. 904–923. doi:10.1016/j.aei.2012.08.003.
- Nepal, M.P., Zhang, J., Webster, A., Staub-French, S., Pottinger, R. and Lawrence, M. (2009) Querying IFC-based building information models to support construction management functions. *Proceeding of the 2009 Construction Research Congress* [online]. pp. 506–515. Available from: [http://ascelibrary.org/doi/abs/10.1061/41020\(339\)52](http://ascelibrary.org/doi/abs/10.1061/41020(339)52)doi:10.1061/41020(339)52.
- Nerur, S., Mahapatra, R. and Mangalaraj, G. (2005) Challenges of Migrating to Agile Methodologies. *Communications of the ACM*. 48 (2), pp. 72–78. doi:10.1145/1060710.1060712.
- Neuman, W.L. (2009) *Social Research Methods: Qualitative and Quantitative approaches*. Boston: Allyn and Bacon.
- O’Cathain, A., Murphy, E. and Nicholl, J. (2007) Why, and how, mixed methods research is undertaken in health services research in England: a mixed methods study. *BMC health services research*. 7 (1), pp. 85. doi:10.1186/1472-6963-7-85.
- Omkar, S.N., Senthilnath, J., Khandelwal, R., Naik, G.N. and Gopalakrishnan, S. (2011) Artificial Bee Colony (ABC) for multi-objective design optimization of composite structures. *Applied Soft Computing*. 11 (1), pp. 489–499.
- Onwuegbuzie, A.J. and Leech, N.L. (2005) On Becoming a Pragmatic Researcher: The Importance of Combining Quantitative and Qualitative Research Methodologies. *International Journal of Social Research Methodology*. 8 (5), pp. 375–387. doi:10.1080/13645570500402447.
- Ortiz, O., Castells, F. and Sonnemann, G. (2009) Sustainability in the construction industry: A review of recent developments based on LCA. *Construction and Building Materials* [online]. 23 (1), pp. 28–39. Available from: <http://www.sciencedirect.com/science/article/pii/S0950061807003005>doi:10.1016/j.conbuildmat.2007.11.012 [Accessed 14 July 2014].
- Osmani, M. (2011) Construction waste. *Waste: A Handbook for Management, Elsevier*. pp. 207–218.
- Osmani, M. (2012a) Construction waste minimization in the UK: current pressures for change and approaches. *Procedia - Social and Behavioral Sciences*. 40 pp. 37–40.
- Osmani, M. (2012b) Construction Waste Minimization in the UK: Current Pressures for Change and Approaches. *Procedia - Social and Behavioral Sciences*. 40 pp. 37–40. doi:10.1016/j.sbspro.2012.03.158.

- Osmani, M. (2013) Design waste mapping: a project life cycle approach. *Proceedings of the ICE-Waste and Resource Management*. 166 (3), pp. 114–127.
- Osmani, M., Glass, J. and Price, A.D.F. (2008) Architects' perspectives on construction waste reduction by design. *Waste Management*. 28 (7), pp. 1147–1158.
- Otto, M. (1990) *Fuzzy expert systems* [online].
- Oyedele, L.O. (2013) Analysis of architects' demotivating factors in design firms. *International Journal of Project Management* [online]. 31 (3), pp. 342–354. Available from: <http://dx.doi.org/10.1016/j.ijproman.2012.11.009>doi:10.1016/j.ijproman.2012.11.009 [Accessed 25 October 2015].
- Oyedele, L.O., Ajayi, S.O. and Kadiri, K.O. (2014) Use of recycled products in UK construction industry: An empirical investigation into critical impediments and strategies for improvement. *Resources, Conservation and Recycling* [online]. 93 pp. 23–31. Available from: <http://www.sciencedirect.com/science/article/pii/S0921344914002018>doi:10.1016/j.resconrec.2014.09.011 [Accessed 20 November 2015].
- Oyedele, L.O., Regan, M., von Meding, J., Ahmed, A., Ebohon, O.J. and Elnokaly, A. (2013) Reducing waste to landfill in the UK: identifying impediments and critical solutions. *World Journal of Science, Technology and Sustainable Development*. 10 (2), pp. 131–142.
- Oyedele, L.O. and Tham, K.W. (2007) Clients' assessment of architects' performance in building delivery process: Evidence from Nigeria. *Building and Environment* [online]. 42 (5), pp. 2090–2099. Available from: <http://www.sciencedirect.com/science/article/pii/S0360132306001107>doi:10.1016/j.buildenv.2005.06.030 [Accessed 15 March 2016].
- Parnas, D.L. and Clements, P.C. (1986) A Rational Design Process: How And Why To Fake It *Transactions on Software Engineering* 12 (2) p.pp. 251–257. doi:10.1007/3-540-15199-0\_6.
- Pasquire, C. and Gibb, A.G.F. (2002) Considerations for assessing the benefits of standardisation and pre- assembly in construction. *Journal of Financial Management of Property and Construction*. Vol. 7 pp. 151–161.
- Patton, M.Q. (1997) Utilisation-focused evaluation: the new century text. *Utilisation-focused evaluation: the new century text*.
- Pazlar, T. and Turk, Ž. (2008) Interoperability in practice: Geometric data exchange using the IFC standard. *Electronic Journal of Information Technology in Construction*. 13 pp. 362–380.
- Petroutsatou, K., Georgopoulos, E., Lambropoulos, S. and Pantouvakis, J.P. (2011) Early cost estimating of road tunnel construction using neural networks. *Journal of construction*

- engineering and management*. 138 (6), pp. 679–687.
- Phillips, P.S., Tudor, T., Bird, H. and Bates, M. (2011) A critical review of a key waste strategy initiative in England: Zero waste places projects 2008–2009. *Resources, Conservation and Recycling*. 55 (3), pp. 335–343.
- Polkinghorne, D.E. (1989) Phenomenological research methods. In: *Existential-phenomenological perspectives in psychology*. (no place) Springer. pp. 41–60.
- Pollack, J. (2007) The changing paradigms of project management. *International Journal of Project Management*. 25 (3), pp. 266–274.
- Poon, C.S. (2007) Reducing construction waste. *Waste management (New York, N.Y.)* [online]. 27 (12), pp. 1715–1716. Available from: <http://www.ncbi.nlm.nih.gov/pubmed/17904489doi:10.1016/j.wasman.2007.08.013> [Accessed 29 December 2014].
- Poon, C.S., Yu, A.T.W. and Jaillon, L. (2004) Reducing building waste at construction sites in Hong Kong. *Construction Management and Economics*. 22 (5), pp. 461–470. doi:10.1080/0144619042000202816.
- Poon, C.S., Yu, A.T.W., Wong, S.W. and Cheung, E. (2004) Management of construction waste in public housing projects in Hong Kong. *Construction Management & Economics*. 22 (7), pp. 675–689.
- Porwal, A. and Hewage, K.N. (2013) Building Information Modeling (BIM) partnering framework for public construction projects. *Automation in Construction*. 31 pp. 204–214. doi:10.1016/j.autcon.2012.12.004.
- Qian, G., Wang, H. and Feng, X. (2013) Generalized hesitant fuzzy sets and their application in decision support system. *Knowledge-Based Systems* [online]. 37 pp. 357–365. Available from: <http://linkinghub.elsevier.com/retrieve/pii/S0950705112002390doi:10.1016/j.knosys.2012.08.019> [Accessed 10 January 2015].
- RIBA (2016) *National BIM Report 2016*. Available from: <https://www.thenbs.com/-/media/uk/files/pdf/bim-report-2016.pdf?la=en> [Accessed 23 October 2016].
- RIBA (2013) *RIBA Plan of Work*. Available from: <https://www.architecture.com/files/ribaprofessionalservices/practice/ribaplanofwork2013template.pdf> [Accessed 31 October 2015].
- Rosmani, C. and Hassan, C. (2012) *Waste quantification models for estimation of construction and demolition waste generation : a review Ahmad Firman Masudi \* and Noor Zalina Mahmood and Siti Nazziera Mokhtar Nik Meriam Sulaiman*. 12 pp. 269–281.



- Royce, W.W. (1970) Managing the Development of Large Software Systems. *Proceedings of IEEE WESCON* [online]. 26 (8), pp. 328–338. Available from: [http://leadinganswers.typepad.com/leading\\_answers/files/original\\_waterfall\\_paper\\_winston\\_royce.pdf](http://leadinganswers.typepad.com/leading_answers/files/original_waterfall_paper_winston_royce.pdf).
- Russell, S.J. and Norvig, P. (2010) *Artificial Intelligence: A Modern Approach* [online].
- Sacks, R., Eastman, C.M. and Lee, G. (2004) Parametric 3D modeling in building construction with examples from precast concrete. *Automation in Construction*. 13 (3), pp. 291–312.
- Sacks, R., Radosavljevic, M. and Barak, R. (2010) Requirements for building information modeling based lean production management systems for construction. *Automation in Construction*. 19 (5), pp. 641–655. doi:10.1016/j.autcon.2010.02.010.
- Sage, D., Dainty, A. and Brookes, N. (2014) A critical argument in favor of theoretical pluralism: Project failure and the many and varied limitations of project management. *International Journal of Project Management*. 32 (4), pp. 544–555. doi:10.1016/j.ijproman.2013.08.005.
- Sahota, P.S. and Jeffrey, P. (2005) Decision-support tools : moving beyond a technical orientation. *Proceedings of the ICE-Engineering Sustainability*,. 158 (3), pp. 127–134.
- Salem, O., Asce, M., Shahin, A. and Khalifa, Y. (2008) *Minimizing Cutting Wastes of Reinforcement Steel Bars Using Genetic Algorithms and Integer Programming Models*. 133 (12), pp. 982–992.
- Sandelowski, M. (2000) *Focus on Research Methods Combining Qualitative and Quantitative Sampling , Data Collection , and Analysis Techniques in Mixed-Method Studies*. 23 (3), pp. 246–255.
- Sawhney, A. and Maheswari, J.U. (2013) Design Coordination Using Cloud-based Smart Building Element Models. *International Journal of Computer Information Systems and Industrial Management Applications*. 5 pp. 445–453.
- Schlueter, a and Thesseling, F. (2009) Building information model based energy/exergy performance assessment in early design stages. *Automation in Construction* [online]. 18 pp. 153–163. Available from: <http://www.scopus.com/inward/record.url?eid=2-s2.0-57749169961&partnerID=40&md5=24651caed0f356b6d8285d0f33ca19c>doi:10.1016/j.autcon.2008.07.003.
- Scriven, M. (1991) *Beyond formative and summative evaluation*. (no place) University of Chicago Press.
- Scriven, M. (1967) The Methodology of Evaluation. In. Tyler, RW, Gagne, RM, Scriven, M.(ed.): Perspectives of Curriculum Evaluation. ‘^’eds.): *Book The Methodology of Evaluation*. In. Tyler, Rw, Gagne, Rm, Scriven, M.(Ed.): *Perspectives of Curriculum Evaluation*, Rand

McNally, Chicago.

- Serpell, A. and Labra, M. (2003) A study on construction waste in Chile. In: George Ofori and Florence Yean Yng Ling (eds.). *Proceedings, Joint Symposium of CIB W55, W65 and W107 on Knowledge Construction*. 2003 pp. 102–111.
- Seymour, D., Crook, D. and Rooke, J. (1997) The role of theory in construction management: a call for debate. *Construction Management and Economics* [online]. 15 (1), pp. 117–119. Available from: <http://www.tandfonline.com/doi/abs/10.1080/014461997373169doi:10.1080/014461997373169> [Accessed 25 April 2017].
- Shadish, W.R., Cook, T.D. and Leviton, L.C. (1991) *Foundations of program evaluation: Theories of practice*. (no place) Sage.
- Shen, L.-Y., Lu, W.-S., Yao, H. and Wu, D.-H. (2005) A computer-based scoring method for measuring the environmental performance of construction activities. *Automation in Construction*. 14 (3), pp. 297–309. doi:10.1016/j.autcon.2004.08.017.
- Shenhar, A.J. and Dvir, D. (1996) Toward a typological theory of project management. *Research Policy* [online]. 25 (4), pp. 607–632. Available from: [http://linkinghub.elsevier.com/retrieve/pii/0048733395008772doi:10.1016/0048-7333\(95\)00877-2](http://linkinghub.elsevier.com/retrieve/pii/0048733395008772doi:10.1016/0048-7333(95)00877-2) [Accessed 25 April 2017].
- Sii, H.S., Ruxton, T. and Wang, J. (2002) Synthesis using fuzzy set theory and a Dempster—Shafer-based approach to compromise decision-making with multiple-attributes applied to risk control options selection. *Proceedings of the Institution of Mechanical Engineers, Part E: Journal of Process Mechanical Engineering*. 216 (1), pp. 15–29.
- Simons, H. (2009) *Case study research in practice*. (no place) SAGE publications.
- Singh, T.N., Kanchan, R., Verma, A.K. and Saigal, K. (2005) A comparative study of ANN and Neuro-fuzzy for the prediction of dynamic constant of rockmass. *J. Earth Syst. Sci.*, 114 (1), pp. 75–86.
- Singh, V., Gu, N. and Wang, X. (2011) A theoretical framework of a BIM-based multi-disciplinary collaboration platform. *Automation in Construction*. 20 (2), pp. 134–144. doi:10.1016/j.autcon.2010.09.011.
- Skoyles, E.R. (1976) Materials wastage—a misuse of resources. *Building Research and Practice*. 4 (4), pp. 232–243.
- Smith, M.L. (1997) Mixing and matching: Methods and models. *New directions for evaluation*. 1997 (74), pp. 73–85.

- Söderlund, J. (2004) Building theories of project management: past research, questions for the future. *International Journal of Project Management* [online]. 22 (3), pp. 183–191. Available from: [http://www.sciencedirect.com/science/article/pii/S026378630300070Xdoi:10.1016/S0263-7863\(03\)00070-X](http://www.sciencedirect.com/science/article/pii/S026378630300070Xdoi:10.1016/S0263-7863(03)00070-X) [Accessed 25 April 2017].
- Sola, J. and Sevilla, J. (1997) Importance of input data normalization for the application of neural networks to complex industrial problems. *IEEE Transactions on Nuclear Science*. 44 (3), pp. 1464–1468.
- Solibri (2016) *Solibri | Solibri Model Checker*. Available from: <https://www.solibri.com/products/solibri-model-checker/> [Accessed 24 April 2016].
- Solis-Guzmán, J., Marrero, M., Montes-Delgado, M.V. and Ramírez-de-Arellano, A. (2009) A Spanish model for quantification and management of construction waste. *Waste Management*. 29 (9), pp. 2542–2548. doi:<http://dx.doi.org/10.1016/j.wasman.2009.05.009>.
- Son, H., Kim, C. and Kim, C. (2012) Hybrid principal component analysis and support vector machine model for predicting the cost performance of commercial building projects using pre-project planning variables. *Automation in Construction*. 27 pp. 60–66.
- Stake, R. (2005) Qualitative case studies. *The Sage handbook of qualitative research*. pp. 443–466.
- Steel, J., Drogemuller, R. and Toth, B. (2012) Model interoperability in building information modelling. *Software & Systems Modeling*. 11 (1), pp. 99–109. doi:[10.1007/s10270-010-0178-4](https://doi.org/10.1007/s10270-010-0178-4).
- Succar, B. (2009) Building information modelling framework: A research and delivery foundation for industry stakeholders. *Automation in Construction* [online]. 18 (3), pp. 357–375. Available from: <http://linkinghub.elsevier.com/retrieve/pii/S0926580508001568doi:10.1016/j.autcon.2008.10.003> [Accessed 11 July 2014].
- Symonds and Associates (1999) Construction and Demolition Waste Management Practices and Their Economic Impacts *Group* [online]. Available from: [http://ec.europa.eu/environment/waste/studies/cdw/cdw\\_chapter1-6.pdf](http://ec.europa.eu/environment/waste/studies/cdw/cdw_chapter1-6.pdf) [Accessed 2 December 2014].
- Tahmasebi, P. and Hezarkhani, A. (2009) Application of optimized neural network by genetic algorithm. *IAMG09Stanford University, California*.
- Tam, C.M., Tong, T.K.L. and Chan, W.K.W. (2001) Genetic algorithm for optimizing supply locations around tower crane. *Journal of construction engineering and management*. 127 (4), pp. 315–321.

- Tam, V.W.Y., Tam, C.M., Zeng, S.X. and Ng, W.C.Y. (2007) Towards adoption of prefabrication in construction. *Building and Environment* [online]. 42 (10), pp. 3642–3654. Available from: <http://linkinghub.elsevier.com/retrieve/pii/S0360132306002873>doi:10.1016/j.buildenv.2006.10.003 [Accessed 23 December 2014].
- Tasevska, F., Damij, T. and Damij, N. (2014) Project planning practices based on enterprise resource planning systems in small and medium enterprises — A case study from the Republic of Macedonia. *International Journal of Project Management*. 32 (3), pp. 529–539. doi:10.1016/j.ijproman.2013.08.001.
- Tashakkori, a. and Creswell, J.W. (2007) Editorial: The New Era of Mixed Methods. *Journal of Mixed Methods Research*. 1 (1), pp. 3–7. doi:10.1177/2345678906293042.
- Teo, M.M.M. and Loosemore, M. (2001) A theory of waste behaviour in the construction industry. *Construction Management and Economics*. 19 (7), pp. 741–751. doi:10.1080/01446190110067037.
- Thomas, D. (2005) Agile programming: Design to accommodate Change. *IEEE Software*. 22 (3), pp. 14–16. doi:10.1109/MS.2005.54.
- Thormark, C. (2001) Assessing the recycling potential in buildings. In: *CIB Task Group 39: Deconstruction and Materials Reuse: Technology, Economic, and Policy*. 2001 (no place) University of Florida. pp. 78–86.
- Tibaut, A., Rebolj, D. and Perc, M.N. (2014) Interoperability requirements for automated manufacturing systems in construction. *Journal of Intelligent Manufacturing*. pp. 1–12.
- Tingley, D.D. (2012) *Design for Deconstruction: An Appraisal*. (no place) PhD thesis, The University of Sheffield.
- Tolman, F.P. (1999) Product modeling standards for the building and construction industry: past, present and future. *Automation in construction*. 8 (3), pp. 227–235.
- Treloar, G.J., Gupta, H., Love, P.E.D. and Nguyen, B. (2003) An analysis of factors influencing waste minimisation and use of recycled materials for the construction of residential buildings. *Management of Environmental Quality: An International Journal*. 14 (1), pp. 134–145.
- Trikha, D.N. (1999) Industrialised building systems: Prospects in Malaysia. In: *Proceedings World Engineering Congress*. 1999 Malaysia: .
- Trochim, W.M.K. (2006) *Unit of Analysis*. Available from: <http://www.socialresearchmethods.net/kb/unitanal.php> [Accessed 10 October 2015].
- Tsoukalas, V.D. and Fragiadakis, N.G. (2016) Prediction of occupational risk in the shipbuilding industry using multivariable linear regression and genetic algorithm analysis. *Safety Science*.

83 pp. 12–22. doi:10.1016/j.ssci.2015.11.010.

- Turban, E. and Aronson, J. (2005) *Decision Support Systems and Intelligent Systems* [online]. 7th edition. (no place) Pearson Prentice Hall.
- Turk, D., France, R. and Rumpe, B. (2002) Limitations of agile software processes. In: *Third International Conference on eXtreme Programming and Agile Processes in Software Engineering*. 2002 pp. 43–46.
- UK Environmental Agency (2014) *Classify different types of waste: Construction and demolition waste* [online]. Available from: <https://www.gov.uk/how-to-classify-different-types-of-waste/construction-and-demolition-waste> [Accessed 13 January 2015].
- USEPA (2003) Estimating 2003 Building-Related Construction and Demolition Materials Amounts *U.S. Environmental Protection Agency (EPA)* [online]. Available from: <http://www.epa.gov/osw/conserve/>.
- Vernikos, V.K., Goodier, C.I., Gibb, a G.F., Robery, P.C. and Broyd, T.W. (2012) *Realising offsite construction and standardisation within a leading UK infrastructure consultancy*. pp. 1–10.
- W3Techs (2016) *Most popular JavaScript libraries*. Available from: <https://w3techs.com/> [Accessed 13 April 2017].
- Walford, G. (2010) Site Selection within Comparative Case Study and Ethnographic Research. *Compare: A Journal of Comparative and International Education*. 31 (2), pp. 151–164. doi:10.1080/03057920120068485.
- Wang, J.-Y., Kang, X.-P. and Tam, V.W.-Y. (2008) An investigation of construction wastes: an empirical study in Shenzhen. *Journal of Engineering, Design and Technology* [online]. 6 pp. 227–236. Available from: <http://ezproxy.itcr.ac.cr:2084/doi/pdfplus/10.1108/17260530810918252>doi:10.1108/17260530810918252.
- Wang, J., Li, Z. and Tam, V.W.Y. (2014) Critical factors in effective construction waste minimization at the design stage: A Shenzhen case study, China. *Resources, Conservation and Recycling*. 82 pp. 1–7. doi:10.1016/j.resconrec.2013.11.003.
- Wang, J.Y., Touran, A., Christoforou, C. and Fadlalla, H. (2004) A systems analysis tool for construction and demolition wastes management. *Waste management (New York, N.Y.)*. 24 (10), pp. 989–997. doi:10.1016/j.wasman.2004.07.010.
- Wang, X. and Chong, H. (2014) *The Challenges and Trends of Building Information Modelling (BIM) for Construction and Resources Sectors*. (Isarc), .
- Warszawski, A. (1999) *Industrialized and automated building systems: A managerial approach*.

2nd edition. New York: Routledge.

- Webster, M.D. and Costello, D. (2005) Designing structural systems for deconstruction: How to extend a new building's useful life and prevent it from going to waste when the end finally comes. In: *Greenbuild Conference, Atlanta, GA. 2005*
- Weise, M., Katranuschkov, P. and Scherer, R.J. (2003) Generalised Model Subset Definition Schema. In: *Proc. CIB-W78 Conf. 2003 - Information Technology for Construction* [online]. 2003 Available from: <https://www.cs.auckland.ac.nz/w78/papers/> [Accessed 23 October 2014].
- Wilmot, C.G. and Mei, B. (2005) Neural network modeling of highway construction costs. *Journal of construction engineering and management*. 131 (7), pp. 765–771.
- Winch, G.M. (2014) Three domains of project organising. *International Journal of Project Management*. 32 (5), pp. 721–731. doi:10.1016/j.ijproman.2013.10.012.
- Won, J., Cheng, J.C.P. and Lee, G. (2016) Quantification of construction waste prevented by BIM-based design validation: Case studies in South Korea. *Waste management (New York, N.Y.)* [online]. Available from: <http://www.sciencedirect.com/science/article/pii/S0956053X15302592>doi:10.1016/j.wasman.2015.12.026 [Accessed 16 February 2016].
- WRAP (2007a) Achieving effective waste minimisation through design: Guidance on designing out waste for construction clients, design teams and contractors. Available from: [http://www2.wrap.org.uk/downloads/Design\\_FINAL.67813ab5.4821.pdf](http://www2.wrap.org.uk/downloads/Design_FINAL.67813ab5.4821.pdf) [online]. Available from: [http://www2.wrap.org.uk/downloads/Design\\_FINAL.67813ab5.4821.pdf](http://www2.wrap.org.uk/downloads/Design_FINAL.67813ab5.4821.pdf) [Accessed 14 April 2014].
- WRAP (2011a) Designing-out Waste Tool for Buildings. Available from: <http://dowtb.wrap.org.uk/> [online]. Available from: <http://dowtb.wrap.org.uk/> [Accessed 14 April 2014].
- WRAP (2009) *Designing out Waste: a design team guide for buildings*. Available from: <http://www.modular.org/marketing/documents/DesigningoutWaste.pdf> [Accessed 14 April 2014].
- WRAP (2007b) Material Logistics Plan Good Practice Guidance. Available from: <http://www.wrap.org.uk/sites/files/wrap/MLP%20Guidance%20Document.pdf> [online]. Available from: [http://www.wrap.org.uk/sites/files/wrap/MLP\\_Guidance\\_Document.pdf](http://www.wrap.org.uk/sites/files/wrap/MLP_Guidance_Document.pdf) [Accessed 14 April 2014].
- WRAP (2011b) Net Waste Tool. Available from: <http://nwtool.wrap.org.uk/> [online]. Available from: <http://nwtool.wrap.org.uk/> [Accessed 14 April 2014].

- WRAP (2010) Setting a requirement for Waste Minimisation and Management. *Available from: <http://www.wrap.org.uk/sites/files/wrap/WRAP%206pp.pdf>* [online]. Available from: <http://www.wrap.org.uk/sites/files/wrap/WRAP 6pp.pdf> [Accessed 14 April 2014].
- WRAP (2008) *Site Waste Management Plans*. Available from: <http://www.wrap.org.uk/content/site-waste-management-plans-1> [Accessed 14 April 2014].
- Wright, J.A., Loosemore, H.A. and Farmani, R. (2002) Optimization of building thermal design and control by multi-criterion genetic algorithm. *Energy and buildings*. 34 (9), pp. 959–972.
- Wu, Z., Fan, H. and Liu, G. (2013) Forecasting Construction and Demolition Waste Using Gene Expression Programming. *Journal of Computing in Civil Engineering*. pp. 4014059. doi:10.1061/(ASCE)CP.1943-5487.0000362.
- Wu, Z., Yu, A.T.W., Shen, L. and Liu, G. (2014) Quantifying construction and demolition waste: an analytical review. *Waste management (New York, N.Y.)*. 34 (9), pp. 1683–1692. doi:10.1016/j.wasman.2014.05.010.
- Xu, X., Ding, L., Luo, H. and Ma, L. (2014) From building information modeling to city information modeling. *Journal of Information Technology in Construction, Special Issue BIM Cloud-based Technology in the AEC Sector: Present Status and Future Trends*. 19 pp. 292–307.
- Yang, L.-R., Huang, C.-F. and Hsu, T.-J. (2014) Knowledge leadership to improve project and organizational performance. *International Journal of Project Management*. 32 (1), pp. 40–53. doi:10.1016/j.ijproman.2013.01.011.
- Yang, R.J. (2014) An investigation of stakeholder analysis in urban development projects: Empirical or rationalistic perspectives. *International Journal of Project Management*. 32 (5), pp. 838–849. doi:10.1016/j.ijproman.2013.10.011.
- Yang, S. and Fu, L. (2014) Critical chain and evidence reasoning applied to multi-project resource schedule in automobile R&D process. *International Journal of Project Management*. 32 (1), pp. 166–177. doi:10.1016/j.ijproman.2013.01.010.
- Yao, X. (1993) A review of evolutionary artificial neural networks. *International Journal of Intelligent Systems*. 8 (4), pp. 539–567. doi:10.1002/int.4550080406.
- Yeang, K. (1995) *Designing with nature: the ecological basis for architectural design*. (no place) McGraw-Hill New York, NY.
- Yeheyis, M., Hewage, K., Alam, M.S., Eskicioglu, C. and Sadiq, R. (2013) An overview of construction and demolition waste management in Canada: a lifecycle analysis approach to sustainability. *Clean Technologies and Environmental Policy*. 15 (1), pp. 81–91.

- Yin, R.K. (2009) *Case Study Research: Design and Methods*. (no place) Sage publications.
- Yu, N., Jiang, Y., Luo, L., Lee, S., Jallow, A., Wu, D., Messner, J.I., Leicht, R.M. and Yen, J. (2013) Integrating BIMserver and OpenStudio for energy efficient building. In: *Proceedings of 2013 ASCE International Workshop on Computing in Civil Engineering*. 2013
- Yu, W. and Skibniewski, M.J. (2009) Integrating neurofuzzy system with conceptual cost estimation to discover cost-related knowledge from residential construction projects. *Journal of Computing in Civil Engineering*. 24 (1), pp. 35–44.
- Yu, W.D. and Skibniewski, M.J. (1999) Quantitative constructability analysis with a neuro-fuzzy knowledge-based multi-criterion decision support system. *Automation in construction*. 8 (5), pp. 553–565. doi:10.1016/S0926-5805(98)00105-8.
- Yuan, H. (2012) A model for evaluating the social performance of construction waste management. *Waste management*. 32 (6), pp. 1218–1228.
- Yuan, H. (2013) Key indicators for assessing the effectiveness of waste management in construction projects. *Ecological Indicators*. 24 pp. 476–484. doi:10.1016/j.ecolind.2012.07.022.
- Yuan, H. and Shen, L. (2011) Trend of the research on construction and demolition waste management. *Waste management (New York, N.Y.)*. 31 (4), pp. 670–679. doi:10.1016/j.wasman.2010.10.030.
- Yuan, H.P., Shen, L.Y., Hao, J.J.L. and Lu, W.S. (2011) A model for cost–benefit analysis of construction and demolition waste management throughout the waste chain. *Resources, Conservation and Recycling*. 55 (6), pp. 604–612. doi:10.1016/j.resconrec.2010.06.004.
- Zade, J.G. and Noori, R. (2008) Prediction of Municipal Solid Waste Generation by Use of Artificial Neural Network: A Case Study of Mashhad. *International Journal of Environmental Research*. 2 (1), pp. 13–22.
- Zadeh, L.A. (1965) Fuzzy sets. *Information and control*. 8 (3), pp. 338–353.
- Zaman, A.U. and Lehmann, S. (2013) The zero waste index: a performance measurement tool for waste management systems in a ‘zero waste city’. *Journal of Cleaner Production*. 50 pp. 123–132. doi:10.1016/j.jclepro.2012.11.041.
- Zhang, H. and Xing, F. (2010) Fuzzy-multi-objective particle swarm optimization for time–cost–quality tradeoff in construction. *Automation in Construction*. 19 (8), pp. 1067–1075.
- Zhang, S., Teizer, J., Lee, J.-K., Eastman, C.M. and Venugopal, M. (2013) Building information modeling (BIM) and safety: Automatic safety checking of construction models and schedules. *Automation in Construction*. 29 pp. 183–195.



- Zhang, X., Arayici, Y., Wu, S., Abbott, C. and Aouad, G. (2009) Integrating BIM and GIS for large-scale facilities asset management: a critical review. *Proc. 12th Int. Conference on Civil Structural and Environmental Engineering Computing*, Civil-Comp Press, Madeira, Portugal.
- Zhang, X., Wu, Y. and Shen, L. (2012) Application of low waste technologies for design and construction: A case study in Hong Kong. *Renewable and Sustainable Energy Reviews*. 16 (5), pp. 2973–2979. doi:10.1016/j.rser.2012.02.020.
- Zhang, X., Wu, Y., Shen, L. and Skitmore, M. (2014) A prototype system dynamic model for assessing the sustainability of construction projects. *International Journal of Project Management*. 32 (1), pp. 66–76. doi:10.1016/j.ijproman.2013.01.009.
- Zhang, Y. and Ng, T.S. (2012) An ant colony system based decision support system for construction time-cost optimization. *Journal of Civil Engineering and Management* [online]. 18 (4), pp. 580–589. Available from: <http://www.scopus.com/inward/record.url?eid=2-s2.0-84866362979&partnerID=tZOtx3y1>doi:10.3846/13923730.2012.704164.

# **APPENDIX A: FOCUS GROUP INTERVIEW SCHEDULE**

## ***Section A - Introduction***

This focus group interview is part of a PhD research and it is designed to identify BIM strategies for Construction Waste management. Please be assured that the interview is strictly for research purpose, and individual responses will remain confidential. As such, you are all encouraged to discuss your expectation on the use of BIM for construction waste management. The data from the research will be used, stored, and destroyed in a safe way. The interview will take about 60 minutes to complete. The discussion will be recorded on a digital device. Please let me know if you have any concern about this.

## ***Section B - Participant Information***

- 1) Give details of the nature of your organisation's operation and the size of your organisation.
- 2) Provide some brief details about your current position within your organisation.
- 3) How long have you worked in the construction industry?
- 4) How is your role related to Building Information Modelling, Sustainability, and Construction Waste Management?

## ***Section C - Causes of Construction Waste and Mitigation Strategies***

- 1) What do you see as material waste in the construction industry?
- 2) From your broad experience, what are the major causes of construction waste and how do you manage them?
- 3) Based on your broad experience, what are the challenges confronting construction and demolition waste management in the construction industry?
- 4) What are the current strategies for diverting construction and demolition waste from landfills?
- 5) Do you currently employ design-based strategies for construction waste management? If yes, please explain the process.

### ***Section D – Construction Waste Management Tools***

- 1) Which software tools do you currently use in your organisation for construction and demolition waste management? Please mention other tools you have heard of.
- 2) Can you explain the process of using the tools? A case study of how the tools are used will be useful.
- 3) From your broad experience, what are the limitations of these construction and demolition waste tools?
- 4) Based on your broad experience, how do you think that the industry can overcome the limitations of these tools?

### ***Section E – What are your Expectations in the use of BIM for Construction Waste Management***

- 1) What is Building Information Modelling (BIM) and what are its key capabilities?
- 2) From your broad experience, do you think BIM has a role in construction and demolition waste management? If so please discuss.
- 3) Is your organisation interested in using BIM for construction waste management? If yes, discuss the key areas that your organisation is employing or looking to employ BIM for construction waste management?
- 4) If a BIM software tool for construction and demolition waste exists, what are the key functionalities you will expect the tool to provide?

## **APPENDIX B: SURVEY COVER LETTER AND QUESTIONNAIRE SAMPLE**



University of the  
West of England

### **REDUCING CONSTRUCTION WASTE USING BUILDING INFORMATION MODELLING**

I am a doctoral researcher at the University of the West of England Bristol. This questionnaire is the basis of my PhD research, and it has been designed to develop BIM strategies for Construction Waste management. Inputs is solicited from all professionals within the built industry, including architects, engineers, project managers, BIM specialists, sustainability experts, etc. Please be assured that this survey is strictly for research purpose, and individual responses will remain confidential. The data from the research will be used, stored, and destroyed in a safe way.

The questionnaire will take about 15 minutes to complete. Should you require further details or clarification, you can please contact me through the details provided below. If you will like to receive a copy of the research findings, please provide your email in the last section of the questionnaire.

Thank you for your anticipated help.

Olugbenga Akinade  
PhD Student  
University of the West of England, Bristol  
Email:Olugbenga2.Akinade@live.uwe.ac.uk

## Particulars of Respondent

Please mark answers with a '☒'

### 1. Type of organisation

- Architectural firm    Engineering consultancy  
 Contractor    Project Management    Demolition Contractor  
 Waste management    Building materials supply  
 Others (please specify)

### 2. Job title of respondent;

- Architect    M&E Engineer    Project Manager  
 Civil/Structural Engineer    Demolition specialist    Lean Practitioner  
 BIM Specialist    Supply-chain Manager    Site Waste Manager  
 Construction operative    Architectural Technologist  
 Others (please specify)

### 3. Years of experience of respondent in construction industry;

- 1 - 5    6 – 10    11 - 15    16 – 20    21 – 25  
 above 25

## BIM Strategies for Construction Waste Management

Please consider each factor with relevance to your perceived competence and kindly rank their importance on a scale of 1-5, where; **1 = Not Important**   **2 = Less Important**   **3 = Moderately Important**   **4 = Important**   **5 = Most Important**

ID	How important are the following design factors in reducing construction waste using BIM?	Importance of factor				
		1	2	3	4	5
1.	Decision-making on waste reduction during design					
2.	Embedding waste-related information into building model					
3.	Support for waste management innovations such as RFID, IoT, big data etc.					
4.	Improved cost-benefit analysis of construction waste management					
5.	Improved materials classification methods					
6.	Automatic generation of waste related documents					

ID	How important are the following design factors in reducing construction waste using BIM?	Importance of factor				
		1	2	3	4	5
7.	Interoperability among waste management tools and software					
8.	Automatic capture of design parameters for waste analysis					
9.	Early supply-chain integration for waste management decisions					
10.	Improved waste minimisation commitment among stakeholders					
11.	Improved waste information sharing among stakeholders using BIM					
12.	Support for whole-life waste analysis					
13.	Preservation of building information in COBie					
14.	Computer aided simulation scenario and visualisation of waste performance					
15.	Use of 3D printing for prefabrication					
16.	Transparency of responsibilities during design process					
17.	Allows the development of BIM federated model for use by all teams					
18.	Foster task harmonisation among stakeholders to reduce duplication of effort					
19.	Improved clash detection in building models to reduce waste					
20.	Capability to capture clients' requirements					
21.	Usage of BIM as a co-ordination tool for designing out waste					
22.	Improved contractual document management					

## General Construction Waste Question

To what extent does your company consider construction waste minimisation in your projects

- Not at all     
 Not Often     
 Not Sure     
 Quite Often     
 Very Often

For each of the following questions, kindly rank their degree of importance on a scale of 1 to 5, where:

- 1 = Not Important    2 = Less Important    3 = Moderately Important    4 = Important    5 = Most Important**

ID	How important are the following design strategies in driving effective construction waste management?	Importance of factor				
		1	2	3	4	5
F.1	Consideration of end-of-life of building from design stage	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
F.2	Consideration for off-site construction during design	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
F.3	Design consideration for material recovery and reuse	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
F.4	Estimating construction waste during design	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

**Additional Comments**

Please state any further information that you feel may have particular importance to the outcome of this questionnaire.

You have reached the end of the survey. If you have any document that could be helpful to this study, please email it to [Olugbenga2.Akinade@live.uwe.ac.uk](mailto:Olugbenga2.Akinade@live.uwe.ac.uk). Please provide your email address if you will like a copy of the findings of the study to be sent to you.

Many thanks for your time and cooperation; it is highly appreciated.