

Investigation of Material Waste at Source in Offsite Construction: Quantification, Analysis, and Mitigation

Ali Abdulzahra Hadi

A thesis submitted in partial fulfilment of the requirements for the degree of
Doctor of Philosophy at Birmingham City University, Faculty of Computing,
Engineering and the Built Environment.

July 2025

Abstract

Offsite construction (OSC) has long been recognised for its potential to deliver environmental benefits, including reductions in material waste. However, existing research provides limited understanding and quantification of material waste generation in OSC. Although several studies have analysed OSC from a lean perspective, their evidence remains fragmented, with limited dedicated analysis of material waste. Other research has quantified material waste in OSC, but the analysis has mainly compared site-based waste generation with that of traditional construction, overlooking the waste generated offsite. Therefore, evidence on how, how much, and why material waste is generated in OSC remains highly limited. The lack of evidence impedes efforts to develop targeted interventions to support waste reduction. Hence, this study aims to develop an empirical understanding of material waste generation at source in OSC by quantifying waste, identifying its root causes, and suggesting targeted interventions to support waste reduction. By conducting empirical investigation across four OSC factories, the study identified five categories of material waste, each mapped to its root causes to explain how it is generated, reduced, or avoided. Key findings reveal that: 1) a poorly integrated design process causes significant material waste due to mismatches with available material sizes and inadequate detailing for assembly; 2) rigid procurement limited to a narrow range of standard and custom sizes restricts the design team's ability to reconcile customer-specific requirements with material availability, thereby increasing material waste; 3) inadequate production capabilities, particularly in material nesting and cutting precision, further drive waste generation; and 4) the prioritisation of production flow often overrides material-efficiency efforts, leaving even proven automated waste-saving technologies underused. Theoretically, this study advances knowledge by offering detailed source-level quantification and analysis of material waste in OSC, thereby deepening understanding of how waste is generated, reduced, and avoided. In doing so, it establishes a grounded evidence base for future research to propose and test interventions aimed at reducing material waste at source in OSC. Practically, the study recommends adopting: 1) a pull-based design process that aligns design decisions with procurable material sizes and production capabilities; 2) an agile procurement process capable of sourcing a wide range of standard and custom material sizes; and 3) efficient production capabilities that enhance material-efficiency without compromising production flow. Collectively, these integrated design, procurement, and production practices act as a protective mechanism to reduce material waste at source in OSC, which would otherwise necessitate significant downstream reuse and recycling efforts to be mitigated.

Declaration

I declare that this thesis is my own work and has not been submitted previously, either in whole or in part, for the award of any academic degree or qualification at Birmingham City University or any other academic institution.

Any material that is not my own work has been clearly identified and referenced in accordance with standard academic practice, and all sources of information, ideas, and quotations from the work of others are fully acknowledged.

This thesis presents original research conducted by me under the supervision of Associate Professor Solomon Adjei and Professor Franco Cheung at Birmingham City University.

Generative artificial intelligence tools were used solely to support language proofreading and stylistic editing (e.g., grammar, clarity, and conciseness). These tools were not used to generate original research content, analysis, results, or conclusions. All suggested edits were reviewed and approved by me, and I take full responsibility for the final version of this thesis.

Signed:



Name: Ali Abdulzahra Hadi

Date: 31st July 2025

Dedication

To my beloved wife, Huda — for your unwavering love, patience, and strength throughout this journey.

To my dear sons, Zaid and Hassan — your laughter and light have been my greatest motivation.

And to my parents — for your endless prayers, sacrifices, and the values you instilled in me.

This work is dedicated to you all, with deepest love and gratitude.

Acknowledgements

I would like to express my sincere gratitude to Birmingham City University for funding this doctoral research and for providing an intellectually stimulating and supportive environment throughout my PhD journey.

I am deeply thankful to my supervisors, Associate Professor Solomon Adjei and Professor Franco Cheung, whose expert guidance, consistent encouragement, and critical insights have been invaluable. Their mentorship has shaped my academic development and greatly enriched this research.

Special thanks are also due to the anonymous participants across the factories I visited, who generously allowed me access to observe and document production practices firsthand. Their willingness to support this research—despite the operational challenges related to health, safety, and workflow—was instrumental to its success. I am sincerely grateful for their openness and cooperation.

To all those who, in various ways, contributed to this endeavour—whether through academic, institutional, or moral support—thank you.

Table of Contents

Abstract.....	i
Declaration.....	ii
Dedication.....	iii
Acknowledgements.....	iv
Table of Contents	v
List of Figures.....	xviii
List of Tables.....	xxi
List of Abbreviations.....	xxiv
List of Publications	xxv
1 Chapter One: Introduction	1
1.1 Background.....	1
1.2 Problem Statement.....	2
1.3 Barriers to Existing Research.....	3
1.3.1 Practical Barriers.....	3
1.3.2 Methodological Barriers	3
1.3.3 Institutional Barriers	4
1.4 Research Aim, Objectives, and Questions	4
1.4.1 Research Aim.....	4
1.4.2 Research Objectives.....	4
1.4.3 Research Questions.....	5
1.5 Research Significance.....	6
1.6 Scope and Delimitations	7
1.7 Outline Research Methodology	8
1.8 Thesis Structure	8
1.8.1 Chapter One	8
1.8.2 Chapter Two.....	8

1.8.3	Chapter Three.....	9
1.8.4	Chapter Four	9
1.8.5	Chapter Five.....	10
1.8.6	Chapter Six.....	10
1.8.7	Chapter Seven	10
1.8.8	Chapter Eight	10
1.8.9	Chapter Nine	10
2	Chapter Two: Lean Uptake in Offsite Construction: Evidence, Limitations, and Research Needs.....	11
2.1	Introduction.....	11
2.2	Offsite Construction.....	11
2.2.1	Categorisation	12
2.2.2	Stages	12
2.2.2.1	Design	12
2.2.2.2	Procurement	13
2.2.2.3	Production	13
2.2.2.4	Transportation	14
2.2.2.5	Onsite Construction	14
2.2.3	Opportunities.....	14
2.2.4	Challenges.....	15
2.3	Lean Production.....	16
2.3.1	Lean Construction.....	17
2.3.2	Defining Waste in Construction.....	18
2.4	Lean Uptake in Offsite Construction	20
2.4.1	Design Practices.....	20
2.4.1.1	Design Modularisation & Standardisation.....	21
2.4.1.2	Design for Manufacture & Assembly	21
2.4.1.3	Design Planning & Monitoring.....	22
2.4.2	Production Practices.....	23

2.4.2.1	Production Planning.....	23
2.4.2.2	Production Planning & Monitoring	23
2.4.2.3	Production Visualisation	24
2.4.3	Cross-process Integration.....	25
2.4.3.1	Cross Process Planning & Monitoring.....	25
2.4.3.2	Cross Process Control (Intelligence)	26
2.4.3.3	Cross Process Monitoring	26
2.4.3.4	Cross Process Planning	27
2.5	Summary	27
3	Chapter Three: Construction Waste in Offsite Construction: Definitions, Evidence, and Gaps	28
3.1	Introduction.....	28
3.2	Defining Construction Waste	28
3.2.1	Design	29
3.2.2	Procurement	30
3.2.3	Logistics.....	30
3.2.4	Construction.....	30
3.3	Quantifying Construction Waste	31
3.3.1	Construction Waste Prediction Models.....	31
3.3.1.1	Waste Generation Rate (WGR).....	31
3.3.1.2	Function-driven Models (FDM)	32
3.3.1.3	Data-driven Models (DDM)	32
3.3.2	Construction Waste Estimation Models.....	33
3.3.2.1	Classification System Accumulation (CSA).....	33
3.3.2.2	Material Balance Approach (MBA).....	34
3.4	Construction Waste in OSC: Measurement, Assumptions & Mitigation.....	34
3.4.1	Construction Waste Quantification in OSC	34
3.4.1.1	Incomplete Quantification Boundaries	35
3.4.1.2	Limited Quantification Granularity	36
3.4.1.3	Data Reliability	37

3.4.2	Construction Waste Reduction through Design Cut Planning and Nesting.....	38
3.4.3	Construction Waste Assumptions in Life Cycle Assessments	39
3.4.4	Research Gap Identification.....	40
3.4.4.1	Lack of Mirco Level Quantification	40
3.4.4.2	Lack of Mirco Level Understanding.....	40
3.4.4.3	Limited Evidence on the Effectiveness of Automated Technologies.....	41
3.5	Summary	41
4	Chapter Four: Research Methodology	42
4.1	Introduction.....	42
4.2	Research Philosophy	42
4.3	Research Approach	43
4.4	Research Design.....	44
4.4.1	Case Study	44
4.4.1.1	Multiple-case Justification	44
4.4.1.2	The Subject	46
4.4.1.3	The object.....	46
4.4.1.4	Unit of Analysis	46
4.4.1.5	The Context.....	46
4.5	Case Selection.....	47
4.6	Data Collection	48
4.6.1	Direct Observations	49
4.6.2	Design Document Analysis.....	50
4.6.3	Semi-structured Interviews	51
4.7	Empirical Data Analysis	53
4.7.1	Root Cause Analysis	53
4.7.2	Descriptive Quantitative Analysis.....	53
4.7.3	Thematic Analysis.....	54
4.7.4	Exploratory Causal Analysis.....	55
4.7.5	Priority-Scenario Analysis	55

4.7.6	Comparative Quantitative Analysis	56
4.7.7	Interpretive Analysis	56
4.8	Validation	56
4.9	Ethical Considerations	57
4.9.1	Ethical Approval	57
4.9.2	Consent and Withdrawal Procedures	57
4.9.3	Confidentiality and Anonymity.....	58
4.9.4	Data Storage, Retention, and Destruction.....	58
4.9.5	Research Integrity	58
4.10	Summary	58
5	Chapter Five: Material Waste Analysis in Offsite Construction: Identification, Quantification, and Root-Cause Diagnosis.....	59
5.1	Introduction.....	59
5.2	Factory A.....	59
5.2.1	Fitting the Structural Frame	60
5.2.2	Cutting and Fitting Plasterboards.....	61
5.2.2.1	Ceiling Plasterboard Offcuts.....	62
5.2.2.2	Length/Width-side Wall Plasterboard Offcuts	64
5.2.2.3	Wall Opening-Related Plasterboard Offcuts.....	65
5.2.3	Cutting and Fitting Rigid Insulation	66
5.2.3.1	Width-side Rigid Insulation Offcuts	67
5.2.3.2	Length-side Rigid Insulation Offcuts.....	68
5.2.4	Cutting and Fitting the Floor Decking	69
5.2.4.1	Length-side Plywood Decking Offcuts.....	70
5.2.4.2	Width-side Plywood Decking Offcuts	71
5.2.5	Fitting the Wall Frames, Studs, and Joists	72
5.2.6	Cutting & Fitting Rockwool Insulation	73
5.2.7	Fitting the Roof Sheet Panels.....	75
5.2.7.1	Length-side Roof Sheet Offcuts.....	75

5.2.7.2	Width-side Roof Sheet Offcuts	76
5.2.8	Cutting and Fitting Cladding Panels	77
5.2.8.1	Width-side Cladding Panels Offcuts	77
5.2.8.2	Length-side Cladding Panels Offcuts	78
5.2.8.3	Cladding Panels Openings Offcuts	79
5.2.9	Summary - Factory A	82
5.3	Factory B	83
5.3.1	Cutting and Fitting Timber Frame Sections	83
5.3.1.1	435 mm Offcuts	84
5.3.1.2	2290 mm Offcuts	86
5.3.1.3	50 mm Offcuts	87
5.3.1.4	Other Offcuts	89
5.3.2	Cutting OSB Boards	90
5.3.2.1	Length-side OSB Board Offcuts	90
5.3.2.2	Width-side OSB Boards Offcuts	92
5.3.2.3	Opening Infill OSB Offcuts	93
5.3.2.4	OSB Opening Offcuts	94
5.3.3	Cutting Polyethene Vapour Barrier	96
5.3.3.1	Width-side Vapour Barrier Offcuts	96
5.3.3.2	Length-side Vapour Barrier Offcuts	97
5.3.3.3	Polyethene Vapour Barrier Opening Offcuts	98
5.3.4	Cutting & Fitting Rockwool Insulation	99
5.3.5	Cutting & Fitting the Brick Slips	100
5.3.5.1	Half-Brick Façade Corner Offcuts	101
5.3.5.2	Other Offcuts	102
5.3.6	Cutting Timber Battens	103
5.3.6.1	178 mm Offcuts	104
5.3.6.2	Other Offcuts	105
5.3.7	Cutting and Fitting Cladding Boards	106
5.3.7.1	Length-side Cladding Board Offcuts	107
5.3.7.2	Width-side Cladding Board Offcuts	108

5.3.7.3	Opening Infill Cladding Boards Offcuts	109
5.3.7.4	Cladding Boards Opening Offcuts	110
5.3.8	Cutting and Fitting Breather Membrane	111
5.3.8.1	Length-side Breather Membrane Excess Overlap	111
5.3.8.2	Width-side Breather Membrane Excess Overlap	112
5.3.8.3	Breather Membrane Opening Offcuts	113
5.3.8.4	Breather Membrane Opening Overlap Offcuts	114
5.3.9	Summary - Factory B	116
5.4	Factory C	117
5.4.1	Cutting Timber Frame Sections	117
5.4.1.1	430 mm Offcuts	118
5.4.1.2	25 mm Offcuts	119
5.4.1.3	Other Offcuts	120
5.4.2	Cutting OSB Boards	121
5.4.2.1	Length-side OSB Board Offcuts	123
5.4.2.2	Width-side OSB Boards Offcuts	124
5.4.2.3	OSB Opening Offcuts	126
5.4.3	Cutting Rigid Insulation Panels	127
5.4.3.1	Length-side Rigid Insulation Offcuts	127
5.4.3.2	Width-side Rigid Insulation Offcuts	128
5.4.4	Fitting and Cutting Breather Membrane	129
5.4.4.1	Length-side Breather Membrane Overuse	130
5.4.4.2	Breather Membrane Width-side Overuse	131
5.4.4.3	Breather Membrane Opening Offcuts	132
5.4.5	Summary - Factory C	133
5.5	Factory D	134
5.5.1	Cutting and fitting Timber Frame Sections	134
5.5.1.1	646 mm Offcuts	135
5.5.1.2	20 mm Offcuts	136
5.5.1.3	Other Offcuts	137
5.5.2	Fitting and Cutting OSB Boards	139

5.5.2.1	Length-side OSB Board Offcuts	139
5.5.2.2	Width-side OSB Boards Offcuts	141
5.5.2.3	OSB Opening Offcuts	142
5.5.3	Cutting & Fitting Rockwool Insulation	144
5.5.4	Summary - Factory D.....	145
5.6	Chapter Summary	145
6	Chapter Six: Material Waste Categories in Offsite Construction: A Thematic Analysis of Root Causes and Influencing Conditions.....	147
6.1	Introduction.....	147
6.2	Material Waste Categories in OSC	147
6.2.1	Standard Size-Induced Waste.....	148
6.2.1.1	Lack of Standard Size Alignment	149
6.2.1.2	Lack of Custom-Size Ordering	149
6.2.1.3	Poor Choice of Material Size	151
6.2.2	Suboptimal Nesting Offcuts.....	151
6.2.3	Opening-Induced Offcuts.....	153
6.2.3.1	Lack of Cut Planning	153
6.2.3.2	Lack of Precision-Adaptive Material Application	155
6.2.4	Inaccuracy-Induced Waste	155
6.2.5	Edge-Squaring Offcuts.....	157
6.2.6	Discussion	157
6.3	Waste Outcomes of Automated Technologies.....	159
6.3.1	Automated Design Modularisation Tools	160
6.3.2	Automated Nesting-Enabled Saws	161
6.3.3	Robotic Arms for Automated Assembly	162
6.4	Waste Outcomes and Operational Priorities	163
6.4.1	Production Flow-Driven Tension Scenarios	164
6.4.1.1	Lack of Cut Planning	165
6.4.1.2	Lack of Effective Nesting	165

6.4.1.3	Lack of Precision-Adaptive Material Application	165
6.4.1.4	Manual Work Inaccuracies.....	166
6.4.2	Third-Priority Dominance Scenarios	166
6.4.2.1	Limited Standard Size Alignment.....	166
6.4.2.2	Lack of Custom-sized Ordering.....	166
6.4.2.3	Inconsistent Material Quality.....	167
6.4.3	Material Efficiency-Driven Tension Scenarios.....	167
6.4.3.1	Cut Planning Adoption.....	167
6.4.4	Synergistic Alignment Scenarios	167
6.4.4.1	Standard Size Alignment.....	167
6.4.4.2	Custom-Sized Ordering	168
6.4.4.3	Effective Manual Nesting	168
6.4.5	Discussion.....	168
6.5	Summary	170
7	Chapter Seven: Cross-Case Analysis of Material Waste Variability at Source in Offsite Construction.....	171
7.1	Introduction.....	171
7.2	Waste Quantification by Factory.....	171
7.2.1	Factory A.....	172
7.2.2	Factory B.....	173
7.2.3	Factory C.....	174
7.2.4	Factory D	175
7.3	Waste Quantification by Material Category.....	176
7.3.1	Opening-Inclusive Materials.....	177
7.3.2	Flexible Materials	177
7.3.3	Materials with High Cut Variability.....	178
7.3.4	Materials with Limited Size Variety	179
7.3.5	Materials with Consistent Near-Fit.....	179
7.4	Waste Quantification by Waste Category	179

7.4.1	Opening-Induced Offcuts.....	180
7.4.2	Inaccuracy-Induced Waste	180
7.4.3	Standard Size-Induced Waste.....	181
7.4.4	Edge-Squaring Offcuts.....	182
7.4.5	Suboptimal Nesting Offcuts.....	182
7.5	Waste Quantification by Root Cause Practice	182
7.5.1	Lack of Precision-Adaptive Application.....	183
7.5.2	Lack of Efficient Cut Planning	184
7.5.3	Lack of Custom-Size Ordering	184
7.5.4	Limited Standard Size Alignment.....	184
7.5.5	Manual Work Inaccuracies.....	184
7.5.6	Lack of Effective Nesting	185
7.5.7	Poor Choice of Material Size.....	185
7.5.8	Inconsistent Material Quality.....	185
7.6	Discussion	185
7.7	Summary	187
8	Chapter Eight: The Development of Targeted Interventions for Material waste Reduction in Offsite Construction.....	189
8.1	Introduction.....	189
8.2	Design-Focused Preventive Measures	189
8.2.1	Designing in Line with Standard Material Sizes or their Multiples	189
8.2.1.1	Cross-functional Design Input Integration.....	190
8.2.1.2	Early Exploration and Selection of Size-compatible Alternatives.....	190
8.2.1.3	Standardising Modular Design Rules and Dimensional Libraries.....	190
8.2.2	Adopting Cut Planning Around Openings	191
8.2.2.1	Standardised Opening Cut Layouts and Detailing Rules.....	192
8.2.2.2	Timely Pre-cut Preparation Aligned with Production Sequence	192
8.3	Procurement-Focused Preventive Measures	192

8.3.1	Sourcing Variety of Standard and Custom Material Sizes	193
8.3.1.1	Developing Reliable Supplier Capability for Size Flexibility	193
8.3.1.2	Making Material-size Procurability Visible to Designers.....	193
8.4	Production-Focused Preventive Measures	194
8.4.1	Performing Efficient Material Nesting	194
8.4.1.1	Delivering Complete Cut-list Information to Enable Planned Nesting	195
8.4.1.2	Activating Nesting Optimisation While Controlling Its Practical Outputs	195
8.4.1.3	Integrating Nesting with Identification, Labelling, and Sorting	195
8.4.2	Adopting Precision Adaptive Material Application.....	196
8.4.2.1	Accurate Digital Definition of Required Membrane Geometry	196
8.4.2.2	Timely Production and Release of Pre-shaped Membranes	197
8.4.3	Standardising Manual Work to Minimise Material Overapplication.....	197
8.4.3.1	Defining a Repeatable Sizing-and-Fitting Procedure	198
8.4.3.2	Physical and Visual Cues for Consistent Sizing	198
8.4.4	Selecting the Right Size of Raw Materials	199
8.4.4.1	Specifying Raw-material Size Selection within the Production Package..	199
8.4.4.2	Controlling Material Release So the Correct Sizes Arrive When Needed.	200
8.4.5	Automating Material Edge Inspection to Minimise Offcuts.....	200
8.4.5.1	Built-in Edge Quality Control at the Cutting Point	201
8.4.5.2	Data Capture to Improve Supplier Performance and Handling Practices..	201
8.5	Summary	202
9	Chapter Nine: Conclusion	203
9.1	Introduction.....	203
9.2	Answers to the Research Questions	203
9.2.1	Research Question 1	203
9.2.2	Research Question 2	204
9.2.3	Research Question 3	204
9.2.4	Research Question 4	205
9.2.5	Research Question 5	205
9.3	Synthesis of Key Findings	206

9.4	Theoretical Contributions	207
9.4.1	Quantifying Material Waste at Source in OSC	207
9.4.2	Detailed Understanding of Material Waste in OSC	208
9.4.3	Empirical Analysis of Automation’s Impact on Material Waste Outcomes...208	
9.4.4	Empirical Analysis of the Impact of Interacting Priorities on Waste Outcomes 209	
9.5	Practical Implications.....	209
9.5.1	Design	209
9.5.2	Procurement	210
9.5.3	Production	210
9.6	Research Limitations	210
9.6.1	Limited Generalisability	211
9.6.2	Potential for Researcher Bias.....	211
9.6.3	Scope Limitation.....	211
9.6.4	Lack of Validation of Proposed Interventions	211
9.7	Future Research Directions.....	212
9.7.1	Evaluating Post-Generation Waste Practices	212
9.7.2	Comparing Waste with Traditional Construction.....	212
9.7.3	Validation of Proposed Interventions.....	212
9.7.4	Exploring Automation for Production flow and Material Efficiency	212
9.8	Conclusions.....	213
References.....		215
Appendices.....		237
Appendix A: Construction Waste Quantification – Factory A.....		237
Appendix B: Construction Waste Quantification – Factory B.....		238
Appendix C: Construction Waste Quantification – Factory C.....		245
Appendix D: Construction Waste Quantification – Factory D		250

Appendix E: Summary of Activity-level Analysis.....	252
Appendix F: Observation Notes.....	255
Appendix G: Sample Interview Transcripts (Anonymised).....	277
Appendix H: Ethics Approval.....	314

List of Figures

Figure 1.1: Research aim, objectives, and questions	5
Figure 1.2: Research scope	7
Figure 1.3: Thesis structure.....	9
Figure 2.1: Gibb's (2001) prefabrication levels; adapted from (Jaillon and Poon, 2014)	12
Figure 2.2: Modern methods of construction categorisations based on MHCL (2019)	13
Figure 2.3: Waste categories in lean manufacturing (Sarhan, 2015)	19
Figure 3.1: Construction waste breakdown	29
Figure 4.1: Conceptual representation of the inductive research approach	43
Figure 4.2: Research design.....	45
Figure 4.3: Case study context, subject, object, and unit of analysis	47
Figure 4.4: Data collection techniques and their complementary objectives	49
Figure 4.5: Activity-level observations of OSC component assembly processes.....	49
Figure 4.6: Empirical data analysis framework	54
Figure 5.1: Factory A - Steel frame module assembly activities	60
Figure 5.2: Structural frame components prepared for assembly	62
Figure 5.3: Ceiling plasterboard assembly plan and generated offcuts	63
Figure 5.4: Ceiling plasterboard assembly activities	64
Figure 5.5: Wall plasterboard assembly practice, left integration gaps, and window openings	65
Figure 5.6: Plasterboard opening offcuts	66
Figure 5.7: Rigid insulation assembly practice, generated offcuts, and integrated offcuts	68
Figure 5.8: Floor decking plywood assembly practice, generated offcuts, and integrated pieces	70
Figure 5.9: Fitting the wall frames components	73
Figure 5.10: Rockwool insulation overstuffing practice.....	75
Figure 5.11: Roof sheet assembly plan	76
Figure 5.12: Cladding panels assembly plan and generated offcuts	81
Figure 5.13: Wall opening-related cladding offcuts.....	81
Figure 5.14: Factory B - Timber frame wall panel assembly activities	83
Figure 5.15 : Separating and measuring timber offcuts	84
Figure 5.16: 435 mm offcuts generation.....	86
Figure 5.17: 2290 mm offcuts generation.....	87

Figure 5.18: Cracked and uneven standard timber edges	89
Figure 5.19: Length-side OSB offcuts	92
Figure 5.20: Width-side OSB offcuts being stored for future reuse	93
Figure 5.21: OSB cuts assembly plan	95
Figure 5.22: Polyethene vapour barrier offcuts	96
Figure 5.23: Rockwool insulation overstuffing practice.....	100
Figure 5.24: Brick slip corner with half brick depth.....	102
Figure 5.25: Brick slips cutting plan and required cuts	103
Figure 5.26: Timber battens cutting activity	104
Figure 5.27: Timber batten section integration	105
Figure 5.28: Required cladding board cuts, opening infill cuts, and width-side offcuts	108
Figure 5.29: Membrane roll cuts.....	115
Figure 5.30: Fitted opening overlap membrane strip.....	115
Figure 5.31: Factory C - Timber frame wall panel assembly activities	117
Figure 5.32: Timber offcuts being repurposed as transportation props	119
Figure 5.33: Various timber offcuts resulting from limited nesting.....	121
Figure 5.34: OSB required and observed offcuts categories	122
Figure 5.35: OSB offcuts being repurposed as transportation props	124
Figure 5.36: Width-side OSB offcut generation	125
Figure 5.37: Rigid insulation cuts being prepared in required sizes.....	129
Figure 5.38: Breather membrane layer, panel boundaries, and actual overlapping area	131
Figure 5.39: Fitting and cutting breather membrane	133
Figure 5.40: Factory D - Timber frame wall panel assembly activities.....	134
Figure 5.41: Excessive accumulation of 646 mm offcuts.....	136
Figure 5.42: Various offcuts generated because of limited nesting practice.....	139
Figure 5.43: Length-side OSB offcut accumulation	141
Figure 5.44: Width-side OSB offcut accumulation.....	142
Figure 5.45: OSB sheathing assembly plan and offcuts	143
Figure 5.46: Overstuffing practice of rockwool insulation.....	145
Figure 6.1: The origins of different material waste categories in relation to the materials and root causes.....	148
Figure 6.2: Standard size-induced waste generation, reduction, and avoidance	150
Figure 6.3: Suboptimal nesting offcuts generation, reduction, and avoidance/ reduction to minimum	152

Figure 6.4: Opening-induced offcut generation and avoidance.	154
Figure 6.5: Inaccuracy-induced waste generation and avoidance.	156
Figure 6.6: Edge-squaring offcuts generation and avoidance.....	158
Figure 6.7: Automated design modularisation tool and associated inefficiencies behind waste generation.....	161
Figure 6.8: Automated nesting enabled saw and associated inefficiencies behind waste generation.....	162
Figure 6.9: Robotic arms for automated assembly and associated inefficiencies behind waste generation.....	163
Figure 6.10: Interaction scenarios between production flow and material efficiency and their impact on material waste (Note: red, green and yellow colours refer to design, procurement, and production practices, respectively).....	164
Figure 7.1: Distribution of waste values by factory.....	174
Figure 7.2: Distribution of waste values by construction materials.....	176
Figure 7.3: Overlapping material characteristics contributing to material waste generation in OSC.....	177
Figure 7.4: Distribution of waste percentages by waste category	181
Figure 7.5: Distribution of waste percentages by root cause practice	183
Figure 8.1: Designing in line with standard material sizes or their multiples	191
Figure 8.2: Adopting cut planning around openings.....	192
Figure 8.3: Sourcing variety of standard and custom material sizes	194
Figure 8.4: Performing efficient material nesting.....	196
Figure 8.5: Adopting precision adaptive material application	197
Figure 8.6: Standardising manual work to minimise material overapplication.....	199
Figure 8.7: Selecting the right size of raw materials	200
Figure 8.8: Automating material edge inspection to minimise offcuts	202

List of Tables

Table 3.1: The limitations of the research quantifying construction waste in OSC.....	36
Table 3.2: Research proposing BIM-based design optimisation tools to reduce waste generation in OSC.....	39
Table 4.1: Anonymised factory profiles included in the multiple case study	48
Table 4.2: Observation sessions and days per factory	50
Table 4.3: Design document types and analysed product samples for factories A-D.....	50
Table 4.4: Roles and number of the interviewees across the four factories.....	51
Table 4.5: Anonymised interviewee codes and roles across the four factories.....	52
Table 5.1: Structural frame waste avoidance - root cause analysis.....	61
Table 5.2: Ceiling plasterboard offcuts - root cause analysis	63
Table 5.3: Wall plasterboard offcuts avoidance - root cause analysis.....	64
Table 5.4: Wall opening-related plasterboard offcuts - root cause analysis.....	65
Table 5.5: Width-side rigid insulation offcuts - root cause analysis	67
Table 5.6: Length-side rigid insulation offcuts avoidance - root cause analysis	68
Table 5.7: Length-side plywood decking offcuts - root cause analysis	70
Table 5.8: Width-side plywood decking offcuts avoidance - root cause analysis.....	71
Table 5.9: Wall frames, studs, and joists waste avoidance - root cause analysis	72
Table 5.10: Rockwool insulation waste - root cause analysis.....	74
Table 5.11: Length-side roof sheet offcuts avoidance - root cause analysis.....	75
Table 5.12: Width-side roof sheet offcuts avoidance - root cause analysis	77
Table 5.13: Width-side cladding panel offcuts - root cause analysis	78
Table 5.14: Length-side cladding panel offcuts avoidance - root cause analysis	79
Table 5.15: Wall opening-related cladding offcuts - root cause analysis.....	80
Table 5.16: 435 mm offcuts - root cause analysis.....	85
Table 5.17: 2290 mm offcuts - root cause analysis.....	86
Table 5.18: 50 mm offcuts - root cause analysis.....	88
Table 5.19: Different length timber offcuts generation - root cause analysis	89
Table 5.20: Length-side OSB board offcuts - root cause analysis	91
Table 5.21: Width-side OSB board offcuts - root cause analysis.....	92
Table 5.22: Opening infill OSB offcuts - root cause analysis.....	94
Table 5.23: OSB opening offcuts - root cause analysis	95
Table 5.24: Width-side polyethylene vapour barrier offcuts - root cause analysis	97

Table 5.25: Length-side polyethene vapour barrier offcuts - root cause analysis.....	98
Table 5.26: Polyethene vapour barrier opening offcuts - root cause analysis.....	98
Table 5.27: Rockwool insulation overstuffing waste - root cause analysis	99
Table 5.28: Brick slip corner offcuts - root cause analysis	101
Table 5.29: Other brick slip offcuts - root cause analysis.....	102
Table 5.30: 178 mm offcuts - root cause analysis.....	104
Table 5.31: Other timber batten offcuts - root cause analysis.....	106
Table 5.32: Length-side cladding board offcuts - root cause analysis	107
Table 5.33: Width-side cladding board offcuts - root cause analysis.....	108
Table 5.34: Opening infill cladding boards offcuts - root cause analysis	109
Table 5.35: Cladding board opening offcuts - root cause analysis	110
Table 5.36: Length-side breather membrane excess overlap - root cause analysis.....	112
Table 5.37: Width-side breather membrane excess overlap avoidance - root cause analysis	113
Table 5.38: Breather membrane opening offcuts - root cause analysis	113
Table 5.39: Breather membrane openings' overlap offcuts avoidance - root cause analysis.	114
Table 5.40: 430 mm offcuts - root cause analysis.....	118
Table 5.41: 25 mm offcuts - root cause analysis.....	120
Table 5.42: Different length timber offcuts generation - root cause analysis	121
Table 5.43: Length-side OSB board offcuts - root cause analysis	123
Table 5.44: Width-side OSB offcuts - root cause analysis.....	124
Table 5.45: OSB opening offcuts - root cause analysis	126
Table 5.46: Length-side rigid insulation offcuts - root cause analysis.....	127
Table 5.47: Width-side rigid insulation offcuts - root cause analysis	128
Table 5.48: Length-side breather membrane overuse - root cause analysis.....	130
Table 5.49: Width-side breather membrane overuse - root cause analysis	131
Table 5.50: Breather membrane opening offcuts - root cause analysis	132
Table 5.51: 646 mm offcuts - root cause analysis.....	135
Table 5.52: 20 mm offcuts - root cause analysis.....	137
Table 5.53: Different length offcuts' generation root cause analysis	138
Table 5.54: Length-side OSB board offcuts - root cause analysis	140
Table 5.55: Width-side OSB board offcuts - root cause analysis.....	141
Table 5.56: OSB opening offcuts - root cause analysis	142
Table 5.57: Rockwool insulation over-stuffing - root cause analysis	144
Table 5.58: Case study replication across the identified root cause themes	146

Table 7.1: Material characteristics in relation to the total generated waste across different materials.....	178

Appendix Table 1: Wall and Ceiling Plasterboard Construction Waste Quantification – Factory A.....	237
Appendix Table 2: Timber Framing Offcuts and Related Cuts - Factory B	238
Appendix Table 3: Required Timber Framing Cuts Across the Observed Wall Panels – Factory B.....	239
Appendix Table 4: Required and Used OSB Sizes and Quantities - Factory B.....	240
Appendix Table 5: Required, Used, and Wasted Areas of Polyethene Vapour Barrier – Factory B.....	242
Appendix Table 6: Brick Slips Required, Used, and Generated Offcuts – Factory B	242
Appendix Table 7: Timber Batten Sections: Requirements, Usage, Offcuts, and Sources – Factory B.....	242
Appendix Table 8: Required, Used, and Wasted Cladding Board Areas – Factory B	243
Appendix Table 9: Required, Used, and Wasted Breather Membrane – Factory B.....	244
Appendix Table 10: Timber Lengths Required, Used, and Wasted - Factory C	245
Appendix Table 11: Total OSB Area Used, Required, and Wasted - Factory C	246
Appendix Table 12: : Total Area of Rigid Insulation Required, Used, and Wasted - Factory C	247
Appendix Table 13: Total Area of Breather Membrane Required, Used, and Overused - Factory C.....	249
Appendix Table 14: Timber Lengths Required, Used, and Wasted - Factory D.....	250
Appendix Table 15: Total OSB Area Used, Required, and Wasted - Factory D.....	251
Appendix Table 16: Summary of Activity-Level Analysis: How, How Much, and Why Material waste is Generated	252

List of Abbreviations

OSC: Offsite construction

DfMA: Design for Manufacture and Assembly

IoT: internet of things

BIM: Building Information Modelling

CPM: Critical Path Method

JIT: just-in-time

VSM: value stream mapping

VA: value adding activities

NVA: non-value adding activities

NNVA: necessary non-value adding activities

BIM: building information modelling

RCA: root cause analysis

WGR: Waste Generation Rate

FDM: Function-driven Models

DDM: Data-driven Models

BoQ: Bill of Quantity

CSA: Classification System Accumulation

MBA: Material Balance Approach

List of Publications

The following publications have been produced during the course of this PhD research:

- Hadi, A., Cheung, F. & Adjei, S.. (2025). Comparative Analysis of Construction Waste: Robotic Vs. Manual Offsite Assembly. In Seppänen, O., Koskela, L., & Murata , K. (Eds.), *Proceedings of the 33rd Annual Conference of the International Group for Lean Construction (IGLC 33)* (pp. 775–786). <https://doi.org/10.24928/2025/0225>
- Hadi, A., Cheung, F., Adjei, S. & Dulaimi, A. (2024) Aligning Digital Technologies in Off-site Construction with Industry 5.0 Design Principles for a Sustainable Future. *Innovations, Disruptions and Future Trends in the Global Construction Industry*, pp. 35–48. <https://doi.org/10.1201/9781003372233-4>
- Hadi, A., Cheung, F., Adjei, S., & Dulaimi, A. (2024) The Application of Lean Manufacturing in Off-site Construction: A Bibliometric Review. *Innovations, Disruptions and Future Trends in the Global Construction Industry*, pp. 122–136. <https://doi.org/10.1201/9781003372233-11>
- Hadi, A., Cheung, F., Adjei, S., & Dulaimi, A. (2023) Evaluation of Lean Off-Site Construction Literature through the Lens of Industry 4.0 and 5.0. *Journal of Construction Engineering and Management*, 149 (12): 03123007. <https://doi.org/10.1061/JCEMD4.COENG-13622>

Chapter One: Introduction

1.1 Background

The construction industry is globally recognised as a major driver for economic growth and prosperity, still faces several challenges related to resource efficiency, productivity, and environmental sustainability (Alaloul *et al.*, 2022). Construction waste is one of the most significant challenges, with the industry being blamed for generating approximately 40% of the total solid waste sent to disposal sites worldwide each year (Oluleye *et al.*, 2022). This wasteful pattern of consumption poses a significant pressure on the planet natural resources, jeopardising the ability of future generations to meet their needs.

Several studies attribute inefficiencies in the construction industry to the fragmented processes, one-of-a-kind designs, and manual implementation widely seen in the traditional stick-built construction approach (Li *et al.*, 2014). Poorly integrated processes are one key characteristic, where fragmented design, planning, and execution results in several inefficiencies, directly promoting construction waste generation (Ajayi and Oyedele, 2018). Particularly, the lack of effective communication and collaboration between key stakeholders are frequently identified for poor constructability, design errors, and material overordering (Kifokeris and Xenidis, 2017). Similarly, excessive design customisation is also blamed to exacerbate construction waste generation due to highly complex and unstandardised material cutting practices, promoting excessive offcut generation (Ajayi *et al.*, 2017). In addition, the lack of automation is also recognised as a key factor promoting construction waste generation. Adopting automated technologies are seen as a buffer against human error, promoting precision in measurement and cutting activities (Abkar *et al.*, 2025).

In response to the challenges seen in traditional construction, offsite construction (OSC) is consistently promoted as a promising building approach, providing significant opportunities for process and product improvement (Innella *et al.*, 2019). It involves building the required construction components in a controlled factory environment and then transporting them to the site for final assembly (Gibb, 2001). The controlled environment is the key distinguishing feature from conventional construction settings, offering significant opportunities for process and product standardisation, automation, and the application of lean principles. Particularly, the controlled environment provides a stable working setting where standardised processes and automated technologies can efficiently be maintained and employed. Several studies (Ayinla *et*

al., 2022; Barkokebas *et al.*, 2023; Sahir *et al.*, 2024; Zheng *et al.*, 2024; Noueihed and Hamzeh, 2024; Ayinla *et al.*, 2025) show that OSC offers substantial gains in productivity, reduced cycle times, lower operational costs, enhanced safety, and improved quality control.

However, evidence on OSC capability to reduce construction waste in practice remains largely anecdotal. Although several studies (Jaillon *et al.*, 2009; Qiankun Wang *et al.*, 2020; W Lu *et al.*, 2021; Loizou *et al.*, 2021; Hao *et al.*, 2021) demonstrate that OSC can reduce construction waste onsite, they overlook the fact that it can also generate construction waste offsite. Hence, as construction activities are increasingly transferred offsite, it becomes crucial to explore how and how much material waste is generated.

In addition, research employing lean principles to optimise OSC performance (El Sakka *et al.*, 2016; Ayinla *et al.*, 2022; Noueihed and Hamzeh, 2024) provides fragmented evidence on waste across design, procurement, and production processes. While time-related inefficiencies are frequently investigated, material waste is rarely explored. As a result, lean-based research offers only limited insight into how and why material waste is generated in OSC.

Collectively, the extant literature on construction waste in the context of OSC provides only limited insight into how, how much, and why material waste is generated offsite. Given these limitations, there is a critical need for empirical investigation of material waste generation at source within OSC settings. Gaining such understanding is essential to unlocking the environmental and operational potential of OSC. The following section outlines the specific problem this research aims to address.

1.2 Problem Statement

OSC is increasingly promoted as a feasible alternative to the traditional construction approach, bringing significant opportunities in terms of productivity, cost-efficiency, safety, and quality (Innella *et al.*, 2019; Ayinla *et al.*, 2022; Zheng *et al.*, 2024). Due to its production-like controlled environment, OSC is viewed as enabler to standardisation, automation, and lean application (Gusmao Brissi *et al.*, 2022).

However, evidence on OSC capability to reduce construction waste remains largely limited. Research quantifying construction waste in OSC (e.g., Lu *et al.*, 2021; Hao *et al.*, 2021) has primarily focused on onsite waste generation for comparison with traditional construction, thereby overlooking waste generated offsite. In addition, lean-based research provides only

fragmented evidence on waste in OSC, offering limited insight into how and why material waste is generated.

Overall, the extant literature provides limited understanding of how, how much, and why material waste is generated in OSC. This gap hinders the industry's ability to identify the root causes of waste generation, implement targeted preventive measures, and ultimately unlock the full potential of OSC. Therefore, there is a pressing need for empirical research that critically examines material waste generation in OSC.

1.3 Barriers to Existing Research

The limited knowledge on construction waste generation in OSC can be attributed to a range of practical, methodological, and institutional barriers that constrain progress in this domain.

1.3.1 Practical Barriers

From a practical perspective, there is a limited availability of detailed construction waste data, obstructing researchers to implement thorough waste analysis. Manufacturers typically do not maintain records of construction waste quantities disaggregated by product or material type (Liu *et al.*, 2019). Instead, waste data is often aggregated at a higher level (e.g., Jaillon *et al.*, 2009; Lu *et al.*, 2021), restricting meaningful analysis to identify the root causes and develop targeted mitigation strategies.

This issue therefore necessitates conducting direct factory observations to quantify and understand construction waste thoroughly. However, accessing OSC facilities to conduct activity-level observations is often restricted due to health and safety regulations and confidentiality concerns. As a result, researchers face significant challenges in accessing direct observations, restricting their ability to collect and analyse detailed construction waste data.

1.3.2 Methodological Barriers

From a methodological perspective, the lack of granular waste data has led researchers to rely on project-level estimates, which provide only a generalised view of construction waste in OSC (Zhang *et al.*, 2024). This approach fails to capture specific waste-generating activities, their quantities, and underlying causes, thereby hindering the development of targeted mitigation strategies.

1.3.3 Institutional Barriers

From an institutional perspective, there is a lack of detailed reporting requirements for construction waste generation in the UK (OEP, 2024). This is further compounded by the absence of incentives to track and mitigate construction waste, which hinders effective industry engagement and investment in waste reduction efforts (DEFRA, 2023).

1.4 Research Aim, Objectives, and Questions

To address the research problem identified earlier, this section presents the research aim, objectives, and questions that guide the study. Figure 1.1 illustrates the relationship between the research aim, objectives, and questions and shows how they structure the investigation of material waste generation at source in OSC.

1.4.1 Research Aim

The research aims to develop an empirical understanding of material waste generation at source in OSC by quantifying waste, identifying its root causes, and suggesting targeted interventions to support waste reduction.

1.4.2 Research Objectives

To achieve the research aim, four research objectives were set as follows:

1. To identify instances of material waste generation at source, quantify the associated waste quantities, and diagnose their root causes through a multiple case study and root-cause analysis.
2. To classify material waste into distinct categories and systematically map each to its contributing root-cause practices using thematic analysis.
3. To analyse how material waste generation instances associated with automated technologies, and those shaped by different operational priority configurations influence waste outcomes in OSC.
4. To analyse variations in material waste quantities across factories, components, and root causes to determine the most and least significant drivers of waste generation.
5. To propose a range of targeted interventions for reducing material waste at source in OSC.

1.4.3 Research Questions

Reviewing the literature on construction waste generation in OSC raised several research questions that are planned to be answered in this research. These questions are:

1. How, how much & why material waste is generated at source in OSC?
2. What distinct categories of material waste emerge in OSC?
3. How do automation-related waste generation instances and varying operational priority configurations shape material waste outcomes in OSC?
4. How does material waste vary by factory, component, waste category, and practice?
5. What targeted interventions can be proposed to reduce material waste at source in OSC?

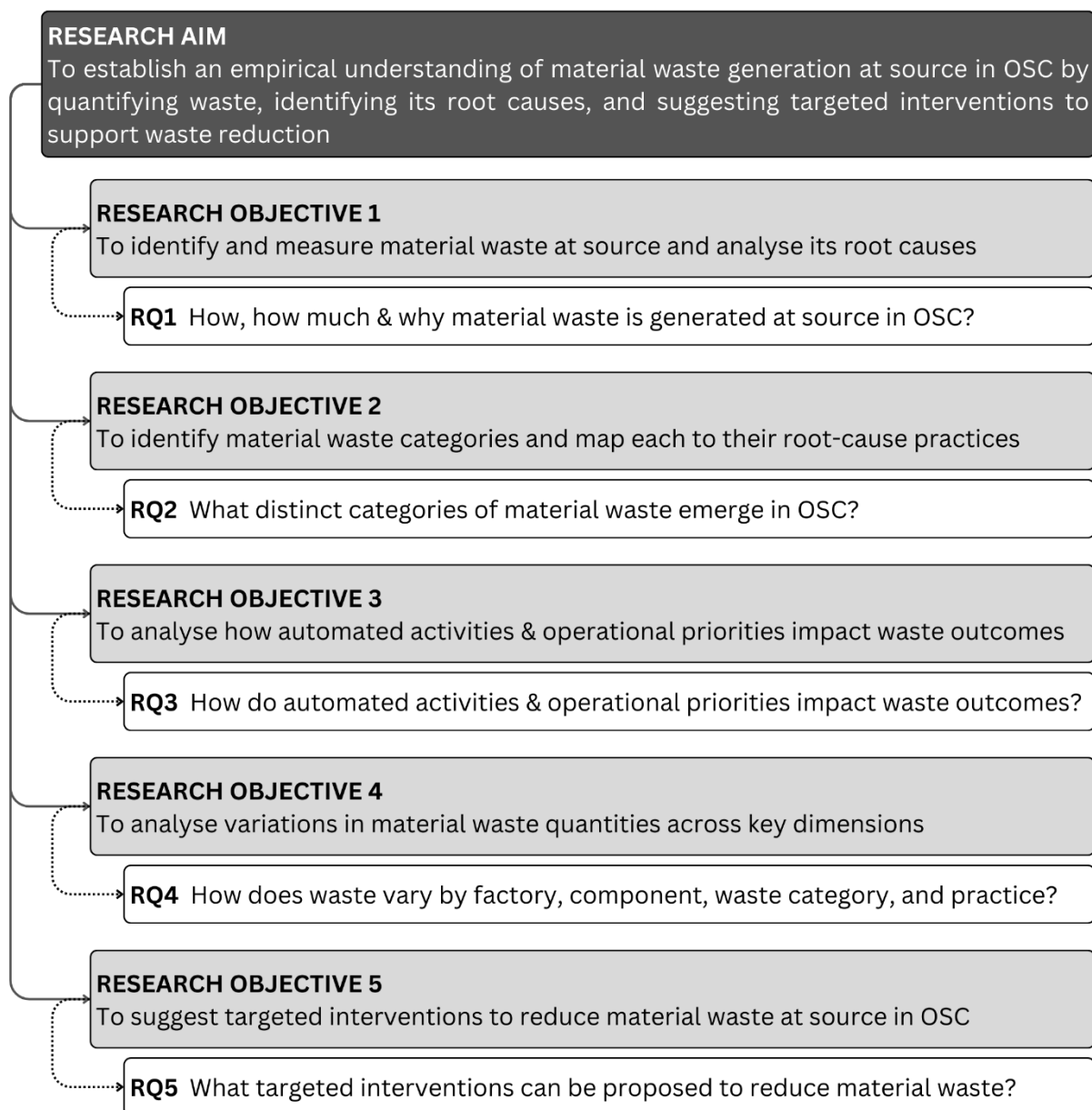


Figure 1.1: Research aim, objectives, and questions

1.5 Research Significance

This study is of both theoretical and practical significance in the context of construction industrialisation and sustainability. OSC is gaining momentum in response to growing need for efficiency, quality, and environmental performance in the construction industry. Although OSC is widely recognised as enabler to material waste reduction, evidence supporting these claims in practice remains anecdotal, lacking empirical support.

This study fills a critical gap in the literature by examining how material waste is generated at source in OSC, exploring its categories, quantities, and root causes. Different from prior studies that tends to generalise waste reduction using generic data, this study takes a fine-grained, source-level perspective in attempt to capture the practical complexity of OSC factories. In doing so, better understanding of material waste generation at operational level can be achieved in the context of OSC, an area remains largely underexplored.

Another key contribution of this study lies in its exploration of the role of automation and competing operational priorities in influencing waste outcomes. Although prior literature has repeatedly argued in favour of automation to reduce construction waste, empirical evidence remains limited. Similarly, the impact of different combinations of competing operational priorities (e.g., production flow, material efficiency) on waste outcomes is rarely explored. Hence, this study provides novel insights into automated technologies and competing priorities, helping to better understand how modern industrialised construction environments contribute to, or mitigate, material waste generation.

In addition, this research sustains methodological challenges that have traditionally limited empirical research in this field. Due to various barriers related to data availability and accessibility, researchers often face significant challenges in conducting detailed analyses of construction waste in OSC. This study, however, benefits from a rare access to multiple OSC factories, adopting a mixed-method approach, including factory observations, design document analysis, and semi-structured interviews. This resulted in a rich dataset capturing waste generation activities with high level of specificity.

Beyond its theoretical contribution, this study also offers practical value through the development of targeted interventions for waste reduction. These interventions can support OSC manufacturers in refining production practices, assist legislators in developing more effective sustainability regulations, and encourage future research to examine their feasibility

and scalability in real-world settings. Overall, this research advances both theory and practice by generating actionable knowledge to reduce waste generation in OSC.

1.6 Scope and Delimitations

This study examines material waste generated within OSC factories, focusing specifically on waste generation at source (i.e., where waste occurs) within component assembly processes (e.g., timber frame assembly). This source-level focus enables a granular understanding of the practices that drive waste and the quantities associated with different assembly activities.

The scope of this study is limited to material waste initially generated during the production process, defined as any material quantity that exceeds the net quantities required by design. This includes all residuals and excess material that are disposed of, recycled, retained in the product, or set aside for potential future reuse. However, materials that are immediately reintegrated into the same product are not accounted for, because this practice is considered in this study as an efficient production practice (i.e., material nesting).

Hence, this study adopts a preventive perspective, accounting for material waste at the point it is initially generated, without deducting quantities that may later be reused or recycled. The purpose of defining these boundaries is to understand and address the root causes of waste generation, rather than evaluate the effectiveness of reuse and recycling practices. Accordingly, the study focuses on quantifying and understanding material waste to propose preventive measures for waste reduction, rather than exploring corrective actions to improve reuse or recycling practices. Figure 1.2 illustrates the research scope.

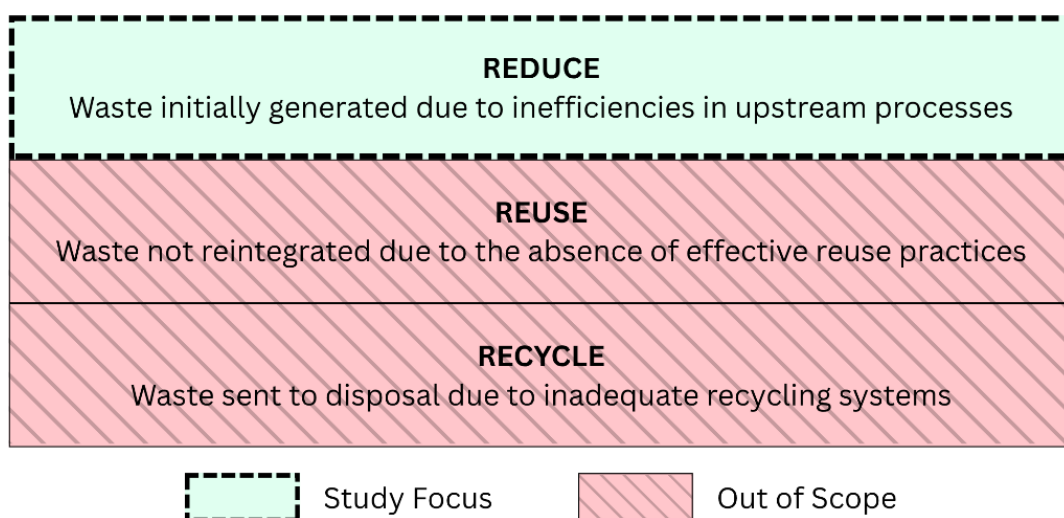


Figure 1.2: Research scope

1.7 Outline Research Methodology

To answer the research questions and address the research aim, this research employs a multiple case study strategy grounded in a pragmatist philosophical stance. A total of four OSC factories were purposively selected to allow rich empirical investigation of material waste generation across different component types and manufacturing settings.

Data were collected using direct factory observations, design document analysis, and semi-structured interviews with design, procurement, and production teams. These multiple sources allowed for triangulation and deeper understanding of waste-generating instances, associated waste quantities, and root causes. Furthermore, follow-up interviews with production managers were conducted to validate the initial findings.

An inductive research approach guided the analysis, facilitating the development of theoretical understandings grounded in empirical evidence. The analysis combined root cause analysis, thematic analysis, descriptive and comparative quantitative techniques, and exploratory causal analysis to identify and map different waste categories, quantify waste rates, and evaluate the influence of automation and operational priorities on waste outcomes. Finally, an interpretive analysis was employed to propose targeted interventions for mitigating different root causes behind material waste generation. A detailed explanation of the research design, data collection procedures, and analysis techniques is provided in Chapter Four.

1.8 Thesis Structure

This study comprises nine chapters. The content of each chapter is briefly outlined below and illustrated in Figure 1.3:

1.8.1 Chapter One

This chapter introduces the research topic by outlining the background, problem statement, barriers to existing research, research aim, objectives and questions, research significance, scope, an overview of the research methodology, and the structure of the thesis. Overall, it sets the scene for conducting the research.

1.8.2 Chapter Two

This chapter reviews lean-based research that seeks to optimise OSC performance. The purpose is to assess whether extant research explains how and why waste is generated. The findings

reveal a fragmented understanding of waste, with several studies prioritising time-related inefficiencies and giving comparatively less attention to material waste.

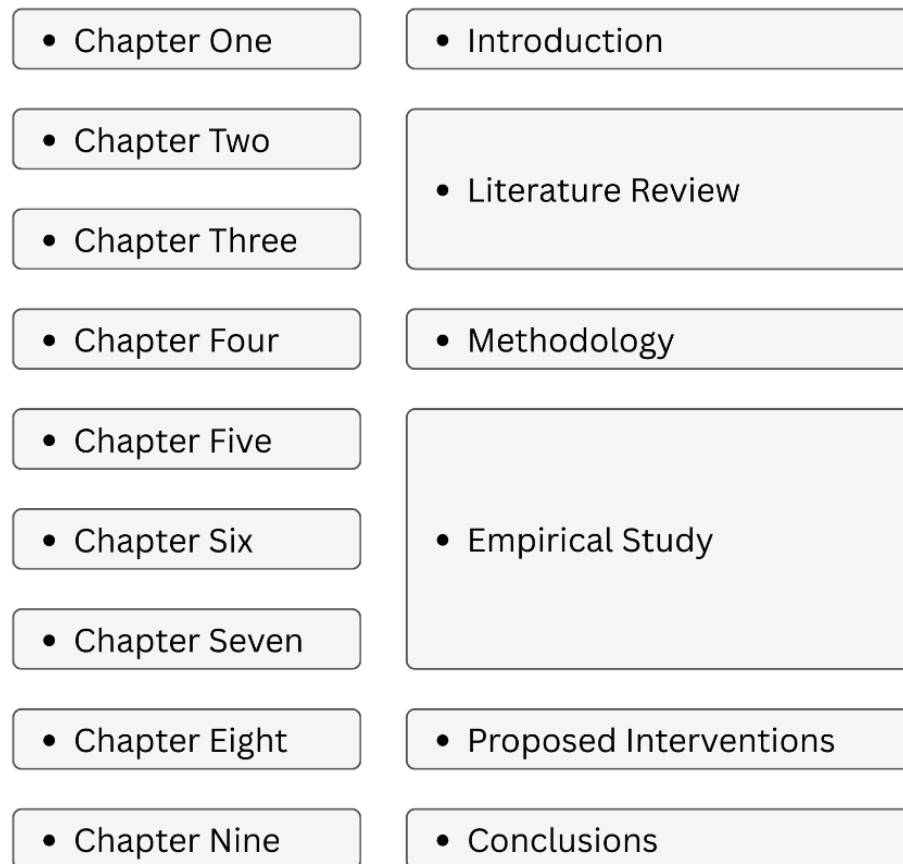


Figure 1.3: Thesis structure

1.8.3 Chapter Three

This chapter builds on the previous chapter by narrowing the focus to material waste research in OSC, assessing how it has been defined, quantified, and addressed. The review highlights limited source-level quantification and understanding of material waste in OSC, revealing the key research gap addressed by this study.

1.8.4 Chapter Four

This chapter introduces the research methodology, outlining the rationale for a multiple case study design. It justifies the selection of four factories, explains data collection methods (observations, documents, and interviews) and outlines the analytical approaches adopted to interpret the data.

1.8.5 Chapter Five

This chapter provides a detailed source-level analysis of waste-generating instances, waste quantities, and their root causes within component assembly processes (e.g., timber frame assembly) across four factories. By producing granular empirical evidence, the chapter supports the development of higher-level findings on the categories, magnitude, and root-cause practices of material waste in OSC.

1.8.6 Chapter Six

This chapter builds on the findings of the previous chapter by employing thematic analysis to identify material waste categories and map them against their root cause practices, providing a systemic understanding of how and why material waste is generated in OSC. It also presents an analysis of the role of automation and competing operational priorities in influencing material waste outcomes.

1.8.7 Chapter Seven

This chapter builds on the findings of Chapters Five and Six by employing comparative quantitative analysis to compare material waste quantities across the four case study factories, the identified waste categories, material characteristics, and root cause practices. The main purpose of this chapter is to develop deeper understanding of material waste variability across different dimensions.

1.8.8 Chapter Eight

Building on the empirically grounded root causes identified in Chapter Six and the waste quantification presented in Chapter Seven, this chapter develops a range of targeted interventions for waste reduction. Informed by lean theory, the proposed interventions balance production flow and material efficiency to support effective implementation in practice.

1.8.9 Chapter Nine

This final chapter synthesises the study's key findings, critically reflects on their implications, and outlines the research's theoretical and practical contributions. The chapter concludes by highlighting the study's original contributions and identifying priorities for further investigation to advance knowledge in the field.

Chapter Two: Lean Uptake in Offsite Construction: Evidence, Limitations, and Research Needs

2.1 Introduction

Lean is a widely acknowledged production philosophy that provides a systematic framework for identifying, analysing, and eliminating waste. This chapter reviews the literature employing lean principles to optimise different aspects of OSC. Its purpose is to assess whether this body of research offers a comprehensive and validated understanding of how and why waste is generated in OSC. The chapter first defines OSC, its categories and stages, and the opportunities and challenges associated with its implementation, before introducing lean theory and framing waste from this perspective. The review indicates a fragmented understanding of waste with many studies propose lean-based interventions to address specific inefficiencies across design, procurement, and production. However, they largely focus on mapping and optimising overall workflows rather than explaining how inefficiencies emerge and propagate through design decisions, procurement constraints, and production practices. In addition, this research has predominantly prioritised time-related inefficiencies, with material waste receiving comparatively less attention. Where lean-based interventions are proposed to mitigate material waste, limited analysis is typically provided on how these interventions can be implemented under real operational conditions. Consequently, holistic evidence explaining how and why material waste is generated in OSC remains limited.

2.2 Offsite Construction

Offsite construction (OSC) is a construction approach in which components (e.g., frames, panels, modules) are manufactured in a controlled environment and then transported to the site for final assembly (Lim *et al.*, 2021). Leveraging its production-like environment, OSC offers a more integrated alternative to the inherently fragmented onsite processes, providing better control over the construction workflow (Yang *et al.*, 2021). Research indicates that OSC can reduce waste by over 50% compared to traditional construction methods (Jaillon *et al.*, 2009). Terms such as modular, prefabricated, panelised, industrialised, and modern methods of construction are often used interchangeably with OSC across the literature (Lawson *et al.*, 2012).

2.2.1 Categorisation

OSC can be categorised according to the level of prefabrication offered under the factory roof. In that respect, earlier categorisation by Gibb (2001) is prevalent in the literature, which includes level 1: components (e.g., staircase, window frames), level 2: two-dimensional assemblies (e.g., wall panels), level 3: volumetric assemblies (e.g., bathrooms, kitchen pods), and level 4: modular building (e.g., whole building) (see Figure 2.1). Other studies (Sierra and Zamora, 2013; Steinhardt *et al.*, 2014)

used a very similar categorisation that starts from components level to fully modular structures. Recent industry' reports (MHCL, 2019) adopted a different methodology, classifying OSC into category 1: 3D structural system (e.g., room structure), category 2: 2D structural system (e.g., bearing wall panels), category 3: structural components (e.g. beams, columns), category 4: structural/non-structural additive manufacturing, and category 5: non-structural assemblies and subassemblies (e.g., bathroom & kitchen assemblies) (see Figure 2.2).

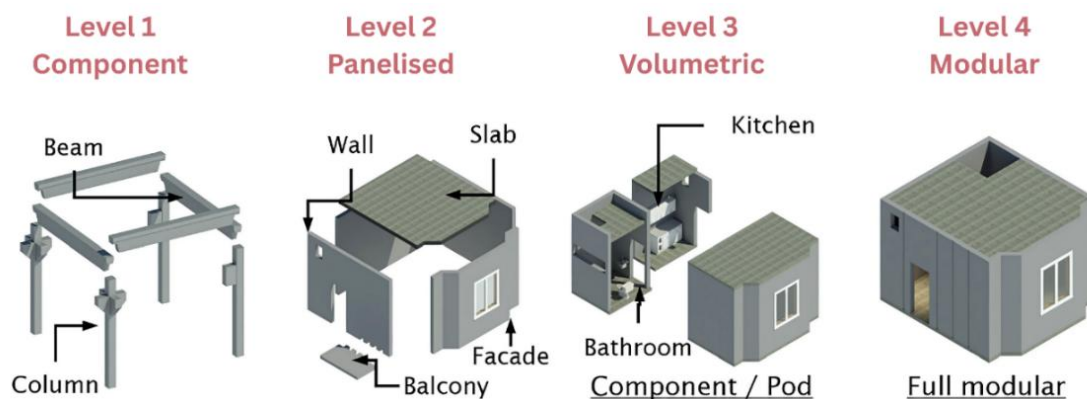


Figure 2.1: Gibb's (2001) prefabrication levels; adapted from (Jaillon and Poon, 2014)

2.2.2 Stages

OSC differs from traditional construction in how each stage is performed. In particular, the controlled environment offered offsite; while requiring additional transportation, it plays a key role in promoting greater certainty in design, procurement, logistics, and construction activities. The following subsections discuss and compare both construction approaches across various stages.

2.2.2.1 Design

In the conventional approach of construction, the design process is widely recognised as sequential and fragmented, with limited cross-disciplinary collaboration, triggering several constructability issues (Bahrami and Zeinali, 2022). This triggers frequent design changes,

which are in turn likely to result in delays and rework. By contrast, the controlled environment in OSC encourages an integrated approach for design where different teams are likely to collaborate to ensure design feasibility for manufacturing and assembly (Gao *et al.*, 2020). BIM is widely employed to promote process integration and collaboration across design, production, and assembly units, reducing potential design conflicts and promoting constructability (Gbadamosi *et al.*, 2019).

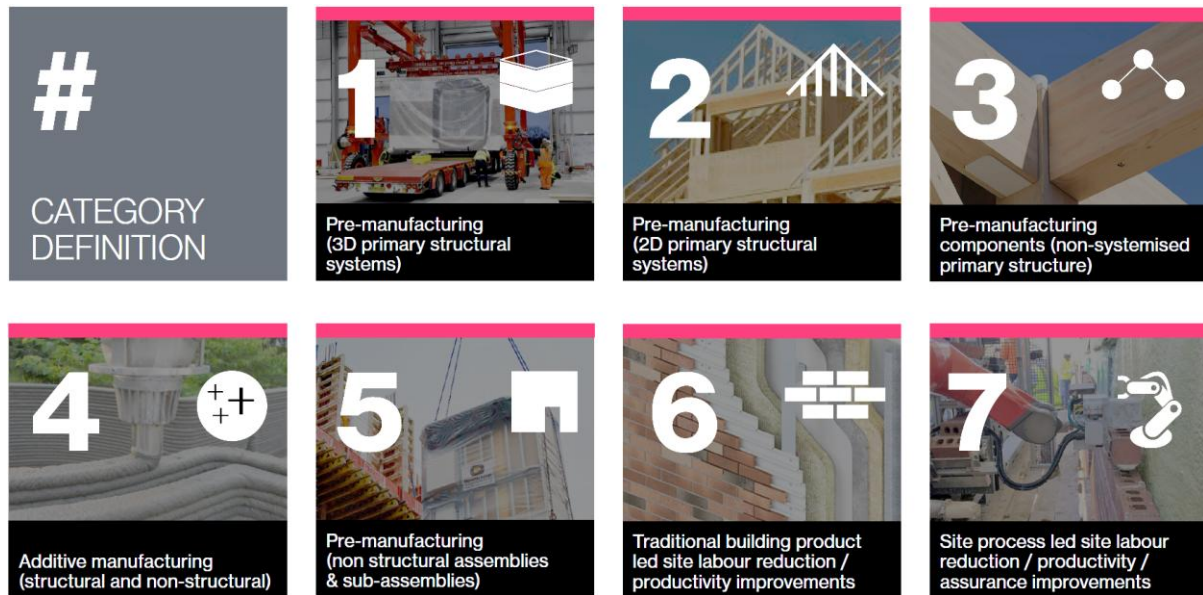


Figure 2.2: Modern methods of construction categorisations based on MHCL (2019)

2.2.2.2 Procurement

Since traditional construction projects are prone to design changes and site uncertainties, material sourcing is typically performed in phases (Nascimento *et al.*, 2017). Although this approach provides immediate flexibility, it is often identified with several inefficiencies, including site congestion, delivery delays, and over-ordering (O'Connor *et al.*, 2015). By contrast, OSC provides higher levels of certainty towards design and prefabrication, encouraging bulk sourcing of materials exactly as required by the production schedule (Gao *et al.*, 2020). Particularly, this level certainly is promoted by the upfront design practice widely seen in OSC, supporting more accurate material planning and procurement (Jaillon *et al.*, 2009).

2.2.2.3 Production

In traditional construction, most of construction activities are implemented onsite, where several uncertainties can impact the process, including bad weather, limited space, and labour shortage (Nazir *et al.*, 2021). In such environment, there is more likelihood of ad-hoc practices,

mistakes, and quality issues (Koskela, 1992). By contrast, in OSC, the traditional construction activities are substituted by production-like activities to produce the required construction component in a controlled factory environment (Liu et al., 2022). In controlled settings, there is more opportunity to adopt standardised practices, automation, and production planning and control (Bataglin *et al.*, 2020).

2.2.2.4 Transportation

In conventional construction projects, there is only one key transportation process required to transport raw materials from suppliers to the site. This process is often characterised by fragmentation and inefficiencies, promoting site congestion, delivery delays, and material damage (O'Connor *et al.*, 2015). By contrast, OSC, although it requires an additional transportation leg to transport prefabricated construction components to the site, the controlled setting is found to promote due planning and control. This includes the coordination of just-in-time logistics activities to ensure delivering the required prefabricated components on time (Bataglin *et al.*, 2020).

2.2.2.5 Onsite Construction

In traditional construction, construction activities are typically implemented onsite using manual labour for extended periods of time. This approach is criticised for being prone to health and safety hazards, climate uncertainties, implementation mistakes, and construction waste generation (Tam and Hao, 2014). By contrast, in OSC, most of the traditional construction activities are implemented offsite, as production activities, and then the ready-to-assemble components are transported to the site for assembly (Lim *et al.*, 2021). This approach promotes clean and fast assembly processes, mitigating safety hazards and promoting production flow (Jaillon and Poon, 2014).

2.2.3 Opportunities

OSC offers a range of opportunities across process, product, organisation, customer, society, and environment (Ayinla *et al.*, 2022). In terms of process, OSC enables more timely logistics (Miles and Whitehouse., 2013), improved standardisation, automation, and economies of scale (Eastman and Sacks, 2008; Pan and Sidwell, 2011; Quale *et al.*, 2012), controlled health and safety environment (Höök and Stehn, 2008; Kolo *et al.*, 2014), and more stable and formalised production system (Pasquire and Connolly, 2002). Heravi and Firoozi (2017) also noted that

OSC facilitates the standardisation of construction processes, which supports continuous improvement and learning from past experiences.

Regarding the product, OSC contributes to improved output quality (Larsson and Simonsson, 2012) and enables the delivery of more affordable, mass-produced building components (Ozaki, 2003). This indicates the potential to shift the construction industry from producing one-off buildings to adopting mass production and mass customisation strategies (Heravi and Firoozi, 2017). For organisations, OSC provides improved frameworks for project management and enhances programme performance overall (Zakaria *et al.*, 2018). From the customer perspective, OSC enables higher satisfaction levels, largely due to its capacity for mass customisation (Cheung *et al.*, 2016).

Finally, social and environmental advantages include improved health and safety conditions (S Liu *et al.*, 2022), and reductions in construction waste (Nahmens and Ikuma, 2012; Mao *et al.*, 2013). However, these benefits are not automatically realised. Without the effective application of efficient manufacturing techniques, OSC risks reproducing the same inefficiencies found in traditional construction, but under a factory roof (Zhang *et al.*, 2020).

2.2.4 Challenges

However, OSC is linked to several challenges in terms of competency, complexity, cost, and logistics. For competency, the literature highlights shortages of skilled labour (Molavi and Barral, 2016) and management knowledge (Yu *et al.*, 2013), impeding efficient uptake of OSC. This is mainly attributed to the traditional one-off craft-based culture still dominating the construction industry (Balkhy *et al.*, 2021). For complexity, production techniques and design variability are underscored as the main sources for complexity in OSC (Zhang *et al.*, 2014). For cost, several aspects are suggested to have cost implications, including the initial cost related to machinery acquisition and factory construction (Luo *et al.*, 2015), extra procurement arrangements (Zhang and Skitmore, 2012), and the additional personnel needed to check, count, label and sort raw materials and produced components (Zhong *et al.*, 2015).

For logistics, three key challenges are identified, including the need for further storage to temporarily stock produced components, transportation for components' delivery to the jobsite, and craning to assemble components on site (Tam *et al.*, 2015). Despite the abovementioned challenges, OSC is increasingly promoted to their long-term economic and environmental benefits (Goh and Goh, 2019).

2.3 Lean Production

OSC is closely associated with manufacturing because offsite methods transfer a significant share of construction activities from the site to factories, where repetitive processes resemble conventional production lines (Gibb, 1999). From manufacturing perspective, lean production is gaining momentum as a consolidated production philosophy that emerged from a range of principles and methods developed extensively in Japan, most notably by Toyota Motor Corporation (Ohno, 1988). This philosophy stresses the removal of waste and the use of minimal resources to deliver customer value (Liker, 2020). It aims to reduce inventories and other forms of waste through small-lot production, reduced set-up times and close collaboration with suppliers (Koskela, 1992). Central to lean are principles such as Just-in-Time (JIT), which seeks to eliminate excess inventories by producing only what is needed, when it is needed, and Total Quality Control (TQC), which focuses on reducing production variability and preventing defects at source through organisation-wide quality assurance mechanisms (Koskela, 1992). As these practices were examined, it became clear that they shared a common conceptual basis, leading Womack et al. (1990) to coin the term ‘Lean Production’ to describe this unified philosophy.

According to Koskela (1992), a central conceptual contribution of lean production is its distinction between conversion and flow activities. Conversion activities are those that directly transform materials or information into something of higher value (e.g., cutting, assembly, or installation). In contrast, flow activities include the actions required to connect conversion activities (e.g., waiting, transporting, inspecting, or storing). Traditional production management, shaped by the mass-production paradigm, focused almost exclusively on conversions and implicitly assumed that all activities added value (Shigeo, 1988). By neglecting flow activities, traditional systems allowed significant inefficiencies to accumulate. These include long waiting times, excessive material handling, unnecessary movement, and other forms of waste that increase cost, extend cycle times, and reduce reliability (Koskela, 1992). Lean production challenges this outdated view by reconceptualising production as a series of interconnected flows between essential conversion stages (Womack and Jones, 2003). This shift brings flow activities to the foreground, enabling them to be measured, managed, and systematically improved. Under the lean approach, the goal is to minimise non-value-adding flow activities, stabilise processes, and optimise the entire value stream rather than individual tasks (Koskela, 1992). This holistic understanding enables organisations to reduce waste, enhance customer value, and deliver more predictable, efficient production systems.

Building on the seminal distinction in lean theory between conversion and flow activities, Koskela (1992) argues that the theoretical understanding of construction remains firmly rooted in a conversion-based view of production. In this paradigm, construction is conceptualised as a series of discrete activities that convert inputs into outputs, with little attention given to the flow processes that connect them. This conversion-centred thinking is evident in traditional cost estimation, sequential project delivery, and Critical Path Method (CPM) planning, all of which overlook the interdependencies and flow activities that occur between tasks, leading to fragmented and poorly coordinated processes (Koskela, 1992). Consequently, traditional construction management is criticised for generating unpredictable flows, expanding non-value-adding activities, and undermining overall production efficiency.

2.3.1 Lean Construction

Lean construction is broadly defined as the extension and adaptation of lean production theory to the construction environment (Lean Construction Institute, 2025). Koskela (2020) explains that lean construction emerged as ‘the counterpart to lean production ... as it has evolved in the context of construction,’ recognising that the unique characteristics of construction, its one-off projects, temporary production systems, and site-based operations, require a tailored theoretical foundation. The lean construction movement therefore seeks to translate the conceptual basis of lean production into principles suitable for construction. Researchers (Lim, 2008; Howell, 1999) hold that lean construction is about reducing waste while maximising customer value.

As a foundational planning and control tool in lean construction, the Last Planner System (LPS) was introduced by Ballard (2000). LPS is set out to promote a collaborative planning environment in which those responsible for executing the work (i.e., the ‘last planners’) actively participate in developing, committing to, and controlling short-term construction plans (Wesz *et al.*, 2013). Traditionally, construction activities have relied on top-down, deterministic planning methods such as CPM, where predictive, activity-based schedules are produced in advance and project success is measured by adherence to those schedules (Ballard, 2020). In contrast, LPS addresses the limitations associated with forecast-driven and rigid planning by promoting a flexible, adaptive, and iterative planning process that continues throughout project delivery. By delegating planning responsibility to the individuals closest to the work, LPS empowers teams to account for real-time project conditions, thereby improving workflow reliability, reducing variability, and enhancing overall production performance.

In LPS, production planning is organised around the Should-Can-Will-Did sequence, a planning logic that translates high-level intentions into reliable, executable tasks (Ballard, 2020). *Should* identifies the activities that ought to be carried out according to the master plan, representing the projected workflow. *Can* filters this list by identifying only tasks that are truly feasible, ensuring that all prerequisites, such as materials, information, and access, are in place to make the work ready. *Will* captures the commitments made by those performing the work, specifying the activities they agree to deliver in the upcoming planning cycle, thus forming the weekly work plan based on actual capacity and current site conditions. Finally, *Did* records what was actually completed, enabling comparison between planned and executed work, measurement of performance, and systematic learning from deviations.

2.3.2 Defining Waste in Construction

Waste is widely recognised as one of the most pressing issues in the construction industry. From lean manufacturing perspective, Ohno (1988) identified seven types of waste as a basis to improve production flow and flow by systematically eliminating non-value-adding activities. However, their adoption in construction is seen problematic due to their manufacturing context and the lack of focus on key construction stages and characteristics.

Ohno (1988) original waste categorisation includes overproduction, waiting, transportation, overprocessing, motion, inventory, and defects (see Figure 2.3). The elimination of these wastes is considered as key driver for cost reduction and improved efficiency. *Overproduction*, often called the ‘mother of all wastes’, refers to producing more than what is needed or earlier than required by customer demand. This type of waste often triggers a cascade of other wastes in a ripple effect (Innella *et al.*, 2019). For example, surplus production output leads to unnecessary transportation, inventory, and inspection efforts. *Waiting* refers to idle time caused by delays such as unbalanced workflows or equipment breakdowns. *Transportation* involves unnecessary movement of materials between process stages or from the factory to the end user. *Overprocessing* arises when more work is done than necessary, such as meeting design specifications that exceed customer requirements. *Motion* waste refers to inefficient worker movements, often caused by poor layout or tool management. *Inventory* waste is the accumulation of raw materials, work-in-progress items, or finished goods awaiting further processing, which ties up resources. *Defects* represent the waste of materials and labour due to errors in production (Liker, 2020).

However, scholars in lean construction have criticised the seven wastes for lacking theoretical justification and empirical ground (Bølviken and Koskela, 2016; Formoso *et al.*, 2020). In construction where the context is highly different with project-based temporary settings, research emphasised that Ohno taxonomy of waste is less likely to capture the complexity of waste (Formoso *et al.*, 2020).



Figure 2.3: Waste categories in lean manufacturing (Sarhan, 2015)

In response, Koskela (2004) identified construction specific waste called ‘making do’ defined as the initiation of tasks with missing or incomplete inputs, often leading to downstream issues such as reduced quality and compromised safety. Similarly, Womack and Jones (2003) introduced the concept of misaligned design, which refers to design outputs that fail to meet customer requirements. These theoretical developments highlight the need to understand waste not only through the classic definitions of the seven lean wastes, but also in relation to specific contextual characteristics (Formoso *et al.*, 2020).

Other studies highlight the interconnected nature of waste in construction, where one form of waste often leads to another, emphasising that waste rarely occurs in isolation (Bølviken and Koskela, 2016; Formoso *et al.*, 2020). Building on Ohno’s (1988) distinction between primary and secondary waste, Formoso and colleagues (Formoso *et al.*, 2002; Formoso *et al.*, 2017; Formoso *et al.*, 2020) advance the concept of waste propagation, viewing waste not as a set of isolated events but as a network of interrelated inefficiencies connected through cause-and-effect relationships. The authors classify waste into three hierarchical levels: 1) Terminal Waste, which refers to the observable and measurable consequences of wasteful processes,

such as waiting and material loss; 2) Core Waste, which acts both as a waste in itself and as a cause of terminal waste, often resulting from upstream inefficiencies; and 3) Lead Waste, a dominant form of core waste that acts as a root cause, prompting both core and terminal waste types and causing a substantial negative impact on the production system.

In this context, (Viana *et al.*, 2012; Formoso *et al.*, 2020) argue that material waste is frequently treated as a terminal outcome rather than as a symptom of upstream inefficiencies. They also note that the literature on material waste is characterised by inconsistent definitions and measurement approaches, which limits comparability across studies. In addition, the authors recognise that some studies define material waste as physical site debris hauled for disposal, whereas others employed lean construction to conceptualise it as the use of resources beyond what is necessary to deliver customer value. Particularly, the latter body of research (Bølviken *et al.*, 2014; Formoso *et al.*, 2017) has attempted to model material waste within cause-effect networks as part of the relationship between lead and terminal waste. However, Formoso *et al.* (2020) argue that this research remains limited in scope and requires further refinement and empirical evidence to clarify different causal relationships.

2.4 Lean Uptake in Offsite Construction

Several studies employed lean thinking to analyse and improve OSC processes, using different tools and technologies. These studies can be categorised into design, production, and cross-stage integration practices reviewed in the following subsections:

2.4.1 Design Practices

This body of research focused on the development of tools, platforms, and methods to boost design efficiency by facilitating modularisation, standardisation, and mass customisation in OSC. The major lean tools underpinning this body of research are standardisation, pull-based design, and set-based design. *Standardisation* refers to the intentional repetition of product or process design to enhance production flow (Liker, 2020), improve performance (Nahmens and Mullens, 2011), and reduce uncertainty (Innella *et al.*, 2019). *Pull-based design* seeks to pull necessary design input from downstream processes to enable more reliable design detailing (Ballard, 1999a; Hamzeh *et al.*, 2009). Finally, *set-based design* involves identifying and exploring different design alternatives early in the process and then narrowing down the options based on their merits to balance competing constraints (Liker, 2020; Ward *et al.*, 2021). These studies then can be categorised into three subcategories as follows:

2.4.1.1 Design Modularisation & Standardisation

This body of research focused on how design modularity can enhance the potential of OSC. Building modularisation is defined as the process of design reconfiguration into smaller design units called modules (Mohamad *et al.*, 2013). To realise the full potentials of modularisation, module standardisation also needs to be adopted to unleash the powers of mass production (Choi *et al.*, 2020). The results of this literature emphasise early module-design definition across the building fabric to assist efficient standardisation (Mohamad *et al.*, 2013), functional compatibility and integration (Mohamad *et al.*, 2014), economic benefits through design reuse, schedule fast-tracking, parallel engineering, experience accumulation, materials optimisation (O'Connor *et al.*, 2015), improvements in cost, schedule, and quality comparing to non-modularised designs (Økland *et al.*, 2017), shortened lead times promoted by timely planning and assembly processes (Økland *et al.*, 2018), advanced techniques and technologies encouraging design standardisation and modularisation (Choi *et al.*, 2020), and higher levels of design standardisation to enhance design and production efficiency (Zhang *et al.*, 2022). In comparison, only few studies stressed wider social and environmental implications, emphasising the need to quantify the broader value of modularisation in a whole life cycle logic (Parrish, 2012), and to overcome barriers in the face of a modular circle economy, where building modules are repaired, reused, and recycled to limit the environmental impact (Mignacca and Locatelli, 2021).

While this literature has predominantly aimed to demonstrate the benefits of design modularisation and standardisation, it remains limited in defining the direct impact of these improvements on material waste generation. Although these studies targeted improvements in areas such as lead times (Økland *et al.*, 2018), cost (Økland *et al.*, 2017), and material utilisation (O'Connor *et al.*, 2015), they do not provide dedicated analysis of how and why material waste can be avoided by design in OSC.

2.4.1.2 Design for Manufacture & Assembly

This body of research focused on employing design for manufacture & assembly (DfMA) principles mainly to develop the design tools necessary to facilitate modules production and assembly. DfMA is defined as a lean-inspired design philosophy aimed at product design simplification and integration with subsequent processes to enhance manufacturability and constructability (Boothroyd *et al.*, 2010). This design principle is linked to several lean concepts, including standardisation (Gao *et al.*, 2020), pull system (Ng and Hall, 2019), waste

reduction (Gbadamosi *et al.*, 2019) and flow (Koskela, 2000). Hence, DfMA goes hand to hand with lean objectives with shared focus on process waste reduction to generate value (Gbadamosi *et al.*, 2019). These studies include Leminen *et al.* (2013) work who developed an assessment and comparison DfMA tool, optimising different designs based on the level of modularity, standardisation, producibility, and assemblability. Relatedly, Gbadamosi *et al.* (2019) proposes a BIM-based design assessment tool using literature review and experts' priority voting. The results showed that adopting DfMA principles improved constructability assessment and reduced inefficiencies in material and labour utilisation. Antoniou and Marinelli (2020) devised a standardised matrix for bridge component design based on data from a low construction industrialisation country; the authors demonstrated significant mass production benefits and highlighted the crucial role of standardisation in realising DfMA objectives. In a related vein, He *et al.* (2021) developed a BIM extension to enhance design modularisation based on DfMA principles, validating the tool using 3D printed prototypes. Moreover, Bao *et al.* (2022) investigated several OSC practices in interior design and construction using DfMA and lean principles, identifying several enablers to more efficient OSC, including early design collaboration, standardised modules, and light material adoption. However, while this research employed DfMA to simplify product design and integrate it with downstream production and assembly processes, it does not provide further analysis on how and why DfMA principles can reduce material waste in OSC.

2.4.1.3 Design Planning & Monitoring

This body of research focused on the planning and monitoring of OSC design process using key lean principles, including pull-based system and visual management through the Last Planner System (LPS). LPS is a collaborative production planning and control tool emphasises workflow reliability by empowering those doing the job (i.e., the last planners) to plan for the next task in a pull-based approach using simple visual signs (Ballard, 1999a). This includes the work of Wesz *et al.* (2018) who employed LPS to develop a design planning and monitoring model, offering significant benefits in shielding design variability, promoting collaboration and transparency, and offering learning opportunities. While this study provides valuable insights into applying visual management and look-ahead planning in design, analysis of the associated design inefficiencies and their impact on material waste generation was limited.

2.4.2 Production Practices

This body of research employed lean principles in the production process in attempt to improve cycle times and reduce process waste. *VSM* is a key lean tool adopted across this body of research to implement process improvement. It involves mapping process activities and classifying them into three categories: value adding, non-value adding, and necessary non-value adding activities (Nikakhtar *et al.*, 2015). Once mapped and defined, non-value adding activities (i.e., waste) can be excluded to enhance process flow (Innella *et al.*, 2019). Other lean principles used across this literature include *JIT*, to reduce waste by producing only what is needed when needed (Goh and Goh, 2019), and *visual management*, to employed clear and efficient visual signs to promote process flow and transparency (Liker, 2020).

2.4.2.1 Production Planning

These studies form a major portion of this research category, where process simulation is widely adopted to virtually examine the feasibility of potential lean improvements before implementing any changes. The results show significant improvements in production flow (Darwish *et al.*, 2020; Sahir *et al.*, 2024; Yu *et al.*, 2013), decision making (Jarkko *et al.*, 2013), labour allocation (Moghadam and Al-Hussein, 2013; Goh and Goh, 2019), lead times (El Sakka *et al.*, 2016; Ayinla *et al.*, 2022; Noueihed and Hamzeh, 2024), and cost efficiency (Heravi and Firoozi, 2017; Brown *et al.*, 2019; Laika *et al.*, 2022; Zheng *et al.*, 2024; Ayinla *et al.*, 2025). Hence, these studies have primarily quantified process improvements in economic terms (e.g., cost, production flow, time). In comparison, only few studies measured process improvements in environmental and social demonstrating reductions in material waste, energy consumption (Nahmens and Ikuma, 2012; Xie *et al.*, 2018), and safety hazards (B Barkokebas *et al.*, 2021).

While VSM is increasingly employed in OSC research, most research adopts it to map and optimise high level production flow with primary focus on time-related indicators (e.g., cycle time, waiting time). By contrast, studies that use VSM to improve material efficiency remain scarce.

2.4.2.2 Production Planning & Monitoring

These studies proposed a range of production planning and monitoring models, based on JIT and visual management principles. The core value of these models is the synchronised production simulation that interactively identifies potential process improvements. Using continuous event simulation, (Afifi *et al.*, 2016; Afifi *et al.*, 2022) simulated the production

process, applied lean improvements, and realised enhanced production flow. Relatedly, Meng Wang et al. (2020) BIM with RFID to visualise and track production activities in real-time, highlighting commitment to JIT production, reduction in cost, and improvement in production efficiency.

In addition, Sahir et al. (2024) augmented the application of the lean tool of VSM with internet of things (IoT) sensors and artificial intelligence (AI) to monitor production flow. The pilot testing of the model provided deeper understanding on how real time tracking of labour and materials can improve overall production flow and promote material efficiency. Similarly, Barkokebas et al. (2023) employed real time sensor input along with BIM and machine learning to support lean implementation. The study included testing a range of lean interventions recommended by experts, promoting data-backed decision making and improvements. Relatedly, Peiris et al. (2023) developed an integrated platform for production planning and control accessible by mobile phones to provide real time tracking of key indicators across the production process. Guided by lean principles of visual management and pull-based approach, the platform provided better visibility of inefficiencies and timely data sharing among project teams. However, despite the valuable proposals and experimentation with various lean-based technologies adopted across this literature, their impact on material waste generation remains unclear.

2.4.2.3 Production Visualisation

This body of research aimed at proposing efficient models to visualise the production process and so offering better opportunities to enhance production performance. Visual management is the major lean principle used in this literature to offer transparent and efficient process visualisations (Liker, 2020). Using BIM and process simulation, Moghadam et al. (2014) developed an interactive model offering synchronised production information in design, schedule, and resources. Relatedly, Arashpour et al. (2015) proposed a production tracking model based on real-time process simulation, underscoring the practical value of the model in detecting process flaws for the short-term efficiency and in adjusting production parameters for long-term efficiency. In addition, McHugh et al. (2019) employed BIM and LPS to model the production process, stressing the value of the model in visualising production plans and performance and supporting continuous process improvements.

Despite the valuable focus of these studies on employing visual management to enhance production visibility, there is only limited analysis of the core issues addressed through

promoting visibility. Only Arashpour et al. (2015) proposed a diagnostic model to identify performance flaws, yet the study remains limited on how it addresses these flaws and measures improvements.

2.4.3 Cross-process Integration

These studies focused on integrating different OSC processes by establishing planned flow of information, materials, and components. The main lean principles used for this purpose are *JIT*, to pull only required resources from former processes just when needed, and *visual management*, to offer transparent and efficient process visualisations. Most of these studies focused on integrating offsite with onsite operations. This category can be explained in the below sub-categories:

2.4.3.1 Cross Process Planning & Monitoring

This body of research proposed several models for cross-process planning and monitoring, integrating different processes including production with assembly and design with procurement. For production-assembly, several studies adopted BIM and LPS to develop interactive process visualisations by linking 3D designs to schedules. The results demonstrated optimised pull-based assembly process (Viana *et al.*, 2013), improved participation and collaboration among involved parties (Viana *et al.*, 2014; Bortolini *et al.*, 2015), enhanced process reliability and transparency (Bataglin *et al.*, 2017), better potentials to mitigate project uncertainty (Bortolini *et al.*, 2019), improved process consistency and production flow (Bataglin *et al.*, 2020), and reduced delivery time and project cost (Salama *et al.*, 2021). For design-procurement process integration, BIM as a central product information and visualisation repository is linked to the procurement database to develop an efficient e-commerce platform (He *et al.*, 2018), and reduce cycle times for procurement and biddings processes (B. Barkokebas *et al.*, 2021).

While these studies highlight the benefits of cross-process integration, such as improved collaboration, transparency, and reduced lead times, there is limited analysis of how such integration can also promote material efficiency in OSC. Although lean principles and BIM were employed to link production with assembly and design with procurement, focused analysis on how these integrations contribute to material savings remains limited.

2.4.3.2 Cross Process Control (Intelligence)

These studies employed optimisation methods to model several of production versus assembly process variables aiming at more JIT operations. This includes the use of constraints programming optimisation to minimise components waiting time at the storage area and improve on-time deliveries to the site (Liu and Lu, 2017), the adoption of mixed integer optimisation to prioritise JIT logistics between the factory, storing yard, and site (Hsu *et al.*, 2017), the use of swarm optimisation to improve the collective selection of modules supplier, planning of modules delivery, and organisation of site layout (Zhang and Yu, 2020), the use of integer programming to device JIT product delivery schedules at lower cost (Wang *et al.*, 2024), the use of mathematical optimisation to coordinate offsite manufacturing with onsite assembly and reduce waiting time and storage requirements (Jaskowski *et al.*, 2024), and the development of an automated component delivery system that integrates design, scheduling, and logistics data to minimise cost, emissions, and site disruptions (Zhang and Zhang, 2024).

While this body of research employed optimisation models in conjunction with the JIT principle to enhance logistics coordination between offsite production and onsite assembly, the primary focus has been on time and cost indicators. Although a few studies (Zhang and Zhang, 2024) considered environmental aspects such as carbon emissions and site pollution, there is limited analysis of how these optimisation models can contribute to reducing associated material waste generation.

2.4.3.3 Cross Process Monitoring

These studies used BIM to enhance offsite/onsite visual management, providing synchronised progress-visualisations. Ezzeddine and García de Soto (2021) integrated BIM with game engine to develop a central simulation platform where project participants can efficiently monitor design, production, and assembly processes. Relatedly, Ma and Qiao (2021) linked BIM to a set of tracking sensors and devices to provide real-time production and assembly tracking, offering significant time reductions.

However, while these studies employed BIM and visual management to enhance real-time visibility in OSC, their focus was primarily on time savings, offering limited insight into how these tools can contribute to reducing material waste. These studies aimed process tracking and monitoring with no planning intent. So, they should be distinguished from the studies discussed in *cross process planning and monitoring*.

2.4.3.4 Cross Process Planning

This body of knowledge focused on the planning for integrated offsite versus onsite processes aiming at realising JIT logistics. Mostafa et al. (2014) proposed a range of supply chain delivery methods that integrate production with assembly based on requested customisation level. Relatedly, Xiong et al. (2018) used Process Specification Language to integrate process information in different software used in design, production, and assembly processes, demonstrating enhanced cross-process flow. Heravi et al. (2020) several lean-based cross process improvements employed LCA and DES to demonstrate favourable reductions in carbon emissions. However, while these studies demonstrate how JIT can be applied to enhance cross-process planning and achieve improvements in logistics time and emissions, they offer limited analysis of how it can also promote material efficiency.

2.5 Summary

This chapter reviewed the lean-focused OSC research to evaluate whether it provides a comprehensive and validated understanding of how and why waste is generated across design, procurement, and production. After outlining OSC categories, stages, and implementation challenges, the chapter introduced lean theory as a lens for interpreting waste and improvement efforts in OSC. The review shows that lean uptake has produced a wide range of tools and interventions, but the resulting evidence remains fragmented, often addressing isolated inefficiencies rather than offering an integrated explanation of waste generation mechanisms. Most studies prioritise workflow mapping and flow-oriented optimisation, with limited attention to how waste emerges and propagates through specific design decisions, procurement constraints, and production practices. In addition, the literature has largely concentrated on time-related inefficiencies, while material waste is comparatively under-examined and rarely analysed with sufficient operational detail to support implementation in real factory conditions. Consequently, robust explanations of material waste generation in OSC remain limited. The next chapter therefore narrows the focus to review OSC studies that explicitly investigate material waste, its drivers, and mitigation strategies.

Chapter Three: Construction Waste in Offsite Construction: Definitions, Evidence, and Gaps

3.1 Introduction

In the previous chapter, lean-based research in OSC was reviewed to examine whether the existing lean literature provides a comprehensive understanding of how and why waste is generated in OSC. The findings indicate a fragmented understanding of waste, with several studies prioritising time-related inefficiencies and giving comparatively less attention to material waste. This chapter narrows the focus to material waste, aiming to assess how it is defined, quantified, and addressed in the OSC literature. The review begins by defining material waste in construction, analysing its sources across different construction stages, and evaluating waste quantification methods. By reviewing studies that quantify, assume, or address material waste in OSC, the chapter identifies a significant research gap: the lack of detailed, source-level quantification and explanation of material waste generation in OSC. This limitation constrains understanding of how, how much, and why material waste is generated in practice, and in turn constrains efforts to develop effective, targeted interventions. Therefore, empirical investigation is required to explore material waste generation at source in OSC.

3.2 Defining Construction Waste

Construction waste can be defined as the residual materials designated for disposal, primarily generated throughout construction, renovation, maintenance, and demolition activities of buildings and infrastructure (Mahamid and Elbadawi, 2014). It is an umbrella term for three key material waste categories in the construction industry, including construction stage waste, renovation & maintenance waste, and demolition waste (Luangcharoenrat *et al.*, 2019). Given the growing uptake of building offsite, research also classifies construction stage waste into onsite and offsite (Yang *et al.*, 2024). According to this literature, onsite construction waste refers to the material waste generated in the construction site, while offsite construction waste refers to the material waste generated at OSC facilities (also known as material waste). Figure 3.1 summarises construction waste breakdown, with offsite construction waste highlighted in light red.

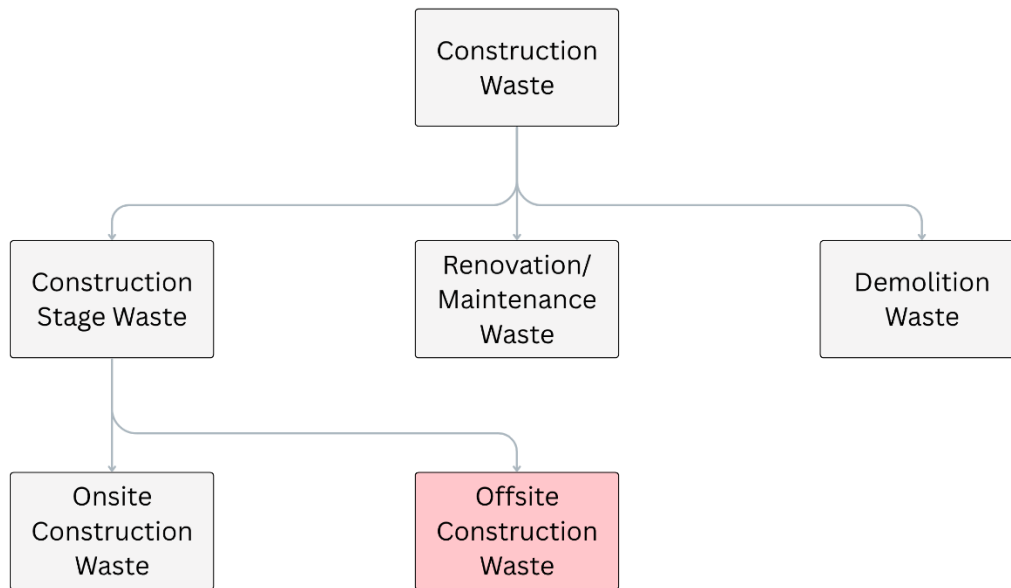


Figure 3.1: Construction waste breakdown

Typically, construction waste encompasses several material residuals, including concrete, plasterboard, timber, glass, packaging, brick, metal, plastic and toxic materials like asbestos and lead-based coatings (Bossink and Brouwers, 1996). It can be classified into inert (i.e., non-biodegradable) and non-inert (i.e., biodegradable) materials, with inert waste is mostly recyclable, while non-inert waste requires special disposal procedures (Lu *et al.*, 2017).

For construction stage waste, the literature is significantly dominated by traditional site-based construction assumptions. That is, several studies (Gavilan and Bernold, 1994; Luangcharoenrat *et al.*, 2019; Vilventhan *et al.*, 2019) analyse material waste in construction according to the traditional construction processes, including design, procurement, logistics, and onsite construction, overlooking potential construction activities conducted offsite. Hence, the literature has mostly based its assumptions on traditional construction paradigms to understand how material waste is generated in construction. This prevailing understanding of construction waste can be summarised in a process-wise manner in the following subsections:

3.2.1 Design

Research shows that the design process is a major source of material waste in construction. Luangcharoenrat *et al.* (2019) employed literature review to identify 28 causes for material waste and through a structured questionnaire, the authors determined that design causes are among the major contributors. One key source is the *bespoke design*, where designers do not consider standard material sizes in design, resulting in the difference between designed versus used material sizes being discarded (Osmani *et al.*, 2008). Another key source is the design

change orders which are mainly caused by *lack of design integration and collaboration*, stimulating inadequate constructability input and frequent design changes to suit available materials, skills, and equipment (Nascimento *et al.*, 2017).

3.2.2 Procurement

This category involves materials ordering inefficiencies mainly caused by disintegrated procurement process, that is based on forecast rather than the actual demand. *Forecast-based ordering* involves ordering materials based on rough estimates, rather than the accurate need of the construction activities, leading to consistent materials overordering (Meng Wang *et al.*, 2020). Among other reasons, Kaliannan *et al.* (2018) identify materials overordering as a major construction waste source, promoting the accumulation of surplus materials, that if not managed well, they could become obsolete or useless.

3.2.3 Logistics

This category includes the inefficiencies related to the transportation and storage of construction materials. Poor handling and storage are defined as major sources of construction waste generation, promoting materials loss and deterioration (Kaliannan *et al.*, 2018). The ultimate cause for such inefficiencies is the *ad hoc logistics* practices adopted, which often lack standardised guidelines to avoid operational disruptions (Xu *et al.*, 2018). Dubois *et al.* (2019) propose a range of standardised logistics configurations with the aim of enhancing logistics efficiency, demonstrating potential savings in materials waste by minimising the need for materials storage and movement.

3.2.4 Construction

Several inefficiencies can be identified to generate material waste throughout different construction activities. Poor implementation and accidents are identified as key sources, promoted by unskilled labour, poor working conditions, and inadequate tools (Vilventhan *et al.*, 2019). Other research identifies material offcut as key source for waste (Adewuyi and Otali, 2013), which several studies link it to the level of standardisation and automation adopted (Liu *et al.*, 2019). Thus, the key source promoting poor implementation and excessive materials offcutting can be attributed to the *ad hoc implementation* practices adopted, that are highly unstable, preventing process improvement and learning cycles (O'Connor *et al.*, 2015).

3.3 Quantifying Construction Waste

The literature quantifying construction waste has adopted a range of prediction and estimation methods mostly based on traditional site-based construction assumptions, ignoring that material waste can also be generated offsite. Critical review of these methods is presented in the following subsections:

3.3.1 Construction Waste Prediction Models

This category of waste quantification literature has adopted predictive models employing historical waste data to predict construction waste in other projects using a range of predictive variables (e.g., number of floors, project scale). The main value of these models is to inform wider waste management strategies and decision making on the current or future waste generation patterns (Li *et al.*, 2016). Hence, these models can only provide gross predictions of construction waste that cannot be used to identify waste streams or root causes in practice. In addition, they do not consider process level attributes that can shape waste generation as predictive variables (e.g., construction practices, equipment efficiency). Growing research highlights the significant advances in modern construction practices and their capability to reduce construction waste (Orlowski, 2020). This category includes three key types of models, including waste generation rate (WGR), function driven models (FDM), and data driven models (DDM).

3.3.1.1 Waste Generation Rate (WGR)

This method involves quantifying the average total mass or volume of construction waste per unit area of buildings that share common attributes (e.g., region, usage, scale) (Tong *et al.*, 2023). These rates are then generalised to predict construction waste in buildings that share similar characteristics to those initially used to determine the waste rate. Several studies were conducted to benchmark construction waste rate and inform waste management strategies in different regions. However, the proposed waste rates in this literature are based on broad assumptions, such as newly constructed residential buildings in China (Qiankun Wang *et al.*, 2020), large- and small-scale concrete structure buildings in Vietnam (Hoang *et al.*, 2020), and high-rise concrete buildings in Malaysia (Mah *et al.*, 2016). Particularly, they lack thorough identification of project or process level characteristics, compromising their generalisability. In addition, this method typically provides information about the total waste generated by a building and does not provide accurate breakdown calculation of waste composition (Bakshan *et al.*, 2015).

3.3.1.2 Function-driven Models (FDM)

Different from WGR, the literature adopting FDM tests the capability of a range of independent variables in predicting construction waste generation, employing predefined mathematical formulas, such as multiple regression, fuzzy set theory, and S-curve (Tong *et al.*, 2023). Several variables being examined in the literature, including the number of floors (Parisi Kern *et al.*, 2015; Maués *et al.*, 2020), building stage (Hu *et al.*, 2021), project duration (Domingo and Batty, 2021), and contract type (Lu *et al.*, 2016). Once a meaningful relationship between the independent variables and waste generation is statistically confirmed, the proposed mathematical model can then be used to predict construction waste in other projects using different values of the independent variables (Lindhard *et al.*, 2023). Despite the power of these models in defining a range of independent variables influencing construction waste generation, they ignore the fact that variables can interact with each other to produce synergistic impact on waste generation. That is, this literature is criticised for oversimplification by subjectively focusing on particular linear relationships while ignoring other potential complex non-linear relationships (Domingo *et al.*, 2024). In addition, only project level variables (e.g., number of floors, duration) were examined in the literature, whereas process level variables that can directly shape construction waste generation have not been explored.

3.3.1.3 Data-driven Models (DDM)

The literature based on DDMs marks an improvement over FDMs by allowing historical data of construction waste generation to define a wide range of complex non-linear mathematical relationships. Several predictive models employed across the literature to capture the underlying patterns of construction waste data, including K-means clustering algorithm (Zhao *et al.*, 2022; Gulghane *et al.*, 2024), neural networks (Nagalli, 2021; Guerra *et al.*, 2024), decision tree (Weisheng Lu *et al.*, 2021; Gulghane *et al.*, 2024), and time-series forecasting (Huang *et al.*, 2020; Hu *et al.*, 2023). Particularly, these models learn from historical data to help predict waste generation rates of future or unseen projects. However, the quality of prediction is highly dependent on the range of predictive variables defined as part of the historical data (Hu *et al.*, 2021). Extant literature adopts predictive variables mostly focused on project characteristics, such as building attributes (Maués *et al.*, 2020), total floor area (Nagalli, 2021), and construction stages (Gulghane *et al.*, 2023). Research focusing on practice-level characteristics as predictive variables are unknown. Another key limitation of DDMs is their significant reliance on the quality and quantity of the historical data used to train the mathematical formulas. Particularly, these models require massive datasets with both process

and project level characteristics to enhance the quality of prediction, which otherwise becomes prone to overfitting. In other words, to be affected by the noise of the input data rather their meaningful patterns (Lu *et al.*, 2016).

3.3.2 Construction Waste Estimation Models

This category of waste quantification models relies on collecting material-wise waste generation data to calculate the total construction waste of the case building under investigation. The main value of these models is to help understanding the efficiency of project resource planning and waste management (Wu *et al.*, 2014). Although material-wise waste quantification is labour intensive and time consuming, it facilitates accurate estimation of the total environmental impact of construction waste. However, these models also lack process level attributes identification (e.g., construction site practices, equipment efficiency) that can shape waste generation as predictive variables. This category of quantification models consists of two key types of models, including classification system accumulation (CSA) and material balance approach (MBA).

3.3.2.1 Classification System Accumulation (CSA)

This method employs the project bill of quantity (BoQ) to develop a waste classification system that codes, estimates, and accumulates material level construction waste to calculate project level waste rate (Tong *et al.*, 2023). For example, Solís-Guzmán *et al.* (2009) introduced the waste management procedure that inspired waste management policy in Spain in 2008. The model adapts the building BoQ as a classification system for waste identification and accumulation and assumes waste rates for each material based on the Andalusian Construction Costs Database. Similarly, Lam *et al.* (2019) proposed practical guidelines for construction waste estimation based on BoQ classification, adopting waste rates from secondary sources and expert judgement to estimate waste at material level. Thanks to the BoQ-based material level waste classification approach, this method facilitates conducting environmental assessment for construction waste. However, the accuracy of this method is highly compromised by the quality of the adopted material level waste rates that are based on non-primary sources. Particularly, the lack of accurate material waste rates that reflect the actual project conditions (e.g., construction practices). Hence, despite the usefulness of this method in providing material level waste quantification, its accuracy is questioned by the lack of reliable material-wise waste rate data.

3.3.2.2 Material Balance Approach (MBA)

Improving from CSA literature, the literature adopting MBA (Li *et al.*, 2013; Bakshan *et al.*, 2015; Guerra *et al.*, 2019; Bakchan *et al.*, 2019; Shahid *et al.*, 2023) employs primary data to estimate material-wise construction waste rates. However, the data does not include direct measurement, such as site weighting or truckload counting, but rather indirect measurement using material ordering records and BoQ of the case building. To calculate material-wise waste rate, the difference between the quantities of the purchased construction materials to construct a building, and the final quantities of materials actually incorporated to that building is determined (Bakshan *et al.*, 2015). One limitation in this method is its consideration to everything not embedded in the final building fabric as construction waste (Bakchan *et al.*, 2019), overlooking the potential that excess materials can be used in other sites (Viswalekshmi and Bendi, 2024). Shahid *et al.* (2023) overcome this limitation by further subtracting excess inventory and used material in the building structure from the total procurement order of each material.

3.4 Construction Waste in OSC: Measurement, Assumptions & Mitigation

OSC, which involves producing required construction products in a controlled factory environment, is largely understood as a powerful and promising construction approach to reduce construction waste (Gibb, 2001). This is facilitated by the advantage of conducting the work in a factory setting, enabling more efficient material planning and utilisation (Lawson *et al.*, 2012). Particularly, the controlled setting is linked to improved design standardisation, manufacturing precision, and process planning and control (Assaad *et al.*, 2023). Collectively, these practices are likely to improve material efficiency and reduce construction waste generation. Research (Jaillon and Poon, 2010; Yu *et al.*, 2021) shows that OSC can bring significant 50-60% construction waste savings onsite as compared to traditional construction. The following subsections review OSC research quantifying, assuming or addressing construction waste in their scope, primarily to identify research gaps. While the first three subsections review key literature categories, the last subsection provides a reflection on the identified research gaps, setting the scene for the empirical exploration presented in the following chapters.

3.4.1 Construction Waste Quantification in OSC

OSC is increasingly praised for its potential to significantly reduce construction waste. Several studies have attempted to quantify waste reductions achieved by OSC compared to traditional

site-based construction. However, various limitations in the existing literature raise questions about the applicability and generalisability of their findings (see Table 3.1). These limitations are discussed in the following subsections:

3.4.1.1 Incomplete Quantification Boundaries

Several studies (Jaillon *et al.*, 2009; Mah *et al.*, 2016; Eghbali *et al.*, 2019; Qiankun Wang *et al.*, 2020; W Lu *et al.*, 2021; Hao *et al.*, 2021) assessed the potential of OSC in reducing construction waste in comparison to site-based construction waste generation. The quantification boundaries were based on site-based waste data collected through surveys and project records.

This includes the earlier work by Jaillon *et al.* (2009) who employed truckload waste records to quantify construction waste associated with prefabricated components in Hong Kong. The study demonstrates over 50% waste savings achieved by adopting OSC compared to traditional construction. Similarly, Mah *et al.* (2016) collected truckload waste records for traditional and prefabricated construction projects, showing that projects built using OSC can generate 65% less construction waste than those seen in traditional construction. The authors employed these rates to develop a theoretical model to assist in estimating construction waste in OSC. Relatedly, W Lu *et al.* (2021) employed a large dataset of 114 high-rise precast projects waste data extracted from associated government waste disposal records to quantify construction waste generation in OSC. The research demonstrates over 15% construction waste reductions achieved through prefabrication.

Despite the valuable findings of these studies highlighting the savings of construction waste when using OSC, they overlook material waste generated offsite (in the factory). These studies have considered OSC as an external procurement stage that reduces downstream onsite construction waste with no further details into its potential upstream inefficiencies (i.e., material waste generation). This highlights incomplete boundaries in quantifying material waste in OSC as compared to traditional construction, raising questions about the generalisability of these findings.

In comparison, only limited studies accounted for offsite-generated material waste when quantifying construction waste in OSC. This includes the work of Mirshekarlou *et al.* (2021) who developed a knowledge-based digital tool to collect, analyse, and monitor waste generation across the lifecycle of prefabricated steel structure. The developed tool helps quantifying waste by materials and phases, including design, production, and site assembly.

Despite the unique consideration of the production stage in quantifying construction waste, the study only provides narrow focus on steel structures. Additionally, the tool is designed to collect waste data at the stage level, without providing activity-level detail to reveal the specific processes or practices behind the recorded waste values.

Table 3.1: The limitations of the research quantifying construction waste in OSC

Authors	Title	Limitations		
		Assessment Boundaries	Estimation Granularity	Data Reliability
(Jaillon <i>et al.</i> , 2009)	Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong	Incomplete Assessment Boundaries	Limited Data Granularity	-
(Mah <i>et al.</i> , 2016)	Construction and demolition waste generation rates for high-rise buildings in Malaysia	Incomplete Assessment Boundaries	Limited Data Granularity	-
(Eghbali <i>et al.</i> , 2019)	Construction waste generation in the Iranian building industry	Incomplete Assessment Boundaries	Limited Data Granularity	Secondary/ Non-empirical Data
(Qiankun Wang <i>et al.</i> , 2020)	An empirical study on waste generation rates at different stages of construction projects in China	Incomplete Assessment Boundaries	Limited Data Granularity	-
(W Lu <i>et al.</i> , 2021)	Revisiting the effects of prefabrication on construction waste minimization: A quantitative study using bigger data	Incomplete Assessment Boundaries	Limited Data Granularity	-
(Loizou <i>et al.</i> , 2021)	Quantifying advantages of modular construction: Waste generation	-	Limited Data Granularity	Secondary/ Non-empirical Data
(Hao <i>et al.</i> , 2021)	Quantifying construction waste reduction through the application of prefabrication: a case study in Anhui, China	Incomplete Assessment Boundaries	Limited Data Granularity	Secondary/ Non-empirical Data
(Mirshekarlou <i>et al.</i> , 2021)	Development of a knowledge-based tool for waste management of prefabricated steel structure projects	-	Limited Data Granularity	Secondary/ Non-empirical Data
(Hernández <i>et al.</i> , 2023)	Assessment of Sustainability and Efficiency Metrics in Modern Methods of Construction: A Case Study Using a Life Cycle Assessment Approach	-	Limited Data Granularity	Secondary/ Non-empirical Data
(Yang <i>et al.</i> , 2024)	Construction Waste Reduction in Buildings through Modular and Offsite Construction	-	Limited Data Granularity	Secondary/ Non-empirical Data

3.4.1.2 Limited Quantification Granularity

Most of the research conducted to quantify construction waste in OSC adopted macro level waste data derived from project disposal records (Jaillon *et al.*, 2009; W Lu *et al.*, 2021; Loizou *et al.*, 2021; Hao *et al.*, 2021; Hernández *et al.*, 2023). That is, construction waste was estimated at the project level using generic methods, which limit detailed understanding of waste generation at activity or material levels. Activity- and material-level estimations are crucial, as they enable further analysis to identify the root causes of waste generation necessary to develop effective mitigation strategies.

In comparison, only few studies adopted more detailed waste data, including material and stage wise records. This includes the work of (Qiankun Wang *et al.*, 2020) who employed direct measurement to sort and weight construction waste across 148 construction sites in China. The study provides construction waste quantification by material inertness and building construction stage, showing that inorganic non-metallic materials and underground stage are the most wasteful. This study is unique in adopting extensive data collection to provide material and stage-wise waste quantifications. Despite the rigorous collection of empirical data and the unique granularity of waste quantification adopted in this study, no further waste analysis was provided at micro level. Understanding construction waste generation at source is essential for identifying root-cause practices, which in turn is necessary for developing targeted interventions to reduce waste.

3.4.1.3 Data Reliability

Several studies (Eghbali *et al.*, 2019; Loizou *et al.*, 2021; Hao *et al.*, 2021; Mirshekarlou *et al.*, 2021; Hernández *et al.*, 2023; Yang *et al.*, 2024) adopted secondary or non-empirical data to quantify construction waste in OSC. For example, Eghbali *et al.* (2019) employed expert survey across four provinces in Iran to estimate construction waste generation in OSC versus the traditional construction approach. The study identified that 40-100% of construction waste can be reduced in projects through prefabrication. Similarly, Loizou *et al.* (2021) employed waste data extracted from the literature to compare waste generation between OSC and conventional construction methods, showing that OSC can provide over 80% construction waste reductions. Relatedly, Hao *et al.* (2021) estimated material level construction waste of high-rise residential building in China using secondary data extracted from national records of material consumption. The study shows that OSC can reduce formwork and masonry waste by 36% and 26%, respectively.

However, the provided waste quantification by these studies is only indicative, lacking rigorous collection process of empirical data. Using secondary or opinion-based data, such as questionnaire surveys or generic records impedes contextual understanding and analysis of waste generation phenomena in practice. Hence, the use of empirical data is likely to provide a start point from which detailed source-level analysis can be provided to understand how and why material waste is generated and develop targeted interventions for waste reduction.

3.4.2 Construction Waste Reduction through Design Cut Planning and Nesting

Several studies developed BIM-based optimisation tools to generate design details that reduce construction waste generation, among other key indicators, such as ease of manufacturing and assembly. Specifically, these studies focus on planning and nesting material cuts during the design phase. Liu and colleagues were among the leading researchers to this domain, have advanced a group of BIM-based tools to optimise the design of different components of light-gauge frame buildings. Their earlier work (Liu *et al.*, 2017) presented an automated optimisation tool to define the wall panel configuration that best meet key indicators, including production flow and reducing construction waste. Their later study (Liu *et al.*, 2018) introduced a BIM-based optimisation tool that embeds trade experience, with a specific focus on optimising the layout design of sheet-based materials to reduce offcuts. In their latest contribution to this domain, Liu *et al.* (2019) developed a hybrid BIM-based tool combining two optimisation models to reduce material offcut generation of roof sheathing materials.

Other similar studies include the work of Gbadamosi *et al.* (2019) which proposed a BIM-based optimiser for assembly based on DfMA principles to evaluate different design alternatives. The developed tool assesses different design choices in terms of potential waste generation and ease of assembly, providing a key decision support tool to promote assembly and material efficiency. Likewise, Malik *et al.* (2021) developed cutting optimisation model to reduce potential offcut generation associated with floor joist cutting. This model was developed using BIM extracted data is capable to reallocate potential offcuts into less essential elements, such as bracing. Tested through three case studies, the model demonstrated enhanced material efficiency by better layout planning.

In addition, Banihashemi *et al.* (2017) developed a similar BIM-based tool for parametric design, integrating modular coordination standards with generative optimisation. The tools demonstrated significant material waste reduction and compliance with modular requirements. Relatedly, Shafiee *et al.* (2025) developed a modular design configurator to help automating design modularisation and detailing. The tool demonstrated enhanced capabilities in customising the design while reducing potential construction waste generation.

Overall, this body of research represents key research direction in OSC, aimed at improving material efficiency through design. However, the applicability of this research is limited for three main reasons: 1) the limited validity of the proposed tools, as most are solely based on simulations and have been validated only through small-scale or no real-world experimentation

(see Table 3.2); 2) limited applicability to other OSC components, such as rockwool insulation or breather membranes, which possess different physical properties and may require alternative design approaches to effectively reduce material waste; and 3) although many of these studies also considered a range of manufacturing constraints (e.g., ease of assembly) (see Table 3.2), it is unclear how the proposed design detailing configurations interact with existing production line capabilities in practice, which could compromise production flow.

Table 3.2: Research proposing BIM-based design optimisation tools to reduce waste generation in OSC

Authors	Research Title	Number of Cases used for Validation	Considered Component/ Materials	Considered Production Indicators
(Banihashemi <i>et al.</i> , 2017)	Modular coordination-based generative algorithm to optimize construction waste	None	Building modules	None
(Liu <i>et al.</i> , 2017)	Optimizing multi-wall panel configuration for panelized construction using BIM	One case	Wall panels	Manufacturing adaptability
(Liu <i>et al.</i> , 2018)	BIM-based automated design and planning for boarding of light-frame residential buildings	One case	Boarding materials	Trades experience
(Liu <i>et al.</i> , 2019)	Towards sustainable construction: BIM-enabled design and planning of roof sheathing installation for prefabricated buildings	Two cases	Roof sheathing materials	Trades experience
(Gbadamosi <i>et al.</i> , 2019)	Offsite construction: Developing a BIM-Based optimizer for assembly	None	Building envelope materials	Ease of assembly
(Malik <i>et al.</i> , 2021)	Minimizing joist cutting waste through dynamic waste allocation in panelized floor manufacturing	Three cases	Timber joists & lateral bracings	Reuse promotion
(Shafiee <i>et al.</i> , 2025)	Enhancing efficiency and sustainability in construction: a product configurator for customizable off-site building solutions	One case	Modular garage components	Manufacturing capabilities

3.4.3 Construction Waste Assumptions in Life Cycle Assessments

The literature assessing the environmental performance of OSC is growing with particular focus on measuring and optimising embodied carbon emissions (Chen *et al.*, 2022). The potential of OSC to reduce material waste and in turn associated carbon emissions is considered a major advantage to the method over the traditional construction approach (Hernández *et al.*, 2023). Several studies (Quale *et al.*, 2012; Hong *et al.*, 2016; Tavares *et al.*, 2021; Balasbaneh and Sher, 2021; Andersen *et al.*, 2022; Jayawardana *et al.*, 2023; Hernández *et al.*, 2023) accounted for construction waste, demonstrating favourable environmental performance to OSC over traditional site-based construction.

However, the calculation of construction waste in these studies are problematic for three reasons. First, the calculated quantities are based on onsite waste generation, ignoring potential waste generation offsite (Yang *et al.*, 2024). This gives significant advantage to OSC since it does only have limited waste generation onsite. Second, in many instances, waste generation is assumed as fixed rates extracted from obsolete literature that is over two decades old (e.g., Chen *et al.*, 2001; Poon *et al.*, 2001). Hence, the assumed waste rates are less likely to reflect the actual practices adopted in OSC in relation to waste generation. Third, material waste values are mostly provided with no details on how they were estimated or calculated. This raises questions on the transparency of data collection and in turn the reliability of the results.

3.4.4 Research Gap Identification

In Chapter One, research employing lean principles to optimise OSC performance was reviewed. The findings indicate a fragmented understanding of waste conceptualisation in OSC, with limited focus on how and why material waste is generated. This chapter narrows the analysis by focusing specifically on material waste. It does so by reviewing OSC studies that quantify, assume, or address material waste within their scope. Across this body of literature, several research gaps can be identified as follows:

3.4.4.1 Lack of Micro Level Quantification

Empirical evidence quantifying construction waste generation at source in OSC remains limited. Quantifying waste at source is key to enable: 1) higher-level comparisons across different aspects, such as materials and practices, which deepen understanding of waste generation in OSC; and 2) more detailed investigation into how and why waste levels vary across different contexts and operational conditions.

3.4.4.2 Lack of Micro Level Understanding

Evidence explaining how and why material waste is generated at source in OSC remains limited. Identifying material waste generation instances and their root causes is crucial for understanding the operational drivers that sustain waste at an organisational level. Developing a holistic understanding of how and why material waste is generated in OSC is therefore essential for manufacturers, as it enables informed decision-making and supports the development of effective waste-reduction strategies.

3.4.4.3 Limited Evidence on the Effectiveness of Automated Technologies

Despite growing research advocating the adoption of automated technologies in OSC to reduce material waste, their practical effectiveness remains limited. Much of the existing research relies on simulation-based approaches with limited or no real-world validation, which reduces confidence in their applicability across different components and operational settings. Furthermore, limited analysis has examined the potential tensions between material-saving technologies and the continuity of production flow, raising further questions about their feasibility and effectiveness in practice.

3.5 Summary

This chapter has reviewed the existing body of research on material waste within the context of OSC. It began by defining material waste, exploring its sources across various construction stages, and evaluating current quantification methods, revealing that most of which remain rooted in traditional construction understanding. The chapter then critically examined the literature that quantifies, assumes, or addresses material waste in OSC, including studies that: 1) quantify waste and compare it to conventional construction, 2) develop design optimisation tools aimed at reducing waste, and 3) assume OSC waste rates for life cycle assessment purposes. The review reveals a significant research gap related to lack of micro-level quantification and understanding of material waste in OSC. This limitation hinders a thorough understanding of how and why material waste is generated at source in OSC settings. Therefore, empirical research is needed to investigate material waste generation at source across various components and offsite production settings. Such investigations can support a more holistic understanding of material waste categories, root causes, and variability, serving as a foundation for the theoretical development of targeted, evidence-based interventions for waste reduction in OSC. The next chapter outlines the methodological choices made to support empirical exploration.

Chapter Four: Research Methodology

4.1 Introduction

This chapter outlines the methodological choices underpinning this study in relation to the different research questions. A case study strategy with a multiple case design was employed to investigate material waste generation at source in OSC. This area remains underexplored because of limited data availability, restricted site access, and weak institutional reporting requirements, which have collectively impeded efforts to identify waste instances, estimate their quantities, and investigate their root causes. Three data collection techniques were adopted, direct factory observations, design document analysis, and semi-structured interviews, to enhance the credibility and reliability of the research findings. The initial findings on how, how much and why material waste is generated at source were validated through follow-up interviews with production managers across the four cases, ensuring the robustness of the results before drawing theoretical inferences. A range of analytical techniques was employed to address the various research questions, including root cause analysis, descriptive quantitative analysis, thematic analysis, exploratory causal analysis, priority scenario analysis, comparative quantitative analysis, and interpretive analysis.

4.2 Research Philosophy

The overarching research philosophy of this study lends itself to pragmatism. This is mainly attributed to the research aim (refer to subsection 1.4.1), which ultimately seeks to propose targeted, practical interventions to reduce material waste in OSC, thereby shaping the overall direction of the enquiry. Pragmatism, as a philosophical stance, encourages the practical application of theories to explain and address real-world problems, supporting what works in real-life rather than a distinct ontological or epistemological position (Saunders *et al.*, 2016). It is a problem-centred standpoint that begins with the issue at hand and favours the methods and tools that are most effective in developing useful, practical solutions (Morgan, 2014).

Pragmatism is closely associated with methodological pluralism. It emphasises drawing on both subjective and objective perspectives and therefore recognises the value of using quantitative and qualitative data to generate practical, context-specific insights (Creswell, 2013). Given that this research seeks to understand material waste generation in OSC and propose targeted interventions for its reduction, it relies on both measurable waste data and interpretive accounts. This mixed-data approach reflects a pragmatist standpoint; where diverse

forms of evidence are purposefully integrated to develop actionable knowledge. The justification for adopting pragmatism can be strengthened by contrasting it with alternative paradigms. Positivism assumes a single, objective reality that can be captured through measurement and explained through causal relationships, favouring theory testing, prediction, and statistical generalisation (Saunders *et al.*, 2016). While this stance is valuable for benchmarking waste quantities and examining statistical relationships between variables, it is limited in providing a deeper understanding of how and why waste is generated in OSC. At the other extreme, interpretivism prioritises meaning, context, and social construction, making it well suited to exploring how stakeholders perceive waste and how practices are shaped by organisational and situational factors (Creswell, 2013). However, a predominantly interpretivist stance offers a weaker basis for quantifying the magnitude and distribution of material waste, evidence that is necessary to justify, compare, and prioritise interventions for waste reduction.

4.3 Research Approach

The inductive approach is adopted in this study due to the limited knowledge on material waste categories, root causes, and quantities in OSC. Inductive research begins with empirical observations to explain the observed phenomenon and answer the research questions (Spens and Kovács, 2006). Particularly, the inductive approach was adopted to answer the research questions of how, how much, and why material waste is generated in OSC. Therefore, this encouraged starting from empirical data to develop novel theoretical understandings, a major feature of inductive research (Spens and Kovács, 2006). Figure 4.1 presents a diagram illustrating the adopted inductive research approach.

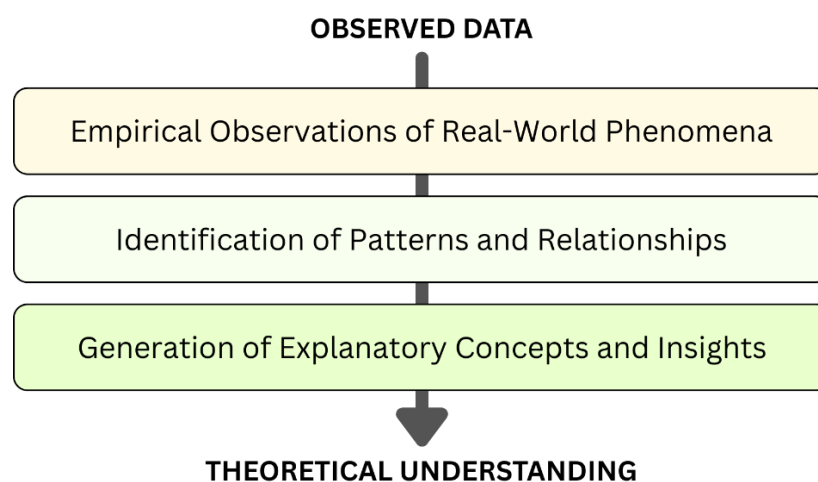


Figure 4.1: Conceptual representation of the inductive research approach

4.4 Research Design

This refers to the practical choices adopted across the study to answer the research questions and meet the study aim. Research design represents the master plan that defines and justifies the procedures and principles for data collection and analysis (Zikmund *et al.*, 2010). The following subsections discuss and justify the choices made in this study (refer to Figure 4.2):

4.4.1 Case Study

Reviewing the literature highlights limited knowledge on material waste categories, quantities, and root causes in OSC. As a result, several research questions were developed to better understand material waste generation in OSC. To answer these questions, case study strategy is employed to its power in answering ‘how’ and ‘why’ questions, facilitating in-depth analysis and understanding of a contemporary phenomenon (Yin, 2014). Unlike experimental and survey-based methods, which typically isolate variables and prioritise breadth over depth, the case study approach enables a comprehensive investigation of multiple interacting variables simultaneously (Flyvbjerg, 2006). In addition, case study helps adopting a mixed method data collection where both quantitative and qualitative data is collected, analysed, and interpreted to provide deeper understanding of the case (Creswell and Clark, 2018). This particularly important since the research questions require both quantification and explanation to material waste generation in OSC. The following subsections explain the attributes and defining layers of the case study.

4.4.1.1 Multiple-case Justification

Since the choice of case study in this research is not motivated by intrinsic case attributes, such as case criticality, uniqueness, or commonality (Saunders *et al.*, 2016), multiple case design is adopted. The major justification of choosing multiple cases is to enhance the research reliability and analytical generalisability through replication logic.

According to Yin (2014), replication is similar to conducting several experiments to verify the results and enhance the research reliability. Literal replication is sought when the results from different cases are expected to confirm each other, whereas theoretical replication is sought when justifiable patterns of theory integrate each other (Yin, 2014). Hence, the power to achieve literal or theoretical replication is a key factor to increase analytical generalisability and to mitigate any criticism from those following sampling logic.

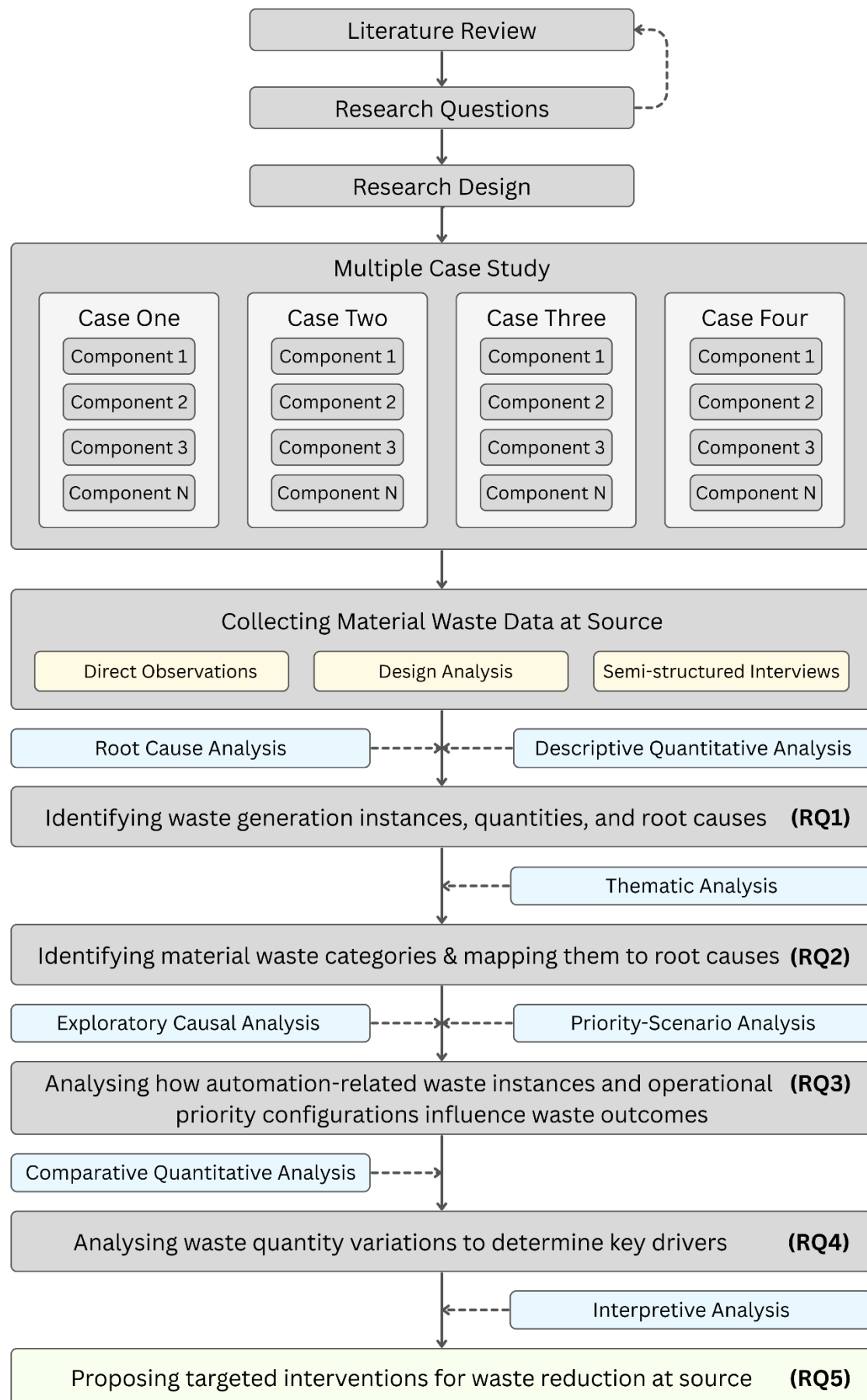


Figure 4.2: Research design

4.4.1.2 The Subject

It is the practical or historical instance (e.g., product, process, person) through which the phenomenon of interest can be observed and explained (Thomas, 2021). The subject is by no mean a sample but selected as an interesting, unusual, or revealing window, through which the contours of the phenomenon can be scrutinised (Thomas, 2021). Hence, the production process of an OSC product was selected as the subject of the case study since it acts as the window through which material waste generation can be investigated.

4.4.1.3 The object

It is the phenomenon being observed throughout the empirical investigation of the subject to develop deeper understanding of the class (i.e., context) (Ragin, 1992). Wieviorka (1992) argues that a case cannot be fully understood through mere observation of the phenomenon, but it requires interpretation in relation to the context in which it unfolds. Hence, within each OSC production process (i.e., the subject), material waste is considered as the phenomenon (i.e., the object) that needs to be observed to understand material waste generation in OSC.

4.4.1.4 Unit of Analysis

It is a unit smaller than the primary component of analysis (i.e., the subject) mainly adopted to facilitate data collection, analysis, and interpretation (Yin, 2014). These units are defined as the major sources of data necessary to develop a holistic picture of each case in relation to the research questions (Grünbaum, 2007). In this study, the assembly activities of major components (within a defined OSC product) are considered as the unit of analysis for material waste generation (i.e., the object). This allows deeper understanding of different construction components and associated practices in relation to material waste generation.

4.4.1.5 The Context

This refers to the environment surrounding the case study (i.e., the subject) and the phenomenon of interest (i.e., the object), incorporating several influencing factors, including social, legal, economic, technological, political, and environmental (Yin, 2014). George and Bennett (2005) hold that understanding the context is the goal of conducting case study, which can be achieved by interpreting the phenomenon (i.e., object) within each case. Yin (2014) postulates that case studies are especially useful for articulating the boundaries between a phenomenon and its context.

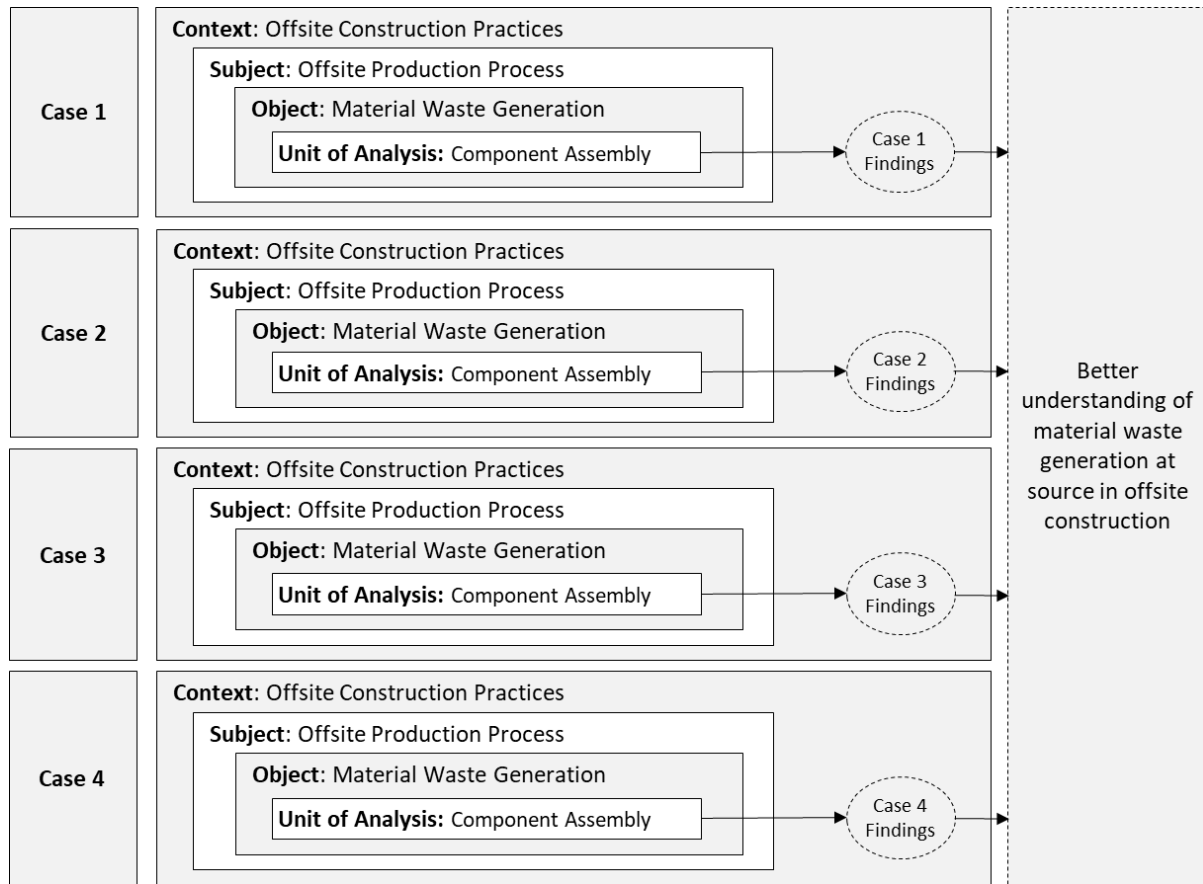


Figure 4.3: Case study context, subject, object, and unit of analysis

Hence, the context represents the broader environment of OSC practices surrounding each subject (i.e., OSC production process) and object (i.e., material waste generation). Particularly, investigating an OSC production process (as a subject) is aimed at observing material waste generation (the object) to develop better understanding of material waste categories, quantities, and root causes. Thus, the findings are expected to define the boundaries between the object (material waste generation) and the context (OSC practices). Figure 4.3 illustrates the case study layers, including the context, subject, object, and unit of analysis.

4.5 Case Selection

This refers to the process of selecting the quality and quantity of the cases to be involved in this research (Flick, 2012). However, qualitative research does not lend itself to the selection of quantitatively representing sample rather than selecting those capable to provide rich description of the phenomenon under investigation (Nicholls, 2017). This means that the priority in selecting the cases is given to those of theoretical value that can answer the research questions (Yin, 2014). Hence, purposive sampling technique was adopted in this research to help selecting the cases based on their capability to provide data.

The criteria for selecting the cases include several aspects, including relevance, data quality, and variability. For relevance, the cases were selected based on their relevance to the understanding of OSC, that can be modular, panelised, or component-based. Data quality is another key requirement in selecting the cases, was checked at the initial stages of negotiating access with potential case providers. This includes the details of the design data, access to direct observations, and the willingness of case providers to provide explanations. For variability, the cases were selected to reflect different levels of manufacturing automation, offsite assembly approach (e.g., modular, panelised), and company sizes. This is informed by the research studies (Mah *et al.*, 2016; W Lu *et al.*, 2021; Hernández *et al.*, 2023) claiming that automation is likely to enhance construction efficiency and reduce material waste generation. A range of company sizes was selected, including two large factories (>250 employees), one medium-sized factory (50-250 employees), and one small factory (>50 employees). These size classifications are based on the European Commission’s definition of enterprise sizes (EU Commission, 2025). Table 4.1 outlines the anonymised details of the four selected factories in this research.

Table 4.1: Anonymised factory profiles included in the multiple case study

Case	Level	Product Type	Company Size	Sector
Factory A	Modular	Steel Frame Module	(>250) Large	Commercial, Healthcare, Educational, Residential
Factory B	Panelised	Timber Frame Wall Panel	(50-250) Medium	Residential, Educational
Factory C	Panelised	Timber Frame Wall Panel	(>250) Large	Residential, Commercial
Factory D	Panelised	Timber Frame Wall Panel	(<50) Small	Educational

4.6 Data Collection

In this research, multiple data collection techniques were employed to ensure depth, reliability, and triangulation of the emerging findings (Saunders *et al.*, 2016). Employing multiple sources of data is recommended to complement each other and in turn establish a more comprehensive picture of the phenomenon under examination (Ahmed *et al.*, 2016). The primary sources of data included direct factory observations, design document analysis, and semi-structured interviews. Figure 4.4 illustrates the data collection techniques adopted, the objectives of each method, and how these objectives contributed to and reinforced one another to confirm and enrich the emerging findings. The adopted techniques and associated objectives are discussed in the following subsections:

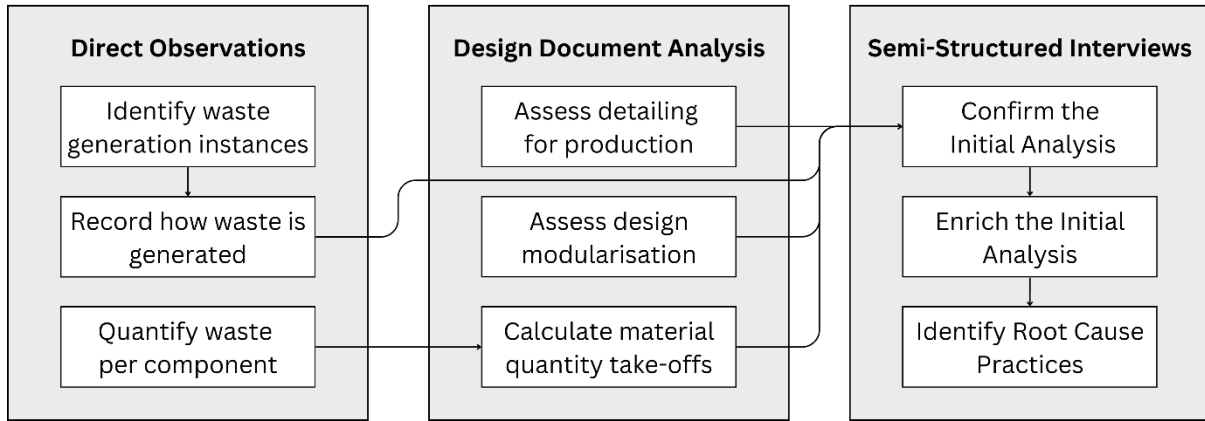


Figure 4.4: Data collection techniques and their complementary objectives

4.6.1 Direct Observations

Direct factory observation constituted the primary empirical method used to investigate material waste generation at source in OSC. This method was employed to identify waste-generation instances across different component assembly activities, explain the mechanisms through which material waste is generated, and quantify the resulting waste. In particular, the observation sessions focused on the activity level (e.g. cutting, fitting) within component assembly processes (e.g. OSB boarding, timber framing) that contribute to an OSC product (e.g. wall panels) across the four case study factories, as illustrated in Figure 4.5.

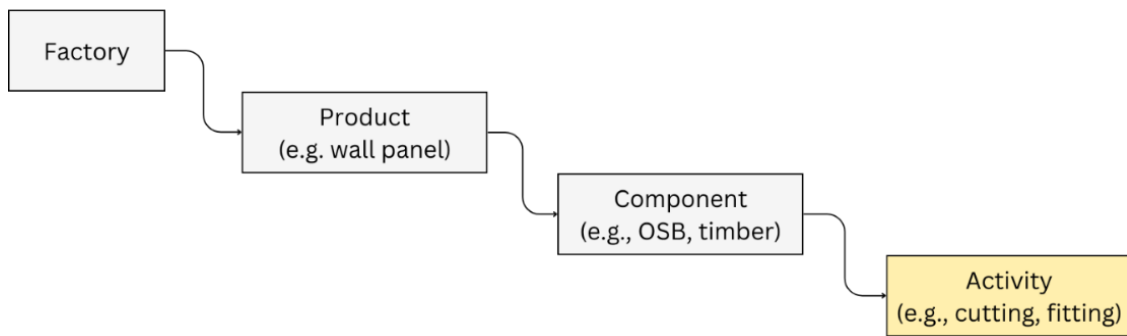


Figure 4.5: Activity-level observations of OSC component assembly processes

To systematically identify waste-generation instances, the OSC product and its constituent components were first mapped at each factory. The assembly activities associated with each component were then examined through 30-60 minutes' sessions of close observation, complemented by interaction with production teams. This approach ensured a comprehensive understanding of how and how much material waste is generated across different components. Accordingly, each component was assigned a dedicated observation session designed to document and explain the specific mechanisms through which material waste arises during production. Detailed observation notes are provided in Appendix F, which outlines the

observation sessions conducted across the four factories. Table 4.2 summarises the number of observation sessions and observation days undertaken in each factory.

Table 4.2: Observation sessions and days per factory

Case Factory	Factory A	Factory B	Factory C	Factory D
No. of observation sessions (about 30-60 minutes each)	7	8	4	3
No. of days spent to conduct the sessions	3	3	2	1

4.6.2 Design Document Analysis

Design documents for the selected OSC product at each factory were requested and analysed. Depending on the level of design detail prepared at each factory, these documents included module-level design drawings (e.g., wall panel layouts) as well as component-level detailing (e.g., OSB cutting list). The purpose of collecting design data was threefold. First, to quantify the material quantity take-offs for each component, enabling comparisons between the designed quantities and the actual material usage observed, and thereby facilitating the calculation of material waste percentages. Second, to assess the level of design detailing provided for assembly (i.e., the provision of cutting lists). Third, to examine modularisation practices within the design, particularly the extent to which specified cut sizes were aligned with standard material sizes or their multiples. Table 4.3 illustrates the design document types, the number of analysed design documents, and the product types across the four factories.

Table 4.3: Design document types and analysed product samples for factories A-D

Case Factory	Factory A	Factory B	Factory C	Factory D
Design Document Type	Module level	Module level/ component level	Module level/ component level	Module level/ component level
No. of researched design units	4	8	8	10
Product Type	Steel frame module	Timber frame wall panel	Timber frame wall panel	Timber frame wall panel

4.6.3 Semi-structured Interviews

To gain a deeper understanding of the data collected through direct observations and design document analysis, semi-structured interviews were conducted. These included 30-60 minutes' interviews with design, procurement, and production managers across the four factories. In addition, operational-level staff from design, procurement, and production were interviewed where possible to obtain broader perspectives and enable triangulation at the case level. Participants were purposefully selected due to their direct involvement in design specification decisions, material ordering, and manufacturing practices, all of which critically influence material waste generation. Interviewing a combination of management and operational staff ensured a comprehensive understanding of material waste generation across different organisational levels.

In total, 30 interviews were conducted across the four factories (see Table 4.4 for detailed breakdown of the interviewees). To maintain confidentiality, the interviewees' names were anonymised and replaced with unique codes, as shown in Table 4.5, which illustrates the codes and roles of the interviewees across the four factories. All interviews were recorded and transcribed to facilitate further analysis (refer to Appendix G which includes transcripts of anonymised interviews). The interviews focused on identifying the root causes of material waste generation across different components. Several 'why' questions were asked to trace these causes not only at the production level but also upstream, including procurement and design processes.

Table 4.4: Roles and number of the interviewees across the four factories

Role	Number of Interviewees			
	Factory A	Factory B	Factory C	Factory D
Design Manager	1	1	1	1
Procurement Manager	1	1	1	1
Production Manager	1	1	1	1
Operational-level Staff	6	4	6	2
Total	9	7	9	5

The interviews contributed to data collection in two key ways. First, they were used to confirm and enrich the initial analysis derived from direct observations and design document analysis at each factory. This included insights into how material waste is generated and the associated quantities at the point of generation (i.e., at source). Second, the interviews also helped identify the root cause practices underlying the identified instances of waste generation and their

corresponding quantities across different components within each OSC product. In doing so, the interviews not only deepened the research findings but also enhanced the study's reliability and validity by supporting data triangulation.

Table 4.5: Anonymised interviewee codes and roles across the four factories

Factory	Interviewee Code	Role
A	A01	Operational-level Staff
	A02	Operational-level Staff
	A03	Operational-level Staff
	A04	Design Manager
	A05	Operational-level Staff
	A06	Operational-level Staff
	A07	Operational-level Staff
	A08	Procurement Manager
	A09	Production Manager
B	B01	Operational-level Staff
	B02	Procurement Manager
	B03	Operational-level Staff
	B04	Operational-level Staff
	B05	Design Manager
	B06	Operational-level Staff
	B07	Production Manager
C	C01	Design Manager
	C02	Operational-level Staff
	C03	Procurement Manager
	C04	Operational-level Staff
	C05	Operational-level Staff
	C06	Operational-level Staff
	C07	Operational-level Staff
	C08	Operational-level Staff
	C09	Production Manager
D	D01	Procurement Manager
	D02	Operational-level Staff
	D03	Design Manager
	D04	Operational-level Staff
	D05	Production Manager

4.7 Empirical Data Analysis

The analysis of data is a crucial part of the research process where the collected data is processed to draw logical conclusions (Ahmed *et al.*, 2016). This section outlines the procedures and concepts adopted for empirical data analysis mainly to answer different research questions. Providing a systematic approach to analyse data plays a key role in promoting more transparent and reliable research findings. Figure 4.6 illustrates the adopted framework for empirical data analysis, along with the interrelations between different analysis techniques. The following subsections introduce the analysis techniques adopted to answer different research questions and their interrelations to other analysis techniques.

4.7.1 Root Cause Analysis

Using the raw data collected through direct observation, design documents, and semi-structured interviews, a structured root cause analysis was conducted to investigate various waste-generation instances and their root cause practices. Specifically, a causal logic approach based on the What-How-Why reasoning chain was adopted to systematically trace each waste-generation instance back to its root cause practice. Within this technique, the recognised lean technique of 5 Whys was used to iteratively question the underlying reasons behind each instance of material waste, moving beyond surface-level symptoms to uncover deeper systematic issues. This analytical approach was employed to answer part of the first research question, related to exploring how and why material waste is generated at source in OSC.

4.7.2 Descriptive Quantitative Analysis

This technique of analysis was employed to process the empirical data collected in response to the second part of the first research question, which focused on quantifying material waste generation across different components. While material waste quantities and/or the total processed materials quantities for different components were recorded through direct measurements conducted during factory observations, material quantity take-offs were extracted from the design documents for each OSC product at the respective factories. The total required quantity of each component was calculated by summing the quantities of its individual elements, for example, the total length of timber sections needed to construct a unit wall panel. This calculated requirement was then subtracted from the total quantity of materials actually processed in practice. The difference was divided by the total processed quantity to determine the percentage of material waste for each component. To ensure accuracy and efficiency, this analysis was conducted using Microsoft Excel.

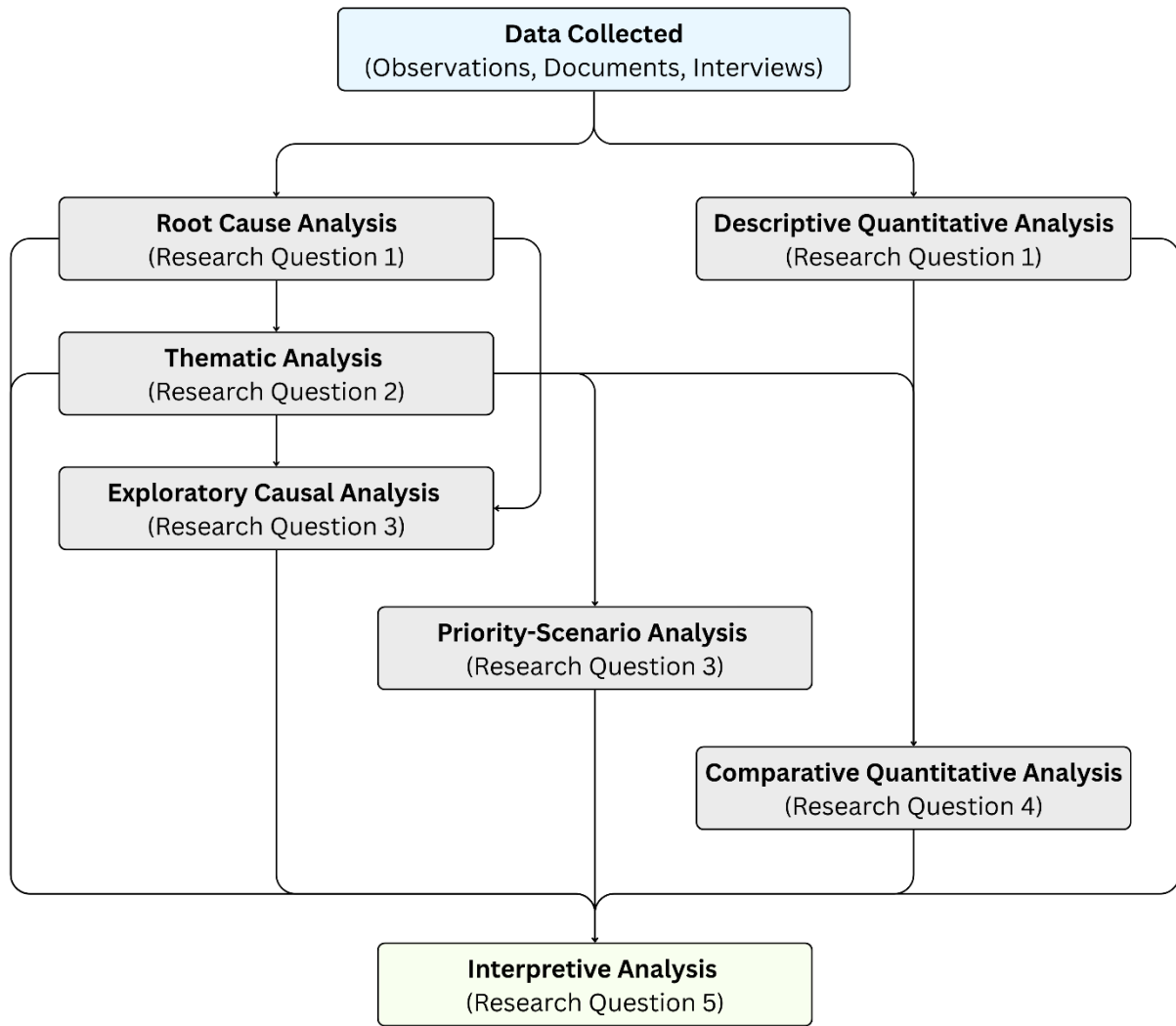


Figure 4.6: Empirical data analysis framework

4.7.3 Thematic Analysis

After identifying instances of waste generation and their underlying root-cause practices using root cause analysis (see 4.7.1), thematic analysis was subsequently employed to identify theoretical patterns (see Figure 4.6). Specifically, this analysis aimed to define distinct categories of material waste and the associated root-cause practices in OSC. As the primary input to the thematic analysis, the detailed root-cause analysis results (reported in Chapter Five) were first coded into initial analytic codes, with close attention to similarities and differences in how waste arose across settings. The initial codes were then grouped into candidate categories that reflect distinct waste mechanisms and demonstrate recurrence across the observed components in the four factories, thereby supporting cross-case comparison. This process was revised several times to ensure meaningful identification and classification of root-cause practices. Finally, the resulting root-cause themes were employed to define distinct categories of material waste in OSC, spanning design, procurement, and production processes

(reported in Chapter Six). This analysis was particularly useful for answering the second research question, which concerns identifying and mapping material waste categories against root-cause practices.

4.7.4 Exploratory Causal Analysis

This technique of analysis is set to identify potential linkage between cause-and-effect across the collected data, especially when existing evidence is limited (Goldberg, 2019). Hence, this technique was employed to assess the impact of automation-related activities on material waste outcomes in OSC. The main input for this analysis was 1) the identification of assembly activities (i.e., whether automated/manual) and their waste behaviour (i.e., generation, reduction, avoidance) which were primarily identified as part of the systematic root cause analysis (see 4.7.1), and 2) the associated categories of material waste and root cause practices identified as part of the thematic analysis (see 4.7.3). This included a focused examination to identify whether and how automated technologies (observed across the four factories) contribute to material waste generation. In doing so, the impact of automation on material waste generation was analysed and explained, bridging a significant gap in the literature. This technique was particularly key to answer the first part of the third research question on how automated technology influences material waste outcomes in OSC.

4.7.5 Priority-Scenario Analysis

This technique of analysis is set to assess how the interaction between competing operational priorities (e.g., production flow vs. material efficiency) produce different results across defined scenarios, helping identify decision-making patterns and their potential consequences (Miles, 1994). This technique of analysis was employed to examine how varying configurations of operational priorities (i.e., production flow, material efficiency, and others) can influence material waste outcomes in OSC. The main input for this analysis is material waste categories and their root cause practices and drivers identified as part of the thematic analysis (see 4.7.3) (see Figure 4.6). Based on the identified root cause drivers across different component assembly activities, four distinct scenarios were identified, including 1) where production flow is prioritised over material efficiency, 2) where material efficiency is prioritised over production flow, 3) where both production flow and material efficiency are compromised in favour of a third factor (such as cost, time, or design customisation), and 4) where both production flow and material efficiency are jointly prioritised. In doing so, this analysis is likely to facilitate understanding how different strategic prioritisations are likely to impact the

adopted practices and in turn material waste generation. This technique is particularly set to answer the second part of the third research question related to understanding how different competing operational priorities impact material waste outcomes in OSC.

4.7.6 Comparative Quantitative Analysis

To better understand how material waste varies across different factories, components, waste categories and root cause practices, comparative quantitative analysis was adopted. The main input for this analysis is material waste percentages of different components, quantified as part of the descriptive quantitative analysis (see 4.7.2) across different factories, materials, waste categories and root cause practices (see Figure 4.6). The analysis included the use of box plot diagrams to facilitate the assessment and comparison of key statistical aspects, including central tendency, spread, and outliers across different dimensions. In doing so, statistical patterns behind material waste generation can be highlighted and justified, allowing for deeper understanding of material waste generation in OSC. This analysis is particularly set to answer the fourth research question related to comparing waste rate across different factories, material types, waste categories, and root cause practices.

4.7.7 Interpretive Analysis

Drawing on the results of the preceding analysis techniques employed in this study, an interpretive analysis was undertaken to reflect on the empirical findings with the primary aim of proposing a range of targeted interventions for material waste prevention at source. This analysis adopts a grounded approach, interpreting the root-cause practices underpinning waste generation in order to develop actionable and context-sensitive interventions. This stage of analysis directly addresses the fifth research question (see Figure 4.6), which focuses on proposing targeted interventions to reduce material waste at source in OSC.

4.8 Validation

To promote the research credibility and reliability, the results of root cause analysis and descriptive quantitative analysis (related to identifying how, how much and why material waste is generated at source in OSC) were validated. The validation process involved a single semi-structured interview with the production manager at each of the four factories. This included a detailed review of the initial findings at each factory, presented component by component, supported by drawings and calculations. The main aim of this step is to ensure that the analysis

is properly conducted, and the emerging findings are justified and backed with validated evidence.

The validation interview included a set of open-ended questions aimed at 1) confirming the initial findings, 2) identifying and addressing potential discrepancies, and 3) collecting feedback for further improvement. Semi-structured interviews were adopted to provide necessary flexibility to navigate and validate different aspects the initial findings. All interviews were recorded, transcribed, analysed, and compared against the original data and initial analysis. Wherever a discrepancy was observed, the findings were critically re-evaluated and refined to align with a validated, triangulated interpretation. This means that only interview perspectives corroborated by both design analysis and field observations were retained for subsequent modelling and conclusion-drawing. Views lacking this multi-source confirmation were not integrated into the final analytic framework. Through this process, the validation step enhanced the reliability and credibility of the research by incorporating robust, case-representative feedback.

4.9 Ethical Considerations

This study followed strict ethical procedures to ensure transparency, objectivity, and confidentiality throughout the study. Ethical compliance was accomplished by conducting formal reviews of the research plan and by obtaining necessary approvals before data collection. Several key ethical considerations were maintained throughout the research process.

4.9.1 Ethical Approval

Ethical approval for this research was sought and obtained from the Birmingham City University Research Ethics Committee prior to the collection of any data. All research activities were carried out in accordance with the University's ethical guidelines for research involving human participants. Documentation relating to ethical approval is provided in Appendix H.

4.9.2 Consent and Withdrawal Procedures

All participants involved in the interviews and site visits across the four factories were formally informed about the research objectives, scope, and intended use of data. This was documented through written consents to ensure understanding and voluntary participation. Participation was entirely voluntary, and participants were informed of their right to withdraw from the study anytime without providing a reason and without any consequences.

4.9.3 Confidentiality and Anonymity

All the data collected in its different forms were coded and anonymised to protect the identifies of the participants and their organisations. This includes, factory designations, participant identifiers, and any other sensitive data related to the participating factories. All participating factories were anonymised and referred to using pseudonyms (Factories A-D), while individual participants were assigned coded identifiers. Potentially identifiable information was removed from interview transcripts, observation notes, and reported findings, and all quotations were carefully screened to prevent identification.

4.9.4 Data Storage, Retention, and Destruction

All data, including audio recordings, interview transcripts, observation notes, and design documents, were stored securely on password-protected and encrypted devices accessible only to the researcher and the supervisory team. In line with university policy, the data will be retained for the specified post-completion period and then permanently destroyed using approved digital and physical data destruction procedures.

4.9.5 Research Integrity

All data collected, including material waste measurement, were recorded and documented with no selective omission or distortion. Throughout the study, triangulation across interviews, observations, and document analysis was employed to enhance research integrity, credibility, and ethical rigour. Validation interviews were used to confirm findings and address discrepancies, ensuring that interpretations were grounded in corroborated evidence.

4.10 Summary

This chapter has outlined the methodological choices made to address the research aim and answer the research questions. A multiple case study design was adopted to investigate material waste generation at source in OSC, with the case, subject, object, unit of analysis, and research context defined in relation to the scope of the study. Data were collected through direct factory observations, analysis of design documents, and semi-structured interviews, with follow-up interviews conducted to validate initial findings. A range of analysis techniques was employed to identify waste types and their underlying causes, quantify waste at the component level, assess the impact of automation and operational priorities on waste outcomes, and develop targeted interventions for waste reduction in OSC. The following chapter presents a detailed analysis of waste across various components in the four participating factories.

Chapter Five: Material Waste Analysis in Offsite Construction: Identification, Quantification, and Root-Cause Diagnosis

5.1 Introduction

This chapter presents an analysis of material waste across various components of OSC products investigated in four OSC factories. Particularly, this chapter addresses the first research question, related to understanding how, how much, and why material waste is generated at source in OSC. Direct factory observations were conducted on a component-wise basis across the four factories to identify instances of material waste generation, quantify their amounts, and investigate the root-cause practices underlying them. To enable data triangulation, the observations were complemented by the analysis of design documents and semi-structured interviews with production, procurement, and design teams. To identify the root cause practices, a structured Root Cause Analysis (RCA) approach was adopted, using a logical What-How-Why reasoning chain. Through this approach, this chapter provides a thorough understanding of material processing inefficiencies and their underlying practices. In doing so, the findings from this detailed analysis provide vital input for identifying material waste categories and linking them to their underlying root-cause practices in OSC, thereby contributing to the higher-level theoretical development presented in the next chapter.

5.2 Factory A

The first case study focuses on a steel-frame modular manufacturer based in the UK, primarily serving commercial, educational, and healthcare projects. This factory produces two categories of modular products: one for sale (permanent use) and the other for hire (temporary use). The main structural materials used in these products are hot-rolled steel, with light-gauge steel sections used for floor and roof joists. Each design is broken down into a defined number of modules that go through several assembly steps before being transported to the construction site for final installation.

The subject of this case study is the offsite assembly process, with material waste generation and avoidance forming the main focus of analysis. The construction materials used in the assembly process are considered as units of analysis to examine material waste generation and avoidance in OSC. Figure 5.1 illustrates the stages and activities involved in producing a

module in this factory. The first stage is primarily concerned with floor and roof assembly, while the second focuses on the installation of internal and external wall finishes. Activities highlighted in yellow represent material application activities where material waste may be generated. Those marked with a worker symbol are manual and performed using basic tools (e.g., handsaw, knife). In contrast, activities marked with a worker-and-gear symbol are semi-automated, involving the use of mechanical tools (e.g., powered saw). Each of these activities was directly observed in the factory to determine how, how much, and why material waste is generated or avoided.

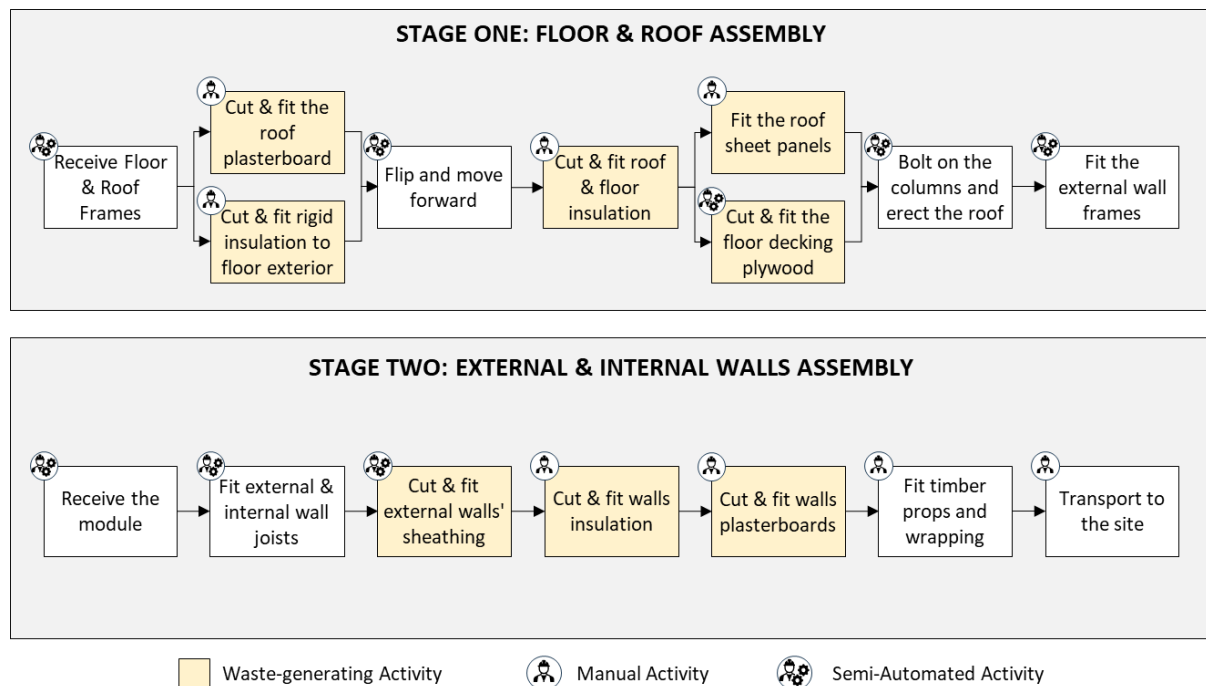


Figure 5.1: Factory A - Steel frame module assembly activities

5.2.1 Fitting the Structural Frame

These activities include receiving and fitting the steel frame components, which include the floor and roof chassis and columns. These components are made of hot-rolled steel and galvanised joists and represent the structural core of the produced modules. As part of the business model, the manufacturing activities of these components are outsourced to a specialised manufacturer, and they only come to the factory in the exact required sizes for final assembly. This was confirmed by the observations (refer to the Observation Session A01 in Appendix F) and the interviews conducted, and hence there is technically no material waste associated with the structural frame assembly. For detailed analysis, a structured RCA approach was adopted using What-How-Why reasoning chain as shown in Table 5.1.

Table 5.1: Structural frame waste avoidance - root cause analysis

#	Questions	Explanations
1	What?	material waste associated with the structural frame manufacturing process is totally avoided in this factory
2	How?	By using pre-finished frame components
3	Why?	Because the structural frame components were outsourced to specialised manufacturers
4	Why?	Because the factory lacks the necessary equipment to safely handle the fumes produced during the welding of galvanised steel sections
5	Why?	Because of the cost, quality, and health and safety implications of in-house welding, outsourcing to a specialised manufacturer with high-precision capabilities is a more effective solution.

The presented analysis in Table 5.1 is supported by input from interviewee A09 who explained that:

'Frames are generally outsourced, historically along with the steelwork. We have a lot of cold-rolled galvanized sections within the frames. In our manufacturing facilities, we don't have the scope to weld anything galvanized. So, welding has historically been done off-site to eliminate any issues with galvanized fumes. The box frames and wall panels are generally procured and made off-site because they are part of the companies we work with, and we use their own systems.'

Therefore, the technical root cause behind material waste avoidance associated with the structural frame at Factory A is the outsourcing decision. This is justified by the lack of equipment needed to safely handle fumes generated during the welding of galvanised steel sections. This outsourcing strategy is reinforced at the organisational level, driven by perceived cost, quality, and health and safety risks associated with in-house production. Consistent with this explanation, observation notes from Session A01 (refer to Appendix F) confirm that structural frames arrive prefabricated and ready for assembly, with no welding activities observed on site. Figure 5.2 illustrates these outsourced structural frame components prepared for the first assembly activity.

5.2.2 Cutting and Fitting Plasterboards

Different plasterboard sizes were used to finish the module ceiling and walls, providing smooth and durable layer for the internal building setting. These boards are usually sourced 1200 mm

wide, and 2400, 2700, or 3000 mm long. The observations of the plasterboard cutting and fitting activities included four modules. While 2700 mm long boards were used for the walls, 3000 mm long boards were used for the ceiling.



Figure 5.2: Structural frame components prepared for assembly

Using the provided drawings of the four modules, the total required area of plasterboards was calculated as 136.53 m². In comparison, the total processed area of plasterboards was 156.54 m², making up to 13% plasterboard offcuts (see Appendix A - Table 1 for detailed calculations). All these offcuts were directly discarded into the recycling bin. Three categories of material waste related to plasterboard fitting and cutting activities can be identified and analysed in the following subsections:

5.2.2.1 Ceiling Plasterboard Offcuts

These offcuts were mostly avoided since the used plasterboard size came exactly as the net ceiling size in most cases. Except the length-side of the plasterboards at the external modules, all other sides of the plasterboard sizes came exactly as required in design (see Figure 5.2). This is because the net ceiling width of the external modules is slightly lower at 2863 mm, requiring a small offcut strip of 137 mm. Hence, five offcuts of 137 mm at each external module were generated, contributing to 1% of the total plasterboard used (see Figure 5.2). For detailed analysis, a structured RCA approach was employed through What–How–Why reasoning chain as shown in Table 5.2.

Table 5.2: Ceiling plasterboard offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts associated with ceiling posterboards was minimal
2	How?	By using plasterboard sizes closely match ceiling dimensions
3	Why?	Because the ceiling design is mostly aligned with the standard plasterboard sizes
4	Why?	Because of the inherent design practices that promote production flow and facilitate assembly

Hence, the technical root cause of the limited ceiling plasterboard offcuts is the factory practice of designing around standard material sizes to streamline the assembly process. This interpretation is supported by observation notes recorded during Observation Session A06 (refer to Appendix F), which indicate minimal measuring and cutting during ceiling installation, as well as by input from Interviewee A01, who explained that:

‘Because plasterboard is a board-based product, small or impractical off-cuts can occur; however, in this case such off-cuts are minimal. This is primarily due to the design being closely aligned with standard plasterboard dimensions, which reduces unnecessary trimming.’

This explanation directly reinforces the analysis by linking design standardisation to reduced cutting activities on the production line, thereby limiting the generation of plasterboard offcuts and lowering labour input. Consistent with these findings, Figure 5.3 illustrates the ceiling plasterboard assembly plan and the small number of offcuts generated at external modules, while Figure 5.4 shows the corresponding ceiling plasterboard assembly activities.

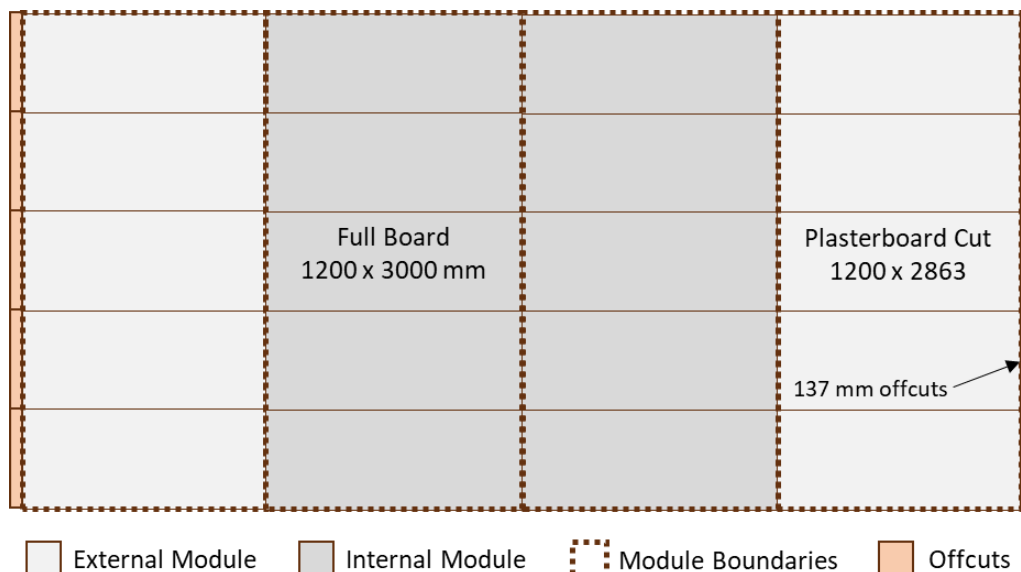


Figure 5.3: Ceiling plasterboard assembly plan and generated offcuts



Figure 5.4: Ceiling plasterboard assembly activities

5.2.2.2 Length/Width-side Wall Plasterboard Offcuts

These offcuts were totally avoided since the used plasterboard size of 2700 mm by 1200 mm covered the net wall dimensions of 2700 mm high and 2400 mm wide exactly with no need for cutting or additional pieces. A closing strip of 400-300 mm at each side of the module was left for final on-site integration (See Figure 5.5). For detailed analysis, a structured RCA approach was adopted using What-How-Why reasoning chain as shown in Table 5.3.

Table 5.3: Wall plasterboard offcuts avoidance - root cause analysis

#	Questions	Explanations
1	What?	Offcuts at the edges of the walls' plasterboard were totally avoided
1	How?	By using plasterboard sizes that match the required wall dimensions
2	Why?	Because of the design consideration to the standard material sizes
3	Why?	Because this design practice promotes production flow and facilitates assembly

Similar to the limited offcuts observed for ceiling plasterboards, the root cause analysis indicates that the avoidance of length- and width-side plasterboard offcuts is primarily attributable to the alignment of design dimensions with standard plasterboard sizes. This strategy is embedded within the factory's practice of designing around standard material dimensions to streamline the assembly process. This interpretation is supported by observation notes from Observation Session A06 (refer to Appendix F), which recorded no trimming activities along board edges during wall lining, as well as by input from Interviewee A06, who noted that '*bays are mostly standard; if they are 3 m height, they buy 3 m boards for those. So, you don't really get waste.*'

In addition, the design analysis presented in Figure 5.5 further supports this interpretation by showing wall layouts that are dimensioned to accommodate full-length plasterboards, with offcuts occurring only locally around openings (discussed at 5.2.2.3). Collectively, the interview, observational, and design evidence confirm that standardised bay dimensions eliminate the need for labour-intensive measuring and cutting, resulting in zero length- and width-side plasterboard offcut generation.

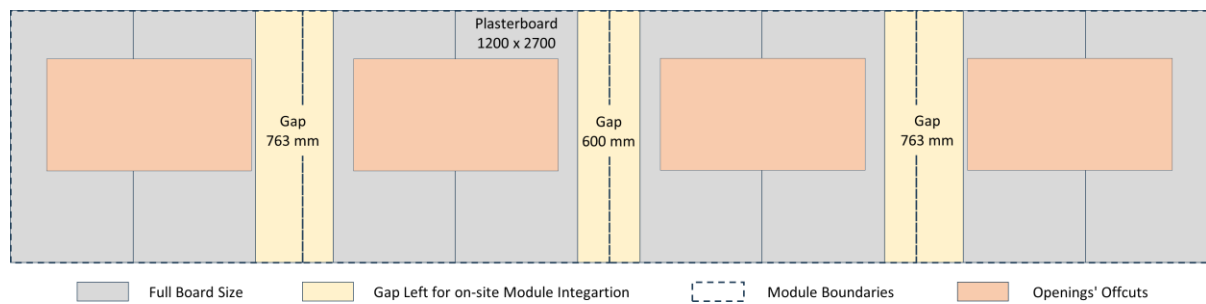


Figure 5.5: Wall plasterboard assembly practice, left integration gaps, and window openings

5.2.2.3 Wall Opening-Related Plasterboard Offcuts

These plasterboards offcuts were generated due to the need to cut out the plasterboard covering the window and door openings, firstly installed as part of the factory practice to streamline production. These offcuts contribute to a significant 12% of the total plasterboard use and over 90% of the total plasterboard offcuts in this project. Based on the observation notes and the interviews conducted, all these offcuts were sent to the recycling bin. For thorough analysis, a structured RCA approach was employed using What-How-Why reasoning chain as shown in Table 5.4:

Table 5.4: Wall opening-related plasterboard offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts at the wall openings are generated in significant amounts
2	How?	By cutting out the plasterboard layer fitted over the openings
3	Why?	Because full plasterboard sizes were firstly fitted over the openings
4	Why?	Because no pre-cutting activity is performed to plan the required cuts around the openings.
5	Why?	Because it is considered more efficient and precise to use full plasterboards and cut out openings as needed
6	Why?	Because the process of optimising and pre-cutting plasterboard around openings is perceived as labour-intensive, time-consuming, and prone to error

Hence, the technical root cause of opening-related plasterboard offcuts is the absence of cut planning around openings at the design and pre-assembly stages. This practice is reinforced at the factory level, as explained by Interviewee A04, who indicated that installing full plasterboards first and subsequently cutting out openings is considered more efficient and accurate than pre-cutting boards to suit opening locations. The justification for this approach is primarily linked to maintaining production flow and reducing the risk of dimensional misalignment during installation, rather than minimising offcut generation. In contrast, planning cuts around openings in advance is perceived as labour-intensive, time-consuming, and more prone to error. This interpretation is further supported by observation notes from Observation Session A06 (refer to Appendix F), which recorded the consistent installation of full boards prior to cutting out window and door openings on the production line. Figure 5.6 illustrates the wall plasterboard assembly plan and the locations of openings that subsequently require cutouts.



Figure 5.6: Plasterboard opening offcuts

5.2.3 Cutting and Fitting Rigid Insulation

As an external sheathing layer, rigid insulation panels of 50 mm in thickness, 1220 mm in width, and 3000 mm in length are used to provide moisture protection and enhance thermal insulation. The observations of rigid insulation cutting and fitting activities covered four modules. Based on the provided drawings, the total required area of rigid insulation for these

modules was 75.6 m², while the total processed area was 76.86 m², resulting in approximately 2% offcuts. Two categories of offcuts were identified: length-side and width-side offcuts. These are described in detail in the following subsections.

5.2.3.1 Width-side Rigid Insulation Offcuts

These offcuts were generated from cutting the required panel strip to fill the last space at each module, given that the module length of 6300 mm requires five full width panels of 1220 mm wide, and a width-side cut of 200 mm. However, the generated offcut at each module was directly integrated into the next, limiting the total generated offcuts at this category to only 2% of total rigid insulation use. Figure 5.7 illustrates rigid insulation assembly practice, generated offcuts, and integrated offcuts. For detailed analysis, a structured RCA approach was adopted using What-How-Why reasoning chain as shown in Table 5.5.

Table 5.5: Width-side rigid insulation offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts associated with the width side of rigid insulation panels were minimal
2	How?	By consistently integrating offcuts from one module into the next
3	Why?	Due to the workers' manual cutting optimisation skills, which enhance material efficiency and prevent offcut accumulation.
4	Why?	Because this practice improves material utilisation without disrupting production flow.

Therefore, the technical root cause of the limited width-side offcuts is the manual cutting optimisation skills of the production team, who systematically integrated offcuts from one module into the next. This approach is driven by the aim of enhancing material efficiency, as long as it does not compromise the overall efficiency of assembly activities. This interpretation is supported by observation notes from Observation Session A04 (refer to Appendix F), which documented the deliberate retention and re-use of insulation offcuts between adjacent bays, as well as by input from Interviewee A01, who explained that:

'For the insulation between joists, very little. We can usually re-use offcuts by fitting them into the next bay. We throw away very little of that; I wouldn't count it as significant off-cut waste.'

Together, the observational and interview evidence directly support the analysis that skilled manual optimisation enables the effective reintegration of width-side offcuts, thereby limiting

material waste without disrupting production efficiency. This finding is further reinforced by the design analysis shown in Figure 5.7, which illustrates the rigid insulation assembly practice, the offcuts generated, and their subsequent integration into adjacent modules.

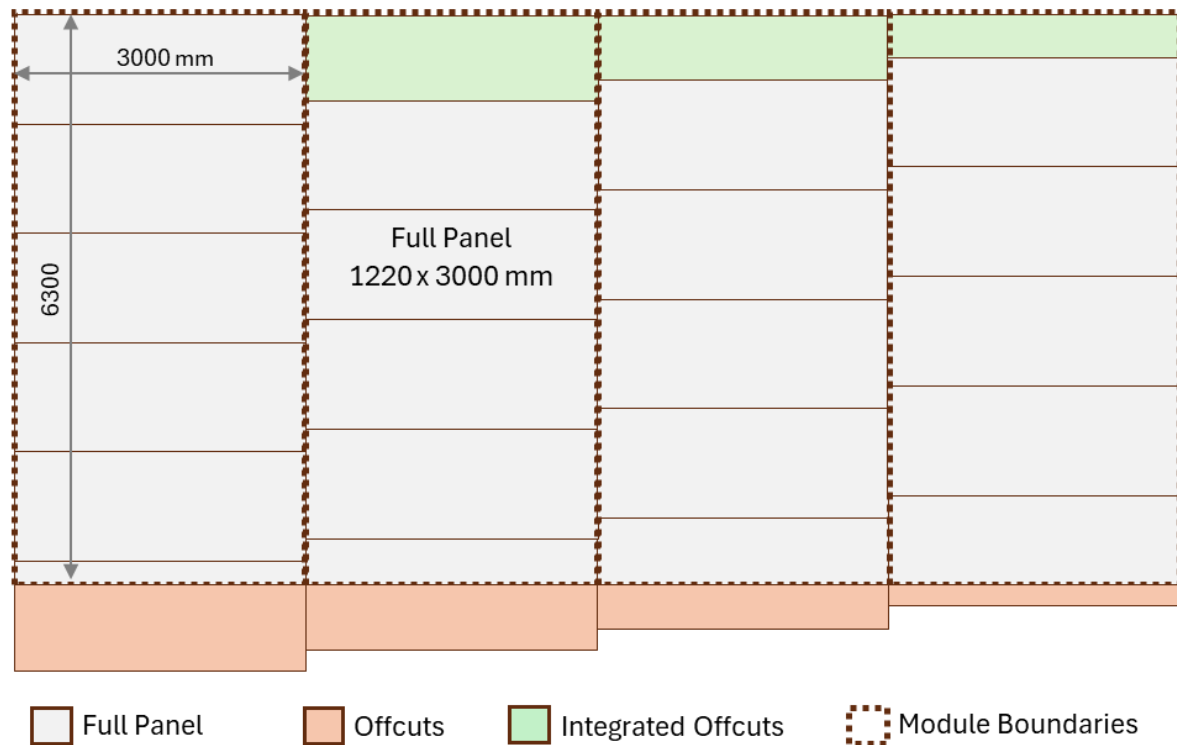


Figure 5.7: Rigid insulation assembly practice, generated offcuts, and integrated offcuts

5.2.3.2 Length-side Rigid Insulation Offcuts

These offcuts were totally avoided by using rigid insulation panel lengths that match modules' width. Both the insulation panels and the module width are at 3000 mm, eliminating the need to cut from the length side of the rigid insulation panels (see Figure 5.7). For thorough analysis, a structured RCA approach was employed using What-How-Why reasoning chain as shown in Table 5.6.

Table 5.6: Length-side rigid insulation offcuts avoidance - root cause analysis

#	Questions	Explanations
1	What?	Offcuts associated with the length-side of the rigid insulation were completely avoided
2	How?	By using rigid insulation panel sizes that match module dimensions
3	Why?	Because of the design consideration to the standard material sizes
4	Why?	Because this design practice promotes production flow and facilitates assembly

Hence, the technical root cause can be identified as the alignment of the design with the standard lengths of rigid insulation panels. This design decision is reinforced at the factory

level because it enhances production flow and streamlines the assembly process by eliminating measuring and cutting. This interpretation is supported by observation notes from Observation Session A04 (refer to Appendix F), which recorded the direct installation of full-length insulation boards without trimming, as well as by input from Interviewee A04, who explained that:

‘Waste was effectively avoided because the bay width was designed to match the standard length of the insulation boards. This alignment meant that the boards fit without trimming, resulting in virtually no insulation waste.’

Together, the observational and interview evidence directly substantiate the analysis by linking dimensional design alignment to zero offcut generation. Figure 5.7 further illustrates the precise fit between the insulation panel length and the module width, confirming how design standardisation results in the complete avoidance of insulation offcuts.

5.2.4 Cutting and Fitting the Floor Decking

For floor decking, 18 mm thick, 1200 mm wide, and 2400 mm tong & groove plywood sheets were used to provide a stable and durable base for further flooring finishes. The observations of the plywood cutting and fitting activities included four modules. The plywood panels were assembled parallel to the module, with the length of both the panels and the module aligned in the same direction as shown in Figure 5.8. Since the used plywood is a tong & groove type, the excess length at the end of each module (the orange pieces in Figure 5.8) can only be reused as a starting piece at the start of the module (the light green pieces in Figure 5.8) to ensure that it can be integrated to other plywood pieces.

Using the drawings provided for the four modules, the total required area of plywood was 75.6 m². In comparison, the total processed area of plywood was 77.76 m², making up to 3% plywood offcuts. Half these offcuts (about 1 m²) were directly discarded in the recycling bin (the dark grey offcuts in Figure 5.8), since their width is just 300 mm, falling below 600 mm, which is the distance between floor joists centres. According to the assembly requirements, plywood offcuts should span at least between two joists to be reused. On the other hand, the other half of offcuts (about 1 m²) was stored for future reuse (the light blue offcuts in Figure 5.8), since its width is 900 mm, spanning between at least two joists. Two offcut categories were observed at each module, including length-side and width-side offcuts. These offcuts are explained in detail in the following subsections.

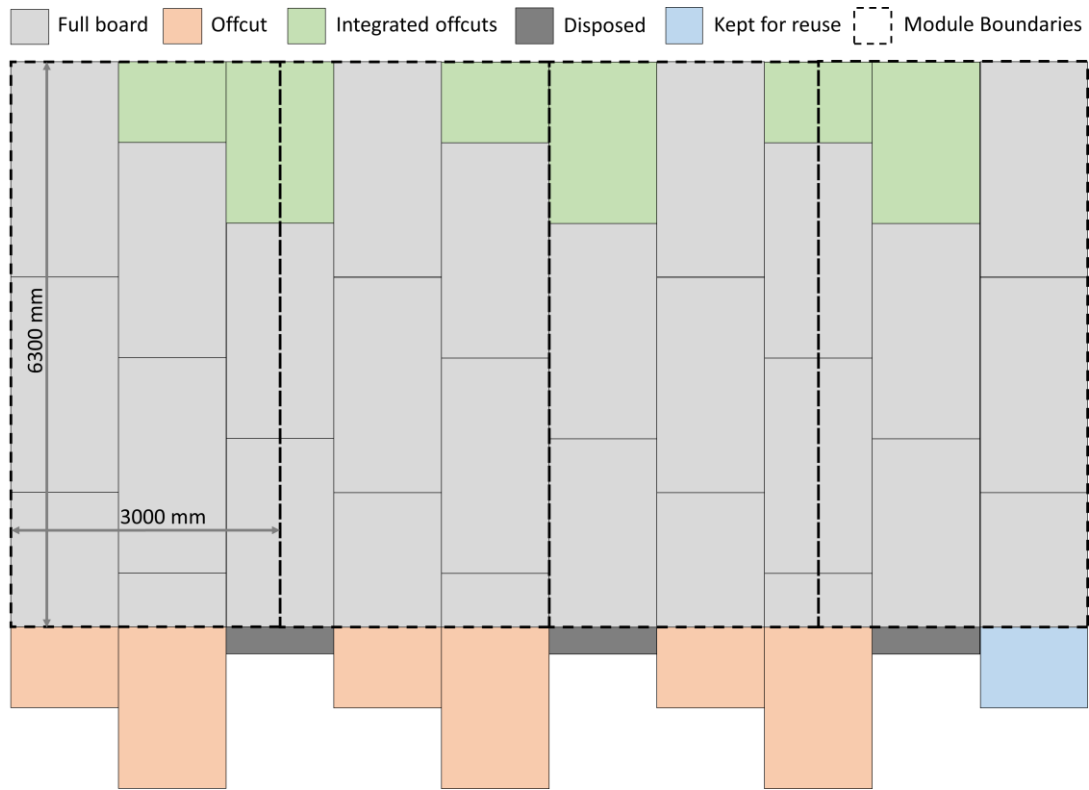


Figure 5.8: Floor decking plywood assembly practice, generated offcuts, and integrated pieces

5.2.4.1 Length-side Plywood Decking Offcuts

These offcuts were generated from the need to cut from the length-side of the last plywood sheets (i.e., the 2400 mm side) to cover the required module length (i.e., the 6300 mm) (see the orange cuts in Figure 5.8). However, these offcuts were consistently integrated as a starting piece in the next line of plywood as long as their length do not fall below 600 mm, which is the minimum length needed to fit on two floor joists. This integration practice saved nearly 10 m² (the light green pieces in Figure 5.8), which makes up to 11% of total material use. Only the offcuts that falls below 600 mm were discarded (the grey pieces) and one piece of 900 mm was stored for further reuse (the light blue piece). Hence, the net generated offcuts are at 3% of the total plywood use. For detailed analysis, a structured RCA approach was adopted using What-How-Why reasoning chain as shown in Table 5.7.

Table 5.7: Length-side plywood decking offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts associated with the length-side of plywood panels were insignificant
2	How?	By consistently integrating offcuts from one module into the next
3	Why?	Due to the workers' manual cutting optimisation skills, which enhance material efficiency and prevent offcut accumulation.
4	Why?	Because this practice improves material utilisation without disrupting production flow.

Therefore, the technical root cause of the minimal length-side plywood offcuts is the manual cutting optimisation skills of the production team, who systematically integrate offcuts generated in one module into subsequent modules. This practice is driven by the objective of enhancing material efficiency, provided that it does not compromise the overall efficiency and flow of assembly operations. This interpretation is supported by observation notes from Observation Session A02 (refer to Appendix F), which recorded the intentional retention and re-use of plywood offcuts across adjacent floor areas, as well as by input from Interviewee A04, who emphasised that: *‘We can usually reuse off-cuts, for example using off-cuts from one side on the other.’*

In addition, the design analysis presented in Figure 5.8 illustrates the floor decking plywood assembly practice, clearly showing the generated length-side offcuts and their subsequent integration into adjacent areas. Collectively, the interview evidence, observational data, and design analysis confirm that skilled manual optimisation plays a central role in minimising length-side plywood offcuts without undermining assembly efficiency.

5.2.4.2 Width-side Plywood Decking Offcuts

These offcuts were totally avoided since the last plywood line at the first and third modules necessitated half board cuts with the other half directly integrated in the second and fourth modules, respectively (see Figure 5.8). In doing so, the direct integration of the generated offcuts saved about 15 m² of plywood (about 16% of total plywood use). For thorough analysis, a structured RCA approach was employed using What-How-Why reasoning chain as shown in Table 5.8.

Table 5.8: Width-side plywood decking offcuts avoidance - root cause analysis

#	Questions	Explanations
1	What?	Offcuts associated with the width-side of plywood panels were avoided
2	How?	By consistently integrating the generated offcuts from one module into the next
3	Why?	Because the offcuts generated in one module are exactly what is needed in the next
4	Why?	Because the design aligns with the width multiples of the plywood panels
5	Why?	Because this design practice promotes production flow and streamlines assembly

Hence, the technical root cause of the avoidance of width-side plywood offcuts is twofold: the alignment of the design with standard plywood width multiples and the production team’s experience in manually integrating usable offcuts into subsequent areas. At the factory level,

these complementary practices are supported because they enhance material efficiency while maintaining a streamlined and reliable assembly process. This interpretation is supported by observation notes from Observation Session A02 (refer to Appendix F), which documented both the use of standard sheet widths and the reallocation of offcuts between floor areas, as well as by input from Interviewee A09, who emphasised that design standardisation is explicitly considered:

‘Yes, it is. The way it’s set up, full sheet, half sheet, helps minimise waste. Your offcut can be used on the next floor.’

In addition, the design analysis presented in Figure 5.8 illustrates the floor decking plywood assembly practice, clearly showing how standard-width sheets generate predictable offcuts that are subsequently integrated into adjacent modules. Collectively, the interview evidence, observational data, and design analysis confirm that the combined effect of design standardisation and skilled manual optimisation enables the effective avoidance of width-side plywood offcuts.

5.2.5 Fitting the Wall Frames, Studs, and Joists

These activities include receiving and fitting the external wall frames, studs, and joists, which are made of light gauge steel. As part of the business model, the manufacturing activities of these sections are outsourced to a light gauge steel manufacturer, and they only arrive to the factory precut in the exact required sizes, ready for final assembly. This was confirmed by the observations and interviews conducted, and hence there is technically no waste associated with the external wall frames, studs, and joists assembly. For detailed analysis, a structured RCA approach was adopted using What-How-Why reasoning chain as shown in Table 5.9.

Table 5.9: Wall frames, studs, and joists waste avoidance - root cause analysis

#	Questions	Explanations
1	What?	material waste associated with the wall frames, studs, and joists manufacturing process is totally avoided in this factory
2	How?	By using pre-finished frame components
3	Why?	Because they were outsourced to specialised manufacturers
4	Why?	Because the factory lacks the necessary equipment to safely handle the fumes produced during the welding of galvanised steel sections.
5	Why?	Because of cost, quality, and safety implications, outsourcing to a specialised manufacturer is seen as more effective.

Hence, the technical root cause behind the avoidance of material waste associated with wall frames, studs, and joists at Factory A is the decision to outsource their production, primarily due to the lack of in-house equipment required to safely manage fumes generated during the welding of galvanised steel sections. This interpretation is supported by input from Interviewee A09 (see subsection 5.2.1), who clarified that the factory does not have the capability to weld galvanised components internally and has therefore historically relied on external suppliers to fabricate box frames and wall panels using their own systems. This technical limitation is reinforced at the organisational level, where outsourcing is justified by perceived advantages in cost efficiency, quality assurance, and health and safety risk mitigation compared to in-house fabrication. Consistent with this production strategy, Figure 5.9 illustrates the wall frame components delivered ready for assembly, with no welding activities undertaken within the factory.



Figure 5.9: Fitting the wall frames components

5.2.6 Cutting & Fitting Rockwool Insulation

These insulation layers come in 150 mm thick, 1160 mm wide, and 6065 mm long rolls for the roof and floor, and 50 mm thick, 600 mm wide, and 1200 mm long blocks for the walls. The main function of using rockwool insulation is to improve the thermal and acoustic insulation

capacity of the modules. The observations of the cutting and fitting activities of the rockwool insulation covered one module. Using the drawings provided for that module, the total required area for the floor and roof is 37.8 m² while for the walls is 30.88 m². In comparison, the observed quantities of the insulation used were 40.67 m² for the floor and roof and 33.41 m² for the walls. This makes around 7% insulation area lost at both the roof/floor and wall cavities. For thorough analysis, a structured RCA approach was employed using What-How-Why reasoning chain as shown in Table 5.10.

Table 5.10: Rockwool insulation waste - root cause analysis

#	Questions	Explanations
1	What?	Loss of rockwool insulation volumes
2	How?	By slightly overfilling the cavities with more insulation than required
3	Why?	Because insulation pieces are intentionally cut slightly larger than the cavity size
4	Why?	To ensure a complete fill with no gaps
5	Why?	Because manual measurement and cutting lack precision
6	Why?	Because speed and convenience are prioritised over precision during installation

Hence, the technical root cause behind the overstuffing of rockwool insulation is the limited precision inherent in manual cutting, combined with the operational need to fill wall cavities as quickly as possible. This relationship is explicitly articulated by Interviewee A09, who explained that:

‘Like with any manual work, there’s some variability in cutting. The insulation rolls come in at 1200 millimetres, and they’re cut by hand with a saw. You sometimes get variation in width 600, 620, or 650 millimetres depending on the cut. This can lead to overstuffing’

This explanation directly supports the analysis by linking cutting variability to the observed overfilling of cavities. Consistent with this account, observation notes from Observation Session A05 (refer to Appendix F) recorded instances of insulation being compressed to fully occupy cavities rather than being re-cut to precise dimensions. Collectively, the interview evidence and observational data indicate that this practice reflects the factory’s prioritisation of assembly flow and speed over cutting precision, thereby compromising material efficiency. Figure 5.10 illustrates the overstuffed insulation within the wall cavities.



Figure 5.10: Rockwool insulation overstuffing practice

5.2.7 Fitting the Roof Sheet Panels

These panels come in 100 mm thick, 1000 mm wide, and in custom lengths. The major functions of these panels are to provide the required structural, thermal, and environmental performance as a roof sheet. Based on the observations and interviews conducted, no waste was reported from the roof sheet assembly. To better understand how waste is avoided, two key categories of offcut avoidance can be identified and justified as per the following subsections:

5.2.7.1 Length-side Roof Sheet Offcuts

These offcuts were totally avoided since the lengths of the roof sheet panels were ordered in the exact required lengths, arriving to the factory ready for assembly. This was confirmed by the observations and interviews conducted, and hence there was technically no waste associated with the roof sheet assembly. For detailed analysis, a structured RCA approach was adopted using What-How-Why reasoning chain as shown in Table 5.11.

Table 5.11: Length-side roof sheet offcuts avoidance - root cause analysis

#	Questions	Explanations
1	What?	Offcuts associated with the length side of the roof sheet were completely avoided
2	How?	By using panel lengths that precisely match the required module dimensions
3	Why?	Because the procurement process was arranged to source custom-length panels
4	Why?	To streamline the assembly process by eliminating the need for in-house cutting
5	Why?	Because in-house cutting is time-consuming and labour-intensive.

Therefore, the technical root cause behind the avoidance of length-side offcuts is the procurement decision to source custom-length roof panels. This practice is actively promoted at the factory level because it streamlines assembly activities and eliminates the need for in-house cutting, which is both time-consuming and labour-intensive. This rationale is clearly articulated by Interviewee A09 when describing the avoidance of length-side roof sheet waste:

‘It’s similar to the cladding. Everything is designed and procured early on, so the supplier provides the correct sizes.’

This explanation directly supports the analysis by linking early design finalisation and procurement to the elimination of in-house cutting and associated offcuts. Consistent with this account, observation notes from Observation Session A03 (refer to Appendix F) confirmed the installation of pre-cut roof sheets without any length-side trimming. In addition, the design analysis presented in Figure 5.11 illustrates the observed roof sheet assembly practice in Factory A, demonstrating how custom-length procurement results in zero length-side offcuts. Collectively, the interview evidence, observational data, and design analysis substantiate the role of procurement-led design alignment in avoiding length-side roof sheet waste.

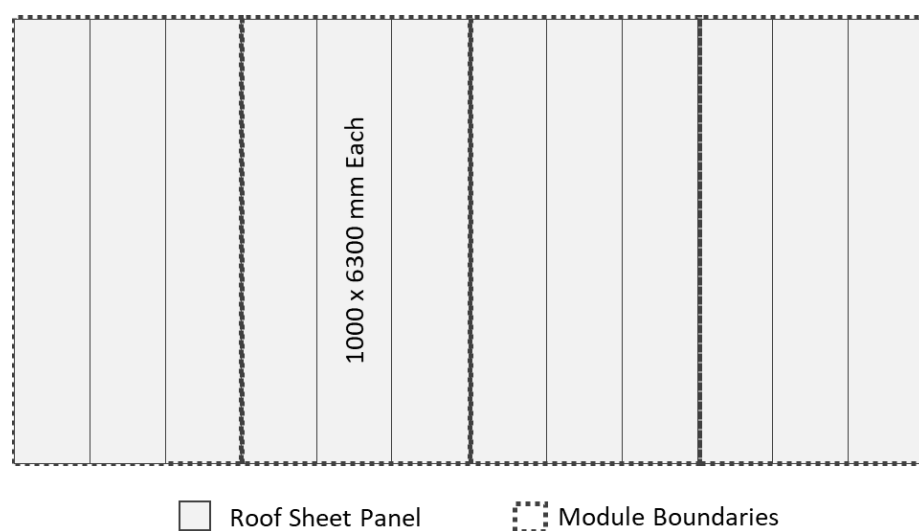


Figure 5.11: Roof sheet assembly plan

5.2.7.2 Width-side Roof Sheet Offcuts

These offcuts were also completely avoided because the width of the roof sheet panel (1000 mm) is an exact multiple of the module width (3000 mm). This resulted in an exact fit of three panels per module with no need for cutting. For thorough analysis, a structured RCA approach was adopted using What-How-Why reasoning chain as shown in Table 5.12.

Table 5.12: Width-side roof sheet offcuts avoidance - root cause analysis

#	Questions	Explanations
1	What?	Offcuts associated with the width-side of the roof sheet panels were completely avoided
2	How?	By using roof sheet panel width that matches module dimensions
3	Why?	Because of the design consideration to the standard panel size
4	Why?	Because this design practice promotes production flow and facilitates assembly

Hence, the technical root cause for the avoidance of width-side roof sheet offcuts is the alignment of the design with standard roof panel widths. This design approach is driven by the factory's prioritisation of streamlining the assembly process by eliminating the need for pre-assembly or on-line cutting. This interpretation is supported by observation notes from Observation Session A03 (refer to Appendix F), which recorded the direct installation of full-width roof sheets without trimming. In addition, the design analysis presented in Figure 5.11 illustrates the roof sheet assembly plan, showing three roof sheet panels fitting precisely within each module, thereby confirming that standard width alignment results in zero width-side offcuts.

5.2.8 Cutting and Fitting Cladding Panels

These panels are made of high-performance composite insulation layer that provides both thermal efficiency and architectural appeal. These panels come in 100 mm thick, 1190 mm wide, and in various lengths. The observations of the cladding panels cutting and fitting activities covered four modules. Based on the provided drawings for the four modules, the total required area of the cladding panels is calculated as 96.24 m², while the total processed area was 129.5 m². This means that the total offcuts generated is 33.28 m², making about 26% of the total material use, all of which were directly discarded into the recycling bin. These offcuts can be categorised in three categories as follows:

5.2.8.1 Width-side Cladding Panels Offcuts

These offcuts were generated from the need to cut from the width-side of the last layer of the cladding panels to meet the required module height (see the orange areas in Figure 5.12). The total module height is 3,175 mm, necessitating two full width cladding panels (1190 mm each) and a final cut of 795 mm. This means that 395 mm wide offcuts being generated around the external walls of the four modules. In total, these offcuts make 11% of the total cladding panels

use. For detailed analysis, a structured RCA approach was adopted using What-How-Why reasoning chain as shown in Table 5.13.

Table 5.13: Width-side cladding panel offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts associated with the width-side of the cladding panels are generated in significant amounts
2	How?	By using a full-width cladding panel of 1190 mm to cover the final 795 mm-high section
3	Why?	Due to the lack of a custom-width cladding panels sourcing
4	Why?	Because custom-width cladding panels are not usually produced by manufacturers and so ordering them can be costly and entail longer lead times

Thus, the technical root cause can be identified as the lack of custom-width ordering, which would be necessary to eliminate these offcuts by sourcing materials in the exact required dimensions. At the organisational level, this option is not pursued due to the perceived higher costs and longer lead times associated with custom-width orders, despite the resulting compromise in material efficiency. This reasoning is clearly articulated by Interviewee A09, who explained that:

‘Historically, when we used Kingspan before Grenfell disaster, you could order any size panel you needed. With Rockwool panels, they generally come in one or two sizes. So, we’ve lost the ability to get them cut to size. Everything we buy now has to be cut at the factory, and unfortunately, that offcut becomes waste.’

This explanation directly supports the analysis by linking procurement constraints and material availability to the generation of unavoidable offcuts. Consistent with this account, observation notes from Observation Session A07 (refer to Appendix F) recorded cutting of standard-width panels and the accumulation of unusable offcuts. In addition, the design analysis presented in Figure 5.12 illustrates the cladding panel assembly plan and the resulting generated offcuts. Collectively, the interview evidence, observational data, and design analysis confirm that limitations in supplier customisation are a key driver of width-side cladding panel waste.

5.2.8.2 Length-side Cladding Panels Offcuts

These offcuts were totally avoided since the lengths of the cladding panels were ordered in the exact needed lengths, come to the factory ready to be assembled. This was confirmed by the

observations and interviews conducted, and therefore there was no offcuts reported at the length-side of the cladding panels. For thorough analysis, a structured RCA approach was adopted using What-How-Why reasoning chain as shown in Table 5.14.

Table 5.14: Length-side cladding panel offcuts avoidance - root cause analysis

#	Questions	Explanations
1	What?	Offcuts associated with the length-side of the cladding were completely avoided
2	How?	By using cladding panel width that matches module dimensions
3	Why?	Because the procurement process was arranged to source custom-length panels
4	Why?	To streamline the assembly process by eliminating the need for in-house cutting
5	Why?	Because cutting the panels in the factory is time-consuming and labour-intensive

Therefore, the technical root cause behind the avoidance of length-side cladding panel offcuts is the procurement decision to source custom-length panels. This decision is reinforced at the organisational level because it streamlines the assembly process by eliminating the need for in-house cutting, which is labour-intensive and time-consuming. This rationale is clearly articulated by Interviewee A09, who explained that:

‘That’s part of the early-stage design and procurement process. The design drawings are provided to the supplier, who then cuts the panels to the exact size. This is all planned during the design and bill-of-materials stage’

This explanation directly supports the analysis by linking early design finalisation and procurement planning to the complete avoidance of length-side offcuts during installation. Consistent with this account, observation notes from Observation Session A07 (refer to Appendix F) recorded the installation of pre-cut cladding panels without any length-side trimming on site. In addition, the design analysis presented in Figure 5.12 illustrates the cladding panel assembly plan and confirms how custom-length procurement results in zero length-side offcuts. Collectively, the interview evidence, observational data, and design analysis substantiate the role of procurement-led design alignment in avoiding length-side cladding panel waste.

5.2.8.3 Cladding Panels Openings Offcuts

These offcuts were generated from the need to cut out the cladding material layer covering door and window openings. These offcuts make up to 15% out of the total cladding panels use and

57% of total cladding panels offcuts. Although all opening heights were designed to match the cladding panel width, the assembly practice involved installing full panels first and then cutting out the openings (see the dark grey area at Figure 5.12). For detailed analysis, a structured RCA approach was followed using What-How-Why reasoning chain as shown in Table 5.15.

Table 5.15: Wall opening-related cladding offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts at the wall openings are generated in significant amounts
2	How?	By cutting out the cladding layer fitted over the openings
3	Why?	Because full cladding panel sizes were firstly fitted over the openings
4	Why?	Due to the lack of pre-cutting procedure for the openings
5	Why?	Because it is considered more efficient and precise to use full panel size and cut out openings as needed
6	Why?	Because the process of optimising and pre-cutting the cladding panels around openings is perceived as labour-intensive, time-consuming, and prone to error

Therefore, the technical root cause of cladding panel offcut generation around openings is the absence of a pre-cutting procedure at the design or pre-assembly stage. Instead, this practice is driven by the factory's preference for an ad hoc cutting approach, which is perceived to streamline production and reduce the risk of dimensional misalignment during installation. This rationale is supported by observation notes from Observation Session A07 (refer to Appendix F), which recorded the installation of full-size cladding panels followed by on-site cutting to form window apertures. It is further reinforced by input from Interviewee A05, who explained that:

‘For windows, we order composite panels sized to cover the full opening, then cut the exact aperture’.

Together, the observational and interview evidence directly support the analysis by linking the absence of pre-cutting to the generation of opening-related offcuts. Figure 5.12 illustrates the wall opening-related cladding offcuts resulting from this installation practice, while Figure 5.13 shows the cutting out of cladding openings being carried out within the factory.

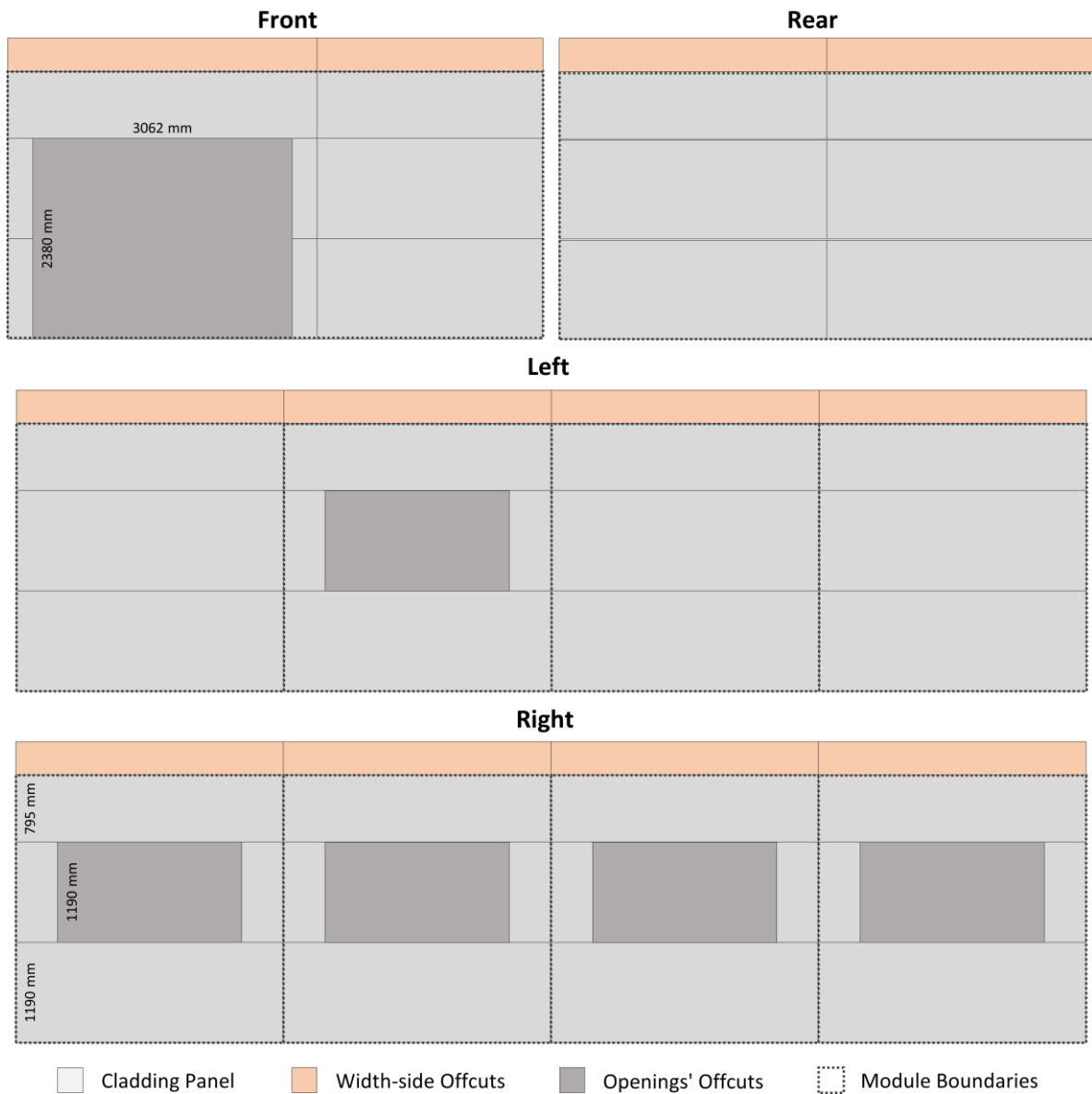


Figure 5.12: Cladding panels assembly plan and generated offcuts

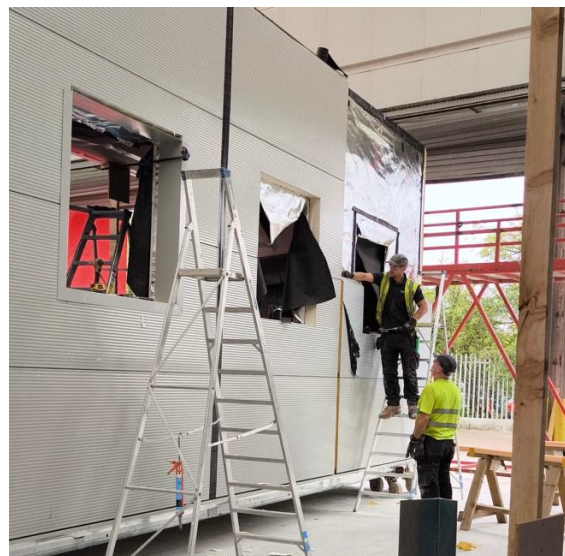


Figure 5.13: Wall opening-related cladding offcuts

5.2.9 Summary - Factory A

This section provided a detailed analysis of how, how much, and why material waste is generated across different components in Factory A. This factory is part of a large-scale firm producing steel-frame modular products with limited automation, primarily serving commercial, educational, and healthcare projects. Material waste was particularly observed and recorded during fitting and cutting activities. Across some fitting activities, waste was generated in two key ways: 1) full material boards were directly fitted over openings, and the sections covering these openings were later cut out, resulting in substantial offcuts amounting to 12-15% of the material used; and 2) excess volumes of rockwool insulation were stuffed into wall cavities, accounting for approximately 7% of total insulation material used. By conducting factory observations, semi-structured interviews and design document analysis, the root causes behind these inefficiencies were identified as 1) the lack of cut planning that excludes openings and 2) the limited accuracy of the manual work. Across some cutting activities, mostly minor offcuts were recorded, typically due to slight material adjustments or nesting prior to assembly. Notably, significant waste reduction was achieved in components such as plasterboards, which were mostly designed to align with standard material sizes.

5.3 Factory B

The second case is a timber frame wall panel manufacturer based in the UK, mainly producing for residential low-rise projects. The subject of the case is the production process of the wall panels with material waste generation, or avoidance represent the object under investigation. The construction materials used in the production process are considered as the units of analysis to study material waste generation and avoidance in OSC.

Figure 5.14 illustrates the stages and activities of producing a wall panel in this factory. The first stage includes panel assembly while the second stage is focused on cladding assembly. The activities highlighted in yellow represent material application activities where material waste can be generated. Activities marked with a worker symbol are manual and performed using basic tools (e.g., handsaw, knife). In contrast, activities marked with a worker-and-gear symbol are semi-automated, involving the use of mechanical tools (e.g., powered saw). Additionally, activities marked with a gear symbol are automated and require only minimal human intervention. Each one of these activities were directly observed in the factory to identify how, how much, and why material waste is generated or avoided.

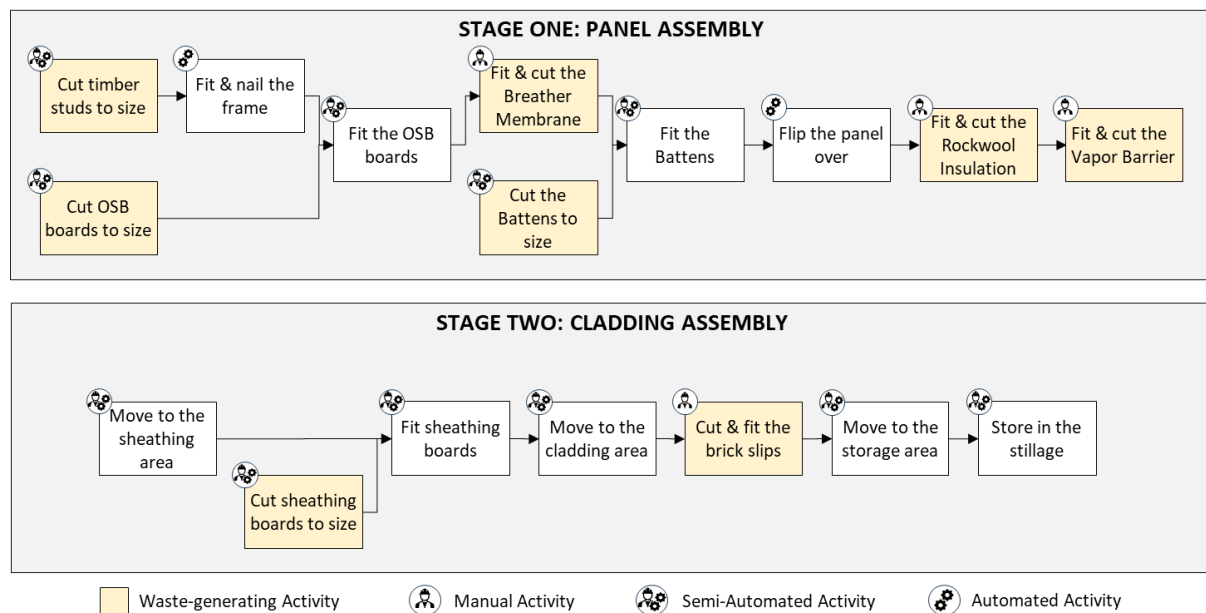


Figure 5.14: Factory B - Timber frame wall panel assembly activities

5.3.1 Cutting and Fitting Timber Frame Sections

The timber frame sections represent the major structural material of the wall panel, where different strength classes are used including C16 and C24. These sections are produced using 4800 mm and 5400 mm timber sizes which are popular in the UK market. The observations of

the cutting activities of the timber sections covered eight panels. However, due to the speed of cutting and the difficulty to follow with saw operator worker which section is being cut and what is generated as a result, the focus was shifted to separating the generated offcuts and measuring them. This is followed by relating different offcuts back to their causing cutting practices with the help of the saw operator as well as the cutting list provided. This was agreed to ensure no, or limited interruptions are caused while conducting the observations. Figure 5.15 shows the separated offcuts of timber during the observations.



Figure 5.15 : Separating and measuring timber offcuts

Based on the drawings provided for the eight panels, the total required length of timber for the eight panels was calculated as 825,207 mm. With this in mind, the total length of offcuts was measured as 120,672 mm, of which 51,057 mm directly sent to the recycling bin while 69,615 mm was separated and stored for further reuse. Based on the factory practice, any timber offcut shorter than 600 mm is directly discarded in the recycling bin. This means that the total generated offcuts make up to 13% of the total material use, 42% of which were directly sent to the recycling bin and 58% were stored for further reuse (see Appendix B – Table 2 & 3 for detailed calculations). In total, three main categories of offcuts were identified, each is explained in the following subsections:

5.3.1.1 435 mm Offcuts

This length of offcuts was repeated 89 times, contributing to 4.1% of the total timber use and 32% of the total generated timber offcuts. Based on the observation notes and the interview with the saw operator, these offcuts were generated from cutting two studs' of 2453 mm out of the 5400 mm standard length of timber. For precise calculation, an initial piece of 50 mm was consistently cut at each new timber lump and nearly 9 mm were wasted in the saw cuts, leaving

a piece of 435 mm offcut (See Figure 5.16). All the 89 offcuts were planned to be discarded directly into the recycling bin as part of the common factory practice. For detailed analysis, a structured RCA approach was followed using What-How-Why reasoning chain as shown in Table 5.16.

Table 5.16: 435 mm offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts measuring 435 mm in length were generated from cutting timber studs
2	How?	By using a timber section that spans more than two stud spaces
3	Why?	Because cutting two studs, each 2453 mm long, from a 5400 mm timber section leaves a remaining piece of approximately 435 mm
4	Why?	Because 5400 mm timber is a popular standard length readily available in the market, while 5000 mm timber is uncommon and require a special order
5	Why?	Because 5100 mm is a non-standard length, ordering it would result in higher costs and longer lead times

Hence, the technical root cause of the 435 mm timber offcuts is the absence of custom-length ordering for 5100 mm timber sections. At the factory level, this decision is reinforced by concerns over the higher costs and longer lead times associated with sourcing non-standard lengths. This trade-off between procurement flexibility and material efficiency is clearly articulated by Interviewee B07, who explained that:

'We generally buy timber in two sizes: 4.8 or 5.4. For apartments, we use 5.4 since we can't get two lengths out of 4.8. Although 5.1 might work, it has a longer lead time. We'd need drawings available well in advance to know which size to order. 4.8 and 5.4 are standard sizes. 5.1 is OK as long as it's preordered with a long lead time.'

This explanation directly supports the analysis by linking standard length procurement practices to the systematic generation of 435 mm offcuts. Consistent with this account, observation notes from Observation Session B01 (refer to Appendix F) recorded the repeated production of uniform short offcuts following cutting operations. In addition, the design analysis presented in Figure 5.16 illustrates the cutting pattern responsible for the generation of 435 mm offcuts. Collectively, the interview evidence, observational data, and design analysis confirm that procurement constraints around timber length selection are the primary driver of this offcut type.

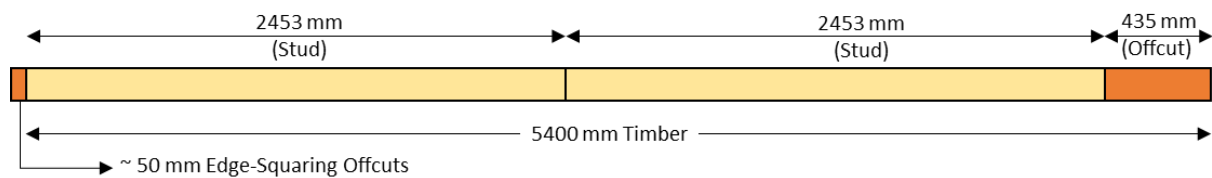


Figure 5.16: 435 mm offcuts generation

5.3.1.2 2290 mm Offcuts

This length of offcuts was repeated 13 times, contributing to 3.1% of the total timber use and 25% of the total timber offcuts. However, all the 13 offcuts were stored for further reuse as part of the common factory practice. Based on the observation notes and the interview with the saw operator, these offcuts were generated from cutting one stud of 2453 mm out of the 4800 mm timber. For precise calculations, an initial cut of 50 mm was consistently cut at each new timber lump and nearly 7 mm were wasted in the saw cuts, leaving a piece of 2290 mm (see Figure 5.17). For thorough analysis, a structured RCA approach was adopted using What-How-Why reasoning chain as shown in Table 5.17.

Table 5.17: 2290 mm offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts measuring 2290 mm in length were generated from cutting timber studs
2	How?	By using a timber section that spans more than one stud space
3	Why?	Because 4800 mm timber was cut to produce a single 2453 mm stud, leaving a significant 2290 mm offcut.
4	Why?	Because the 5400 mm timber was not readily accessible when needed, and using the 4800 mm timber was a faster choice.
5	Why?	Because of the clear prioritisation of production flow, with labour seen as the most expensive resource.

Thus, the technical root cause behind the generation of the 2290 mm offcuts is the failure to coordinate the timely delivery of the closest-sized timber section (i.e., 5400 mm) to the factory cutting area. This logistical constraint is explicitly highlighted by Interviewee B07, who stated:

‘Yes, either the 5.4 material isn’t available in the factory, or we’re waiting for transport to bring it to the saw. It’s all logistics.’

This explanation directly supports the analysis by linking material availability and internal logistics to the cutting decisions made on the production line. Consistent with this account, observation notes from Observation Session B01 (refer to Appendix F) recorded instances where 4800 mm timber was temporarily used to maintain production flow, resulting in the generation of 2290 mm offcuts. This issue, combined with the factory’s clear prioritisation of production continuity over material efficiency, led to the decision to cut 4800 mm sections to produce a single 2453 mm stud until 5400 mm timber was made available near the saw. Although 5400 mm timber is not a perfect fit, it enables two 2453 mm studs to be cut, producing only a 235 mm offcut and thereby significantly reducing offcuts. In addition, the design analysis presented in Figure 5.17 illustrates the cutting pattern responsible for the generation of 2290 mm offcuts. Collectively, the interview evidence, observational data, and design analysis confirm that internal logistics and material handling constraints are the primary drivers of this offcut type.

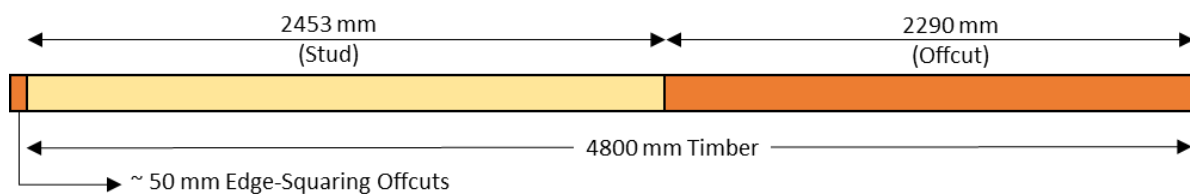


Figure 5.17: 2290 mm offcuts generation

5.3.1.3 50 mm Offcuts

This length of offcuts was repeated 163 times, contributing 0.9% of the total timber use and 7% to the total generated timber offcuts. Based on the observation notes and the interview with saw operator, all the 163 offcuts were directly discarded into the recycling bin as part of the common factory practice. For detailed analysis, a structured RCA approach was employed using What-How-Why reasoning chain as shown in Table 5.18.

Table 5.18: 50 mm offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts measuring about 50 mm were generated at the start of each new timber section
2	How?	By conducting a trim cut to the new timber sections
3	Why?	To ensure a clean, square, and structurally sound edges
4	Why?	Because the mass cutting of raw timber is likely to be uneven and timber drying is likely to cause defected edges.
5	Why?	Because achieving consistently square cuts and protecting edges is time-consuming and costly, making factory trimming more feasible.
6	Why?	Because prefabricators rely on supplier tolerances to avoid extra inspection, ensuring a uniform and efficient production process.

Hence, the technical root cause of these offcuts is the inconsistent quality of supplied timber edges, which are frequently uneven due to mass cutting at the supplier and cracked as a result of natural timber drying. At this factory, the decision to perform a trim cut on all timber edges without prior inspection is a deliberate standard practice aimed at ensuring dimensional consistency and maintaining production efficiency. In addition, timber suppliers typically provide positive length tolerances, which further encourages manufacturers to square all edges before processing. This rationale is explicitly supported by Interviewee B07, who explained the necessity of the initial trim cut:

‘To ensure the stud end is square. It’s the first step in calibrating the saw. Although the timber is ordered at 5.4, lengths can vary slightly, so the CNC saw does an initial cut to set the pusher and blade calibration’.

Consistent with this account, observation notes from Observation Session B01 (refer to Appendix F) recorded the routine execution of initial trim cuts on all incoming timber, regardless of visible edge quality. Figure 5.18 further illustrates the condition of standard timber edges, many of which appear cracked or inconsistent, thereby substantiating the need for this practice.



Figure 5.18: Cracked and uneven standard timber edges

5.3.1.4 Other Offcuts

These offcuts are associated with the cutting process of other timber sections, including top/bottom rails, sill plates, and lintels. These sections come with various lengths and as a result there is no common offcut length that can be investigated in its own. These offcuts accounts for 4.8% of the total timber use. Based on observation notes and an interview with the saw operator, these offcuts were consistently produced despite the saw operator's experience in maximising material use. For thorough analysis, a structured RCA approach was adopted using What-How-Why reasoning chain as shown in Table 5.19.

Table 5.19: Different length timber offcuts generation - root cause analysis

#	Questions	Explanations
1	What?	Offcuts in various lengths are generated
2	How?	By cutting different lengths of different timber sections
3	Why?	Because the cutting process was not optimised across the panels included in the production patch.
4	Why?	Because the current practice favour panel-by-panel cutting practice.
5	Why	Because of the need to adhere to strict production schedule, necessitating a panel-by-panel cutting practice.

Hence, the technical root cause behind these offcuts is the absence of an effective nesting practice that integrates cutting operations across different wall panels. Instead, cutting activities are organised on a panel-by-panel basis to align with the production schedule, reflecting the factory's prioritisation of time efficiency and workflow continuity over material optimisation. This interpretation is supported by observation notes from Observation Session B01 (refer to

Appendix F), which recorded sequential cutting of individual panels rather than batch-based or cross-panel optimisation.

The one-by-one cutting approach practice is explained by Interviewee B01, who noted that:

‘These sections are individual, so there’s only one of them, and I’m putting each one of these through singularly’.

In addition, Interviewee B05 contrasted this with automated optimisation methods, explaining that:

‘Instead of cutting one panel at a time, an optimisation program would cut all the panels all at once—but it would cut a bit from this panel, a bit from that panel, a bit from another panel. It can get very confusing.’

Collectively, the interview evidence and observational data confirm that the deliberate avoidance of cross-panel nesting, driven by concerns over production complexity and schedule control is the primary contributor to the generation of these offcuts.

5.3.2 Cutting OSB Boards

The OSB boards were used as a sheathing material to enhance the timber frame rigidity and structural integrity. The standard dimensions of these boards are 9 mm thick, 1200 mm wide, and 2400 and 2700 mm long. The observations of the cutting activities of the OSB boards covered 12 panels. Due to the slow process of cutting using a wall saw, the cutting activities were recorded in detail to understand how offcuts are generated.

Based on the drawings provided for the 12 panels, the total required area of OSB material is calculated as 241.63m². In comparison, the total processed area of OSB boards was 286.2 m². This means that the total offcuts generated is 44.56 m², making about 15.6% of the total material use, of which 6.3% were directly discarded into the recycling bin and the remaining 9.2% was separated and stored for further reuse (see Appendix B – Table 4 for full OSB cutting data). For detailed analysis, four key categories of offcuts were identified as per the following subsections:

5.3.2.1 Length-side OSB Board Offcuts

These offcuts were generated from cutting 115 mm strip from the 2700 mm side of the OSB boards, contributing to 5.6% of total OSB use and 36% of the total OSB waste (see Figure

5.19). Based on the observation notes and the interview with the saw operator, all these offcuts were directly discarded into the recycling bin as part of common factory practice, which includes discarding any OSB strip smaller than 150 mm. For thorough analysis, a structured RCA approach was adopted using What-How-Why reasoning chain as shown in Table 5.20.

Table 5.20: Length-side OSB board offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts associated with the length-side of the OSB boards were generated
2	How?	By using OSB boards larger than the required panel height
3	Why?	Because the closest standard OSB length is 2700 mm, which is 115 mm longer than the required panel height
4	Why?	Because of the limited design consideration to the standard OSB size
5	Why?	Because design customisation is prioritised over material efficiency and production flow

Hence, the technical root cause of the 115 mm OSB offcut generation is the limited consideration given to standard OSB sheet sizes during the design stage. This practice reflects a tendency to prioritise design customisation over material efficiency and production production flow, resulting in repetitive small offcuts at the panel edges. This interpretation is supported by observation notes from Observation Session B02 (refer to Appendix F), which recorded the routine generation and disposal of narrow OSB strips during panel sheathing operations.

The analysis is further reinforced by input from Interviewee B02, who explicitly highlighted the importance of aligning design with standard material dimensions, stating that

‘Standardisation of design around standard material sizes is possible—so, designing around OSB sizes and stud sizes’

This comment directly supports the analytical interpretation that greater dimensional coordination at the design stage could have prevented the observed offcuts. In addition, the design document analysis presented 5.21 illustrates the repeated generation and disposal of 115 mm OSB offcuts, thereby visually substantiating the link between design dimensional choices and material waste. Collectively, the interview evidence, observational data, and design analysis confirm that insufficient design alignment with standard OSB sizes is the primary driver of this offcut type.



Figure 5.19: Length-side OSB offcuts

5.3.2.2 Width-side OSB Boards Offcuts

These offcuts were produced from cutting different widths from the 1200 mm side of the OSB boards, contributing to 6.6% of total OSB use and 42% of the total generated OSB offcuts. Based on the observation notes and the interview with the worker in charge of cutting OSB boards, all these offcuts were stored for further reuse as part of the common factory practice. For detailed analysis, a structured RCA method was followed using What-How-Why reasoning chain as shown in Table 5.21.

Table 5.21: Width-side OSB board offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts associated with the width-side of the OSB boards were generated
2	How?	By cutting 1200 mm OSB sheets into random sizes to fit varying inter-stud spaces
3	Why?	Because of the automated design tool that auto-generates random ranges of OSB width cuts.
4	Why?	Because the design tool is not configured to generate complementary cuts that align with standard OSB width multiples (e.g., quarters, halves, thirds)

Therefore, the technical root cause of the excessive width-side OSB offcuts is the limited consideration, within design tools and detailing practices, of standard OSB width multiples. Greater restriction of required cuts to predictable fractions of a board, such as halves, thirds, or quarters, would improve material efficiency and accelerate cutting operations. This interpretation is supported by input from Interviewee B03, who highlighted the limited level of production-stage analysis undertaken to integrate cuts across panels, indicating that width

optimisation is not systematically addressed. It is further reinforced by Interviewee B07, who explained the practical implications of current design layouts:

‘We use full-width boards at 1200 wherever they fit in the panel. Width cuts often happen near structural openings like windows or doors. So, depending on the panel layout, there might be a 700-mil width left before a window.’

This explanation directly links design-driven layout constraints around openings to the generation of irregular width-side offcuts. Consistent with this account, observation notes from Observation Session B02 (refer to Appendix F) recorded the accumulation of width-side OSB offcuts stored for potential future reuse, as illustrated in Figure 5.20, although their eventual reuse remained uncertain. In addition, the design document analysis presented in Figure 5.21 illustrates the OSB assembly plan, visually confirming how current panel layouts give rise to non-standard width cuts. Collectively, the interview evidence, observational data, and design analysis substantiate that insufficient design alignment with standard OSB width multiples is the primary driver of excessive width-side OSB offcuts.



Figure 5.20: Width-side OSB offcuts being stored for future reuse

5.3.2.3 Opening Infill OSB Offcuts

These offcuts were generated from the need to produce various opening infill cuts to cover the door and window headers (see sections C and F at Figure 5.21). These offcuts contribute to nearly 3.3% of total OSB use and 21% of the total generated OSB offcuts. Based on the observation notes and the interview with the saw operator, offcuts bigger than 150 mm were stored for further reuse as part of the common factory practice. For thorough analysis, a

structured RCA method was adopted using What-How-Why reasoning chain as shown in Table 5.22.

Table 5.22: Opening infill OSB offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts in different sizes are generated
2	How?	By cutting the opening infill pieces (i.e., door/window headers)
3	Why?	Because the cutting process was not optimised across the panels included in the production patch
4	Why?	Because the current practice favour panel-by-panel cutting practice
5	Why?	Because of the need to adhere to strict production schedule, necessitating a panel-by-panel cutting practice

Therefore, the technical root cause behind these offcuts is the lack of effective nesting applied across the entire design package, which results in missed opportunities to maximise material utilisation across multiple panels. At the factory level, this approach is reinforced by a clear prioritisation of production flow and production flow over material efficiency. Consequently, opening infill cuts are generated on a panel-by-panel basis to ensure that the production line remains continuously supplied with the required components, rather than being optimised across jobs or panels.

This interpretation is supported by observation notes from Observation Session B02 (refer to Appendix F), which recorded isolated cutting of opening infill pieces without reference to potential reuse from other panels. It is further reinforced by input from Interviewee B03, who highlighted the practical constraints on implementing nesting at the shop-floor level:

‘He’s new on the saw. The guy that’s on the saw right now is new. We haven’t had time to tell him about it: “Use this for this,” or, “When this comes down, use it”.’

Collectively, the observational and interview evidence confirm that limited cross-panel nesting driven by skill availability, time pressures, and the prioritisation of uninterrupted production is the primary contributor to the generation of these offcuts.

5.3.2.4 OSB Opening Offcuts

These offcuts were totally avoided at the 12 observed wall panels which have 26 window/door openings. Thanks to the pre-cutting list produced in advance, significant offcuts of about 13%

of the total OSB use (51.44 m²) at the openings were avoided. For detailed analysis, a structured RCA method was pursued using What–How–Why reasoning chain as shown in Table 5.23.

Table 5.23: OSB opening offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts associated with the OSB wall openings are avoided
2	How?	By cutting and fitting the required OSB cuts around the openings
3	Why?	Because the required OSB cuts were pre-planned around the openings in a cutting list
4	Why?	Because the cuts pre-planning comes as part of an automated design tool that produces shop drawings
5	Why?	Due to the perceived feasibility of adopting the automated cutting output in terms of both material efficiency and production flow

Thus, the technical root cause behind the avoidance of opening-related offcuts is the use of pre-planned cutting around openings, enabled through an automated design tool that generates OSB cutting patterns while explicitly excluding door and window areas. This design-led approach is supported at the factory level due to its perceived feasibility in enhancing both production flow and material efficiency.

This interpretation is supported by observation notes recorded during Observation Session B02 (refer to Appendix F), which documented the installation of OSB panels with openings already accounted for in the cutting layouts. In addition, the design document analysis presented in Figure 5.21 illustrates the OSB cutting plan for one of the observed panels, where the letters A-I denote individual OSB cuts and clearly show that door openings are intentionally avoided. Collectively, the observational and design evidence confirm that pre-planned, automated cutting is the key mechanism enabling the avoidance of opening-related OSB offcuts.

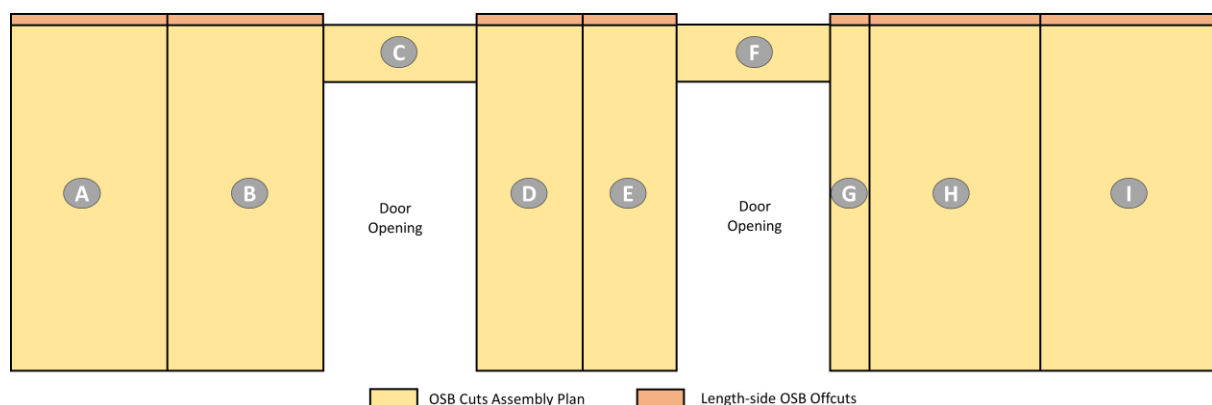


Figure 5.21: OSB cuts assembly plan

5.3.3 Cutting Polyethene Vapour Barrier

The polyethene vapour barrier was cut and fitted on the internal face of the panel to prevent moisture from permeating to the wall panel components. The standard width of the polyethene used is 3000 mm while the required width to cover the panel is 2543 mm. The observations of the cutting activities of the polyethene layer covered eight panels.

Using the drawings provided for the eight panels, the total required area of polyethene is 144.44 m². In comparison, the total processed area of polyethene was 223.95m². This means that the total offcuts generated is 79.51 m², making about 36% of the total material use, all of which were directly discarded into the recycling bin (see Appendix B - Table 5 for detailed polyethene vapour barrier offcuts calculations). These offcuts can be categorised into three major categories explained in the following subsections:



Figure 5.22: Polyethene vapour barrier offcuts

5.3.3.1 Width-side Vapour Barrier Offcuts

These offcuts were generated from cutting the surplus width of polyethene fitted on the internal face of the panels. The required width to be covered at the panel is 2543 mm while the standard width of the sourced polyethene is 3000 mm. This means that 457 mm offcuts were generated consistently across all the observed panels, making about 33 m², all of which were sent to the recycling bin as part of the common factory practice (see the left hand-side excess layer at Figure 5.22). This makes 15% of total polyethene use and 42% of total polyethene offcuts. For thorough analysis, a structured RCA method was followed using What-How-Why reasoning chain as shown in Table 5.24.

Table 5.24: Width-side polyethene vapour barrier offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts associated with width-side polythene layer is generated in significant amounts
2	How?	By using standard polyethene sheet width bigger than required
3	Why?	Because the used polyethene roll is a standard size, that is more readily available and cost-effective to source.
4	Why?	Because sourcing custom-size polyethene rolls is likely to be more expensive and require longer time to source.

Hence, the technical root cause of the width-side polyethene offcuts is the absence of custom-width roll sourcing (e.g., 2500 mm), which would otherwise allow the material to match panel dimensions more closely. At the factory level, this option is not pursued due to the perceived longer lead times and higher costs associated with sourcing custom-size polyethene rolls, leading to a trade-off that favours procurement simplicity over material efficiency.

This interpretation is supported by observation notes from Observation Session B03 (refer to Appendix F), which recorded excess polyethene trimmed along panel edges, as illustrated in Figure 5.22. It is further reinforced by input from Interviewee B04, who explained the dimensional mismatch driving this waste:

‘We have three different sizes of plastic. That’s 3 metres, 4 metres and something over 4 metres. That depends on the size of panels... So, the waste is from the 3 m width when the panel is 2.7.’

5.3.3.2 Length-side Vapour Barrier Offcuts

These offcuts were generated from cutting the surplus length of polyethene fitted on the internal face of the panels. The required length to cover each panel varies according to the panel length indicated in the drawings. However, in most cases 250-300mm polyethene length were consistently added to each panel, generating 6.72 m² offcuts in total, all of which were sent to the recycling bin as part of the common factory practice. This makes 3% of the total polyethene use and 8% of total polyethene offcuts (see the front side excess layer at Figure 5.22). For thorough analysis, a structured RCA method was adopted using What-How-Why reasoning chain as shown in Table 5.25

Table 5.25: Length-side polyethene vapour barrier offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts associated with length-side polythene layer is generated
2	How?	By using polyethene sheet length bigger than required
3	Why?	To facilitate the rapid manual covering of the panel's far edge
4	Why?	Because precise measuring and fitting are seen as time-consuming.
5	Why?	Because labour cost is perceived as the primary source of waste compared to material cost

Therefore, the technical root cause of the length-side polyethene offcuts is the limited precision associated with manual work, which leads operators to apply excess material length to ensure rapid and uninterrupted panel coverage. At the factory level, this practice is explicitly supported because it enhances production flow by reducing the time and labour required for precise measuring and trimming, thereby prioritising speed of installation over material efficiency.

This interpretation is supported by observation notes from Observation Session B03 (refer to Appendix F), which recorded the deliberate use of additional polyethene length beyond panel boundaries, as illustrated in Figure 5.22. It is further reinforced by input from Interviewee B07, who articulated the underlying cost rationale:

'If you're 50-60 mm over, it's not detrimental to the product. The cost of the vapour barrier is not comparable to the cost of the labour. Labour is the biggest cost.'

5.3.3.3 Polyethene Vapour Barrier Opening Offcuts

These offcuts were generated from the need to cut out the polyethene layer covering the openings (i.e., windows and doors). This generates about 39.7 m² offcuts, contributing to 18% of total polyethene use and 50% of total polyethene waste, all of which were sent to the recycling bin as part of the common factory practice. For detailed analysis, a structured RCA method was pursued using What-How-Why reasoning chain as shown in Table 5.26.

Table 5.26: Polyethene vapour barrier opening offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts at the wall openings are generated in significant amounts
2	How?	By cutting out the polyethene layer fitted over the openings
3	Why?	Because full vapour barrier layer is fitted over the entire panel, including openings
4	Why?	Because the vapour barrier must be continuous to ensure airtightness
5	Why?	Because applying a full sheet is the most feasible and time-efficient assembly method known
6	Why?	Due to the lack of advanced material application technology capable of producing custom-shaped sheets that precisely match required panel geometries

Hence, the technical root cause clearly indicates that the generation of these offcuts is linked to the absence of precision-adaptive material application technology capable of producing custom-sized sheets that precisely match the required panel geometry. In the absence of such technology, standard roll dimensions are applied manually, leading to systematic over-application and subsequent trimming. This interpretation is supported by observation notes recorded during Observation Session B03 (refer to Appendix F), which documented manual cutting and adjustment of vapour barrier sheets around openings. In addition, the design document analysis and the sourced vapour barrier roll dimensions confirms that available roll sizes do not correspond to panel-specific requirements, thereby reinforcing the inevitability of these offcuts under current technological and procurement constraints.

5.3.4 Cutting & Fitting Rockwool Insulation

These insulation blocks come in 100 mm thick, 600 mm wide, and 1200 mm long. For the 195 mm panel thickness, two layers were used to insulate the cavities between the panel studs. The main purpose of using rockwool insulation is to enhance the thermal and acoustic insulation capacity of the panels. The observations for the cutting and fitting activities of the rockwool insulation covered one panel.

Using the drawings provided for that panel, the total required volume of rockwool of insulation is calculated as 3.154 m³. In comparison, the total processed volume of insulation was recorded as 3.45755 m³. This means that the total waste is 0.303 m³, making about 9% of the total material use. Particularly, this insulation material volume was wasted when more insulation is packed into a space than required. This happens when the workers put the insulation layers over the cavities required to be filled and cut the needed pieces using a traditional saw. However, the cuts are never perfect with many cuts being performed in different angles rather than right ones. For thorough analysis, a structured RCA approach was adopted using What-How-Why reasoning chain as shown in Table 5.27.

Table 5.27: Rockwool insulation overstuffing waste - root cause analysis

#	Questions	Explanations
1	What?	Loss of rockwool insulation volumes
2	How?	By slightly overfilling the cavities with more insulation than required
3	Why?	Because insulation pieces are intentionally cut slightly larger than the cavity size
4	Why?	To ensure a complete fill with no gaps
5	Why?	Because manual measurement and hand saw cutting lack precision
6	Why?	Because speed and convenience are prioritised over precision during installation

Therefore, the technical root cause of the overstuffing of rockwool insulation is the inadequate precision inherent in manual cutting, combined with the operational need to fill cavities as quickly as possible. This practice reflects the factory's prioritisation of assembly flow over precision in measurement and cutting, thereby compromising material efficiency. This interpretation is supported by observation notes recorded during Observation Session B04 (refer to Appendix F), as illustrated in Figure 5.23, which highlights both manual cutting imperfections (circled) and the resulting overstuffing of rockwool insulation (arrowed). In addition, Interviewee B02 explicitly confirmed the systemic nature of this issue, stating that:

'Only really on the 600 centres, because you've only got 560, and you're always pushing a 600 piece in. So you've got 5–7% extra going in every time, guaranteed. But that extra would otherwise have been cut off and thrown in the bin.'



Figure 5.23: Rockwool insulation overstuffing practice

5.3.5 Cutting & Fitting the Brick Slips

As part of the second stage assembly (see Figure 5.14), the facade of a false brick layer is fitted, which is both lightweight and weather resistant. This layer comes in the form of brick slips, each slip includes 20 standard dimension bricks (i.e., each slip is a third square metre). A special mortar is used to stick these slips on the glass mat sheathing material. The observations of the brick slips cutting and fitting activities covered one panel.

Using the drawings provided for that panel, the total required area of the brick layer is 15.4 m². In comparison, the total processed area of brick slips was 19.2 m². This means that the total offcuts are 3.8 m², making about 20.3% of the total material use. About 3.8% were directly sent

to the recycling bin, whereas 16.5% were kept for further reuse (refer to Table 6 at Appendix B for detailed offcuts calculations). However, due to the fragile nature of the brick slips, many of the kept offcuts are likely to be damaged, ending up also in the recycling bin. The following subsections explain the major categories of brick slip waste generation.

5.3.5.1 Half-Brick Façade Corner Offcuts

These offcuts were generated when using the corner type brick slips around the door and window openings. Particularly, a half brick was cut from the internal side of the corner because the opening design can only accommodate a half brick depth (see the green shapes in Figure 5.25). These offcuts were responsible for 3.8% of the total brick slip use and 19% of the total brick slip waste, all of which was sent to the recycling bin. For detailed analysis, a structured RCA method was pursued using What-How-Why reasoning chain as shown in Table 5.28.

Table 5.28: Brick slip corner offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts associated with the use of brick-slip corners at openings are generated
2	How?	By using oversized corner brick slips at openings
	Why?	Because standard brick slip corners come with full brick shape, while the internal side of the openings only accommodate a half, necessitating half brick cuts.
	Why?	Because of the perceived higher cost and longer lead times associated with sourcing custom-size brick slips

Hence, the technical root cause of these offcuts is the absence of custom-sized brick slip corner units that would fit precisely around openings without requiring half-brick cuts on the internal side. At the factory level, this practice is driven by the perception that sourcing custom corner sizes would involve higher costs and longer lead times, making standard units the preferred procurement option despite the associated waste.

This interpretation is supported by observation notes recorded during Observation Session B05 (refer to Appendix F), which documented repeated cutting of brick slip corners at window and door openings as shown in Figure 5.24. Interviewee B07 explicitly confirmed the scale of this practice, stating that:

‘They come with four “half bricks” in between on both sides. But 70% of all the corners we buy—70%—we cut off 50 mm to make the window and door reveals.’



Figure 5.24: Brick slip corner with half brick depth

5.3.5.2 Other Offcuts

These offcuts were generated due to the need to cut different shapes out of the standard brick slip pieces (see the required cuts' shapes identified in Figure 5.25). These offcuts make 16.5% of total brick slips use and over 81% of total brick slips waste. However, all these offcuts were stored further reuse. The observations included the assembly activities of one wall panel (see Figure 5.25). For comprehensive analysis, a structured RCA method was employed using What-How-Why reasoning chain as shown in Table 5.29.

Table 5.29: Other brick slip offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts in different sizes are generated in significant amounts
2	How?	By cutting different sizes out of the standard brick slip shape
3	Why?	Because the standard brick slip size occasionally matches the required cuts, resulting in excessive offcuts.
4	Why?	Due to the lack of standardised procedure to precut and integrate the required shapes
5	Why?	Because the brick slips are easy to cut and customise, and pre-cutting was excluded to streamline the process and save time.

Therefore, the technical root cause of the excessive brick slip offcuts is the absence of effective nesting practices, which results in missed opportunities to maximise brick slip utilisation across panels and openings. At the factory level, this approach is driven by a clear prioritisation of production flow and workflow continuity over material efficiency, with cutting activities organised to maintain production pace rather than to optimise material yield.

This interpretation is supported by observation notes recorded during Observation Session B05 (refer to Appendix F), which documented panel-by-panel cutting of brick slips without cross-panel optimisation. In addition, the design analysis presented in Figure 5.25 illustrates the brick slip cutting plan and the required cuts, visually confirming how the lack of nesting contributes to the generation of excessive offcuts. Collectively, the observational and design evidence substantiate that insufficient nesting is the primary driver of brick slip offcut generation.

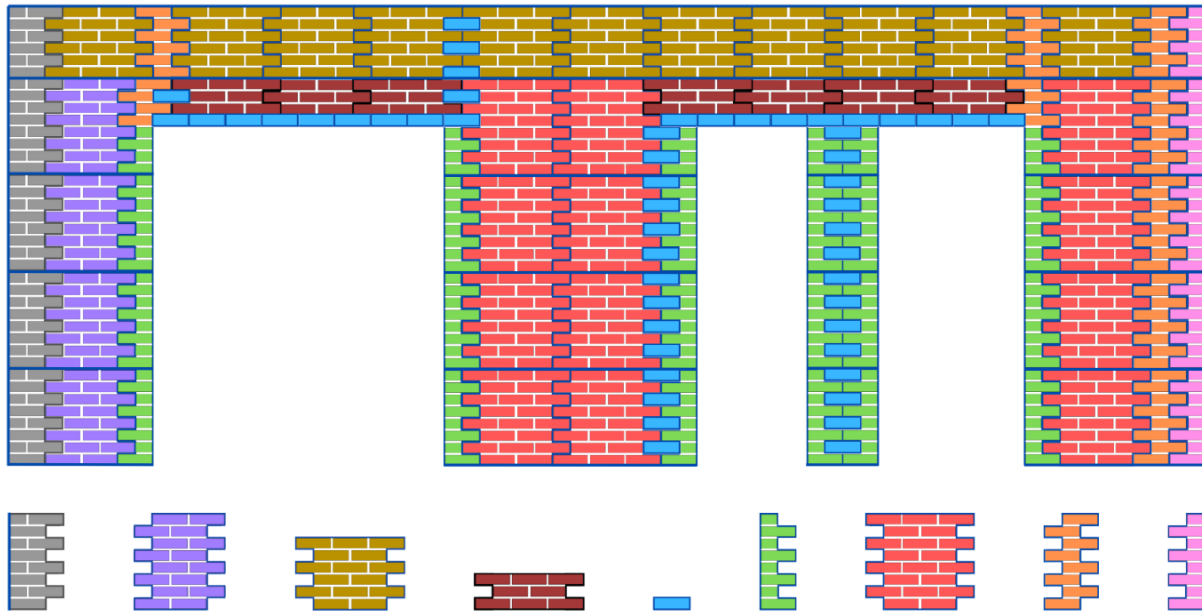


Figure 5.25: Brick slips cutting plan and required cuts

5.3.6 Cutting Timber Battens

Timber batten sections of 60x35 mm were used to provide ventilated cavity and support to the external cladding layer. These battens were pre-cut according to a predetermined cutting list to support more timely and efficient assembly process. The cutting process was performed using an electrical saw that is fully dependent on the worker manual measurement and effort to cut the needed sections (see Figure 5.21). The observations of the timber battens cutting activities covered 15 panels.

Using the cutting list provided for each panel, the total required length of timber battens was calculated as 498.5 m. In comparison, the total processed length of new sections was 534 m. This means that the total offcuts generated is 35.5 m, making about 7% of the total material use. The offcuts smaller than 400 mm made up to 6% of total offcuts and were all sent to the recycling bin. However, the offcuts bigger than 400 mm made only 1% and were all stored for

further reuse bin (see Appendix B - Table 7 for detailed calculations). The following subsections outline two categories of timber battens waste avoidance/generation.



Figure 5.26: Timber battens cutting activity

5.3.6.1 178 mm Offcuts

These offcuts were generated from cutting full timber sections of 3000 mm to produce 2822 mm timber battens. These offcuts were repeated 105 times and all of them were directly discarded in the recycling bin. The total amount of these offcuts was 18.69 m, making about 3.5% of total timber batten sections used and 50% of total timber batten sections offcuts. For detailed analysis, a structured RCA method was adopted using What–How–Why reasoning chain as shown in Table 5.30.

Table 5.30: 178 mm offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts measuring 178 mm of timber battens are generated
2	How?	By using timber sections (3000 mm) larger than required (2822 mm)
3	Why?	Because the 3000 mm sections are the closest standard size in the market that yields the least offcuts
4	Why?	Because of the limited design alignment with the standard material sizes
5	Why?	Because design customisation is prioritised over workflow and material efficiency

Therefore, the technical root cause behind the generation of the 178 mm offcuts can be attributed to the lack of design alignment with standard material sizes. This outcome reflects a clear prioritisation of design customisation over production flow and material efficiency,

resulting in non-standard cut lengths and systematic offcut generation. This interpretation is supported by observation notes recorded during Observation Session B06 (refer to Appendix F), which documented repeated production of uniform short offcuts during batten cutting operations. It is further reinforced by the design document analysis presented in Figure 5.27, which illustrates the dimensional requirements leading to these offcuts.

In addition, Interviewee B03 explicitly confirmed the design-driven nature of the issue, explaining that batten dimensions are dictated by the design team: *‘Battens... to get them put to size—it’s the size that we’ve been given from upstairs,’* referring to dimensions specified by the design team. Collectively, the observational, design, and interview evidence confirm that insufficient design standardisation is the primary driver of the 178 mm offcuts.

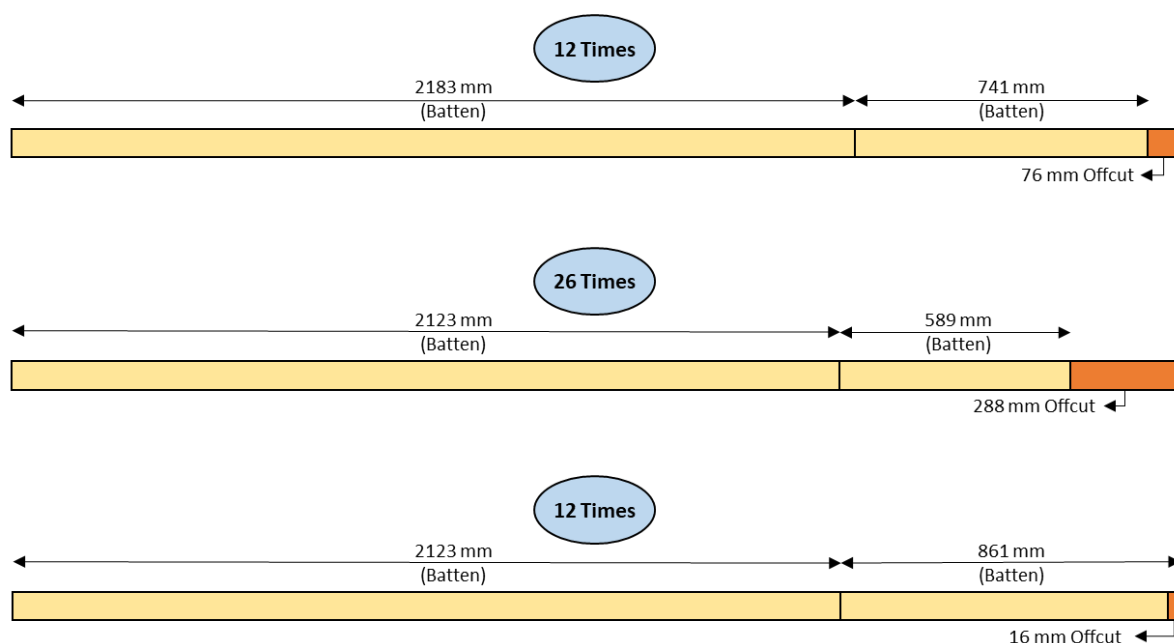


Figure 5.27: Timber batten section integration

5.3.6.2 Other Offcuts

These offcuts were generated from cutting various batten lengths from the standard 3000 mm timber sections. However, a significant portion of these offcuts was efficiently reintegrated into the same job across different panels, with a clear aim to maximise material utilisation. As a result of this cutting optimisation, the remaining offcuts were reduced to just 3.5% of the total timber batten usage. For instance, combining twelve 2183 mm pieces with 741 mm sections resulted in only 76 mm of offcut per full-length batten (see Figure 5.27). Similarly, integrating thirty-eight 2123 mm lengths with twenty-six 589 mm and twelve 861 mm lengths produced offcuts of just 288 mm and 16 mm, respectively (see Figure 5.27). This strategic integration

saved approximately 7% of potential offcuts that would otherwise have been diverted for uncertain reuse. For a detailed evaluation, a structured RCA was conducted using the What-How-Why reasoning chain, as presented in Table 5.31.

Table 5.31: Other timber batten offcuts - root cause analysis

#	Questions	Explanations
1	What?	Limited offcuts generated from cutting different timber batten sections
2	How?	By consistently integrating offcuts from one section into the next
3	Why?	Because of the worker's manual cutting optimisation skills, which enhanced material utilisation and reduced offcut accumulation.
4	Why?	Because this practice improves material utilisation without disrupting production flow

Therefore, the technical root cause for batten cuts integration is the effective manual nesting practice promoted by the saw operator skills and experience. At factory level, this practice is promoted due to its limited implications on production flow and production flow. This interpretation is supported by observation notes recorded during Observation Session B06 (refer to Appendix F), which documented the deliberate identification and retention of usable batten offcuts for subsequent panels.

This practice is explicitly reinforced by input from Interviewee B03, who emphasised the importance of operator experience:

'Someone that knows, that's got experience on the saw—for instance, yeah, on the saw—will know, "This offcut I'll need for another panel".'

In addition, Interviewee B04 highlighted the cognitive aspect of this optimisation, referring to mental nesting prior to cutting:

'If you check all drawings you receive, you can make a plan in your head... same like I was doing on the wall saw.'

5.3.7 Cutting and Fitting Cladding Boards

Gypsum-based boards are used as a backing internal cladding material where external cladding materials (the brick slips in this case) can be fitted. This layer provides better resistance against moisture and fire, improving overall cladding durability. These boards come with standard dimensions of 1200x2400 mm and being cut according to predetermined cutting list to support

more timely and efficient assembly process. The observations of the cladding boards cutting and fitting activities covered four panels.

Using the cutting list provided for each panel, the total required area of boards was calculated as 49.5 m², while the total processed board area was recorded as 63.36 m². This generates about 20.45 m² offcuts, making about 33% of total cladding boards use (refer to Table 8 at Appendix B for further details on the Cladding Boards Offcuts calculations). The observation records shows that 99% of these offcuts were sent for further reuse and the rest were sent to the recycling bin. To explain why these offcuts are generated, the following subsection outlines three key offcuts' categories along with their root cause analyses.

5.3.7.1 Length-side Cladding Board Offcuts

These offcuts were generated from cutting different lengths from the 2400 mm side of the cladding boards, contributing to 19.3% of the total cladding board use and 59% of total cladding board offcuts. Based on the observation notes and the interview with the worker in charge of cutting the cladding boards, all these offcuts were stored for further reuse as part of the common factory practice. For detailed analysis, a structured RCA method was conducted using What-How-Why reasoning chain as shown in Table 5.32.

Table 5.32: Length-side cladding board offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts associated with the length-side of the cladding boards were generated in significant amounts
2	How?	By cutting the panel length into random sizes to fit varying inter-stud spaces
3	Why?	Because of the automated design tool that auto-generates random ranges of cuts.
4	Why?	Because the design tool is not configured to generate complementary cuts that align with standard cladding panel length multiples (e.g., half, one-third, two-thirds)

Therefore, the root cause of the significant length-side cladding offcuts is the limited consideration, within the design tools and detailing practices, of standard cladding board length multiples. Greater restriction of required cuts to predictable fractions of a board, such as halves, thirds, or quarters, would improve material utilisation and streamline the cutting process.

This interpretation is supported by observation notes recorded during Observation Session B07 (refer to Appendix F), which documented repeated cutting of cladding boards into non-standard lengths. In addition, the design document analysis presented in Figure 5.28 illustrates the required cladding board pieces with irregular, non-standard lengths obtained through

lengthwise cutting. Collectively, the observational and design evidence confirm that insufficient design alignment with standard cladding length multiples is the primary driver of these length-side cladding offcuts.

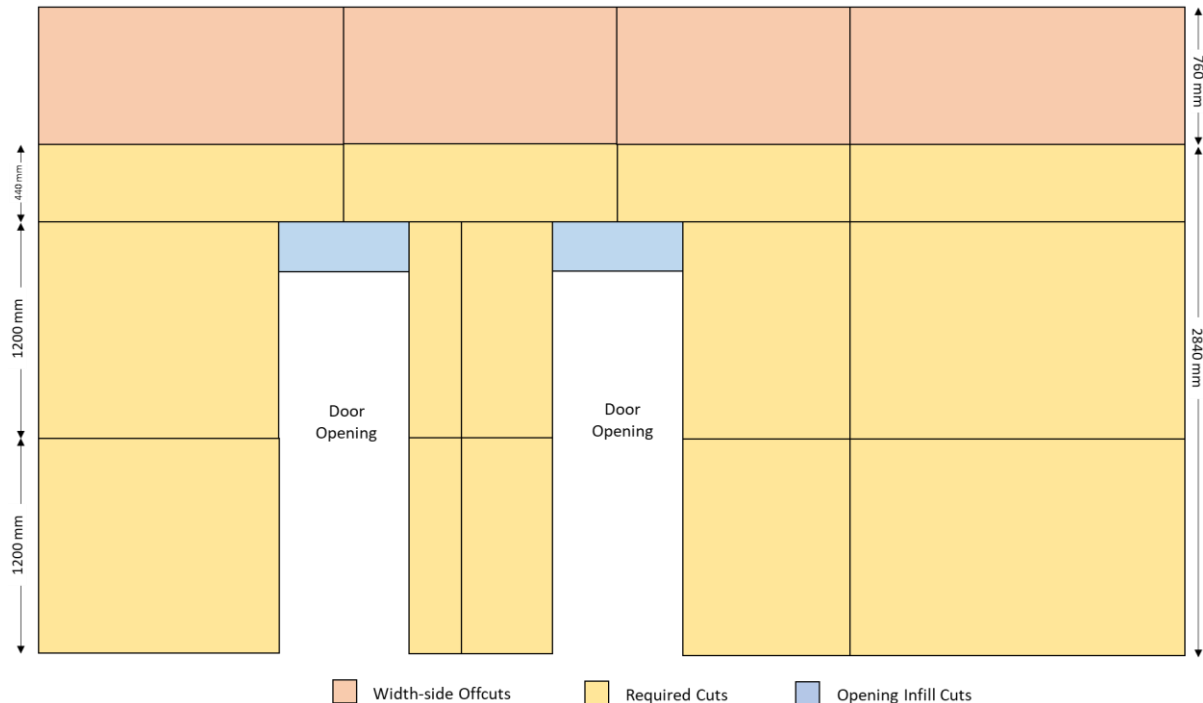


Figure 5.28: Required cladding board cuts, opening infill cuts, and width-side offcuts

5.3.7.2 Width-side Cladding Board Offcuts

These offcuts were generated from cutting 760 mm out of the 1200 mm board width to reach the required height of the panel (see the red areas at Figure 5.23). These offcuts contribute to 11.1% of the total generated offcuts, all of which stored for further reuse as part of common factory practice. For detailed analysis, a structured RCA method was pursued using What-How-Why reasoning chain as shown in Table 5.33.

Table 5.33: Width-side cladding board offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts associated with width-side cladding boards are generated in significant amounts
2	How?	By using standard cladding boards with a width multiple of (3 x 400 mm) slightly smaller than the required cut height of 440 mm
3	Why?	Because of the limited design consideration to the standard board width multiples (i.e., thirds), resulting in missed opportunities for cuts nesting
4	Why?	Because design customisation is prioritised over production flow and material efficiency

Hence, the technical root cause can be identified as the limited consideration, at the design stage, of standard material size multiples (e.g., thirds). This waste-generating practice is supported at the factory level due to the clear prioritisation of design customisation over material efficiency, with production activities configured to comply with architect-driven dimensions rather than optimised material modules.

This interpretation is supported by observation notes recorded during Observation Session B07 (refer to Appendix F), which documented the generation of width-side offcuts during panel fabrication. It is further reinforced by the design document analysis presented in Figure 5.23, which illustrates the width-side offcuts (highlighted in red) being cut to achieve the required panel height. In addition, Interviewee B02 explicitly confirmed the dominance of architectural intent over material optimisation, stating that:

‘Everything we do is driven by architecture... the architect has already predetermined the heights, widths, structural openings, and gaps between them, and we’re then pricing our panelised system to manufacture to that design.’

Collectively, the observational, design, and interview evidence confirm that limited design alignment with standard material multiples is the primary driver of these width-side offcuts.

5.3.7.3 Opening Infill Cladding Boards Offcuts

These offcuts were generated from the need to produce various opening infill cuts to cover the door and window headers (see the light blue pieces in Figure 5.23). These offcuts contribute to nearly 2.3% of total cladding use and 7% of the total generated cladding offcuts. For thorough analysis, a structured RCA method was adopted using What–How–Why reasoning chain as shown in Table 5.34.

Table 5.34: Opening infill cladding boards offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts in different sizes are generated
2	How?	By cutting the opening infill pieces (i.e., door/window headers)
3	Why?	Because the cutting process was not optimised across the panels included in the production patch
4	Why?	Because the current practice favour panel-by-panel cutting practice
5	Why?	Because of the need to adhere to strict production schedule, necessitating a panel-by-panel cutting practice

Therefore, the technical root cause of these offcuts is the absence of effective nesting applied across the design package, leading to missed opportunities to maximise material utilisation across multiple panels. At the factory level, this practice is reinforced by a clear prioritisation of production flow and throughput over material efficiency. Consequently, opening infill cuts are produced on a panel-by-panel basis to keep the production line continuously supplied with the required components, rather than being optimised across panels or jobs.

This interpretation is supported by observation notes recorded during Observation Session B07 (refer to Appendix F), which documented sequential cutting and the immediate disposal of offcuts during CNC operations. It is further reinforced by the design document analysis presented in Figure 5.28, where the light blue pieces illustrate opening infill cuts as separate sections. In addition, Interviewee B04 highlighted the operational pressures contributing to this practice, explaining that a new CNC operator prioritises speed over planning because of perceived time pressure:

‘If he is not fast enough, he simply cuts multiple panels ahead and throws offcuts directly into the skip, accumulating a pallet of waste. The experienced colleague noted that the new operator “doesn’t have a plan” for reusing offcuts and doesn’t look at all the drawings.’

5.3.7.4 Cladding Boards Opening Offcuts

These offcuts were completely avoided thanks to the pre-cutting activity done before assembly. This resulted in a significant reduction of approximately 22% of the total cladding board usage (13.82 m²) at the openings. For a thorough analysis, a structured RCA approach was applied using the What-How-Why reasoning chain, as shown in Table 5.35.

Table 5.35: Cladding board opening offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts associated with the cladding board openings are avoided
2	How?	By cutting and fitting the required cladding board cuts around the openings
3	Why?	Because the required cuts were pre-planned around the openings in a cutting list
4	Why?	Because the cuts pre-planning comes as part of an automated design tool that produces shop drawings
5	Why?	Because of the perceived feasibility of adopting the automated cutting output in terms of both production flow and material efficiency

Thus, the technical root cause for avoiding offcuts at openings is the adoption of pre-planned cutting around these areas, enabled through an automated design tool that generates cutting layouts while explicitly excluding door and window zones. This design-led approach is supported at the factory level because it is perceived as a practical means of enhancing both production flow and material efficiency by eliminating cutting and reducing rework.

This interpretation is supported by observation notes recorded during Observation Session B07 (refer to Appendix F), which documented the installation of components with openings already accounted for in the cutting layouts. It is further reinforced by the design document analysis presented in Figure 5.28, where door openings are intentionally excluded from the cutting patterns by design. Collectively, the observational and design evidence confirm that automated, pre-planned cutting is the key mechanism enabling the avoidance of opening-related offcuts.

5.3.8 Cutting and Fitting Breather Membrane

Breather membrane is a protective layer used in the external side of buildings. This membrane is both permeable to allow the moisture escapes from the building fabric and waterproof to prevent water from leaking into the internal building components. It comes in limited standard width rolls, including 1500 mm and 3000 mm. The observations of the breather membrane cutting and fitting activities covered 15 panels.

Based on the drawings provided, the total required area of membrane was calculated as 194 m², while the actual use was 255 m². This generates about 61 m² waste, making about 24% of total membrane use, 14% of which is sent to the recycling bin and the rest is kept in within the panel as excess material (refer to Table 9 at Appendix B for detailed breather membrane waste calculations). These wastes can be explained in detail on how, how, much and why they are generated in the following subsections:

5.3.8.1 Length-side Breather Membrane Excess Overlap

This waste was generated when the membrane along the panel's length side was cut with a greater overlap than necessary, exceeding the standard 150 mm on each side. In particular, the factory applied overlaps of approximately 350 mm on both sides, resulting in an excess of 400 mm of membrane per panel for the vertical overlaps. This accounts for 10% of the total breather membrane waste. For a thorough analysis, a structured RCA method was applied using the What-How-Why reasoning chain, as shown in Table 5.36.

Table 5.36: Length-side breather membrane excess overlap - root cause analysis

#	Questions	Explanations
1	What?	Excess membrane length was added to the vertical overlap
2	How?	By using more membrane overlap than required
3	Why?	Because the membrane layer was intentionally cut larger
4	Why?	To ensure meeting the minimum overlap quickly on both sides
5	Why?	Because manual measurement, cutting, and fitting are time-consuming and prone to errors
6	Why?	Because speed and convenience are prioritised over precision and material efficiency during installation

Therefore, the technical root cause of this excess membrane use can be attributed to inaccuracies inherent in manual installation, where precise measuring and cutting are considered time-consuming. This waste-generating practice is reinforced at the factory level due to a clear emphasis on speed and production flow over material efficiency, with labour cost taking precedence over membrane cost.

This interpretation is supported by observation notes recorded during Observation Session B08 (refer to Appendix F), which documented variable and often excessive overlaps along membrane joints. It is further reinforced by input from Interviewee B07, who explained that overlaps are ‘*never measured perfectly*’ because they are cut manually with a knife; to avoid under-lapping, operators deliberately exceed the nominal 250 mm overlap. He also noted that while a more accurate measuring and cutting system could reduce membrane waste, the current approach is maintained because production flow pressures and labour costs outweigh the cost of the membrane material.

5.3.8.2 Width-side Breather Membrane Excess Overlap

This waste was totally avoided as the used breather membrane layer of 3000 mm came exactly as needed, covering the required panel height of 2850 mm with an overlap of 150 mm. For detailed analysis, a structured RCA method was applied using the What-How-Why reasoning chain, as shown in Table 5.37.

Table 5.37: Width-side breather membrane excess overlap avoidance - root cause analysis

#	Questions	Explanations
1	What?	Excess overlap associated with the width-side of the breather membrane is avoided
2	How?	By using breather membrane width that matches the required panel height
3	Why?	Because of the apparent design alignment of the panel width with the standard breather membrane width
4	Why?	To promote material efficiency when possible

Thus, the technical root cause for this waste avoidance is the alignment of panel design with the standard membrane width. This design decision is supported at the factory level because it enhances material efficiency without disrupting production flow or increasing installation time.

This interpretation is supported by observation notes recorded during Observation Session B08 (refer to Appendix F), which documented full-width membrane application with no need for trimming or excessive overlap, thereby confirming the effectiveness of design alignment in preventing membrane waste. It is further reinforced by the design document analysis, which demonstrates a clear alignment between panel widths and the supplied membrane roll sizes.

5.3.8.3 Breather Membrane Opening Offcuts

These offcuts were generated from the need to cut the membrane layer covering the door/window openings. The total number of openings recorded are 19, making more than 36 m² offcuts. These offcuts contribute to 14% of the total breather membrane use. For detailed evaluation, a structured RCA approach was conducted using the What–How–Why reasoning chain, as shown in Table 5.38.

Table 5.38: Breather membrane opening offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts of breather membrane are generated in significant amounts at panel openings
2	How?	By cutting out the membrane layer that was initially fitted over the openings.
3	Why?	Because full membrane sheet is fitted over the entire panel, including openings
4	Why?	Because the membrane must be continuous to ensure weather resistance, vapour permeability, and thermal performance.
5	Why?	Because applying a full sheet is the most feasible and time-efficient assembly method known
6	Why?	Due to the lack of advanced material application technology capable of producing custom-shaped membranes that precisely match required panel geometries

Therefore, the technical root cause indicates that the generation of these offcuts stems from the absence of precision-adaptive material application technology capable of producing custom-shaped sheets that precisely match the required panel geometries. In the absence of such technology, standard sheets are manually applied and trimmed, leading to systematic offcut generation.

This interpretation is supported by observation notes recorded during Observation Session B08 (refer to Appendix F), which documented consistent fitting and trimming activities around openings. It is further reinforced by input from the production team during interviews, who confirmed that opening-related offcuts are routinely generated as a consequence of the current manual application practice.

5.3.8.4 Breather Membrane Opening Overlap Offcuts

These 300 mm membrane strips were fitted to ensure proper overlapping around window/door frames. These cuts were performed in a way that generates zero offcuts, providing an excellent example of efficient use of materials. Particularly, a 2700 mm wide membrane roll being cut into nine smaller rolls, each is 300 mm wide. In doing so, the exact required width of membrane strip is provided to overlap at the window/door frames with the external membrane. This practice saves nearly 1% of total membrane waste, since cutting 300 mm directly from the 3000 mm membrane roll will necessitate at least one overlap of 300 mm. For thorough analysis, a structured RCA method was applied using the What-How-Why reasoning chain, as shown in Table 5.39.

Table 5.39: Breather membrane openings' overlap offcuts avoidance - root cause analysis

#	Questions	Explanations
1	What?	Excess overlap associated with the openings overlap is avoided
2	How?	By cutting 2700 mm membrane roll precisely into the 300 mm as required
3	Why?	Because of the production experience accumulated over the years to use the 2700 mm rolls and the saw to produce the needed membrane strip with zero waste
4	Why?	Because this practice both improves material utilisation and contributes to production flow

Therefore, the technical root cause for this waste avoidance is the effective manual nesting practice enabled by the experience of the production team. At the factory level, this practice is actively supported because it both streamlines production flow and enhances material efficiency without introducing additional process complexity. This interpretation is supported

by observation notes recorded during Observation Session B08 (refer to Appendix F), as illustrated in Figures 5.29 and 5.30, which show membrane roll offcuts being deliberately cut and reused as narrow strips around door and window frames to overlap with the main membrane layer.

This practice is further reinforced by input from Interviewee B03, who emphasised the role of experience in recognising and acting upon reuse opportunities. He noted that an experienced operator will instinctively identify reusable pieces, stating, *‘this off-cut I’ll need for another panel.’* He further explained that such offcuts are deliberately retained rather than discarded, adding, *‘I’ll never throw it away; I always put it to the side... that’s because I’ve been working there for so long.’*



Figure 5.29: Membrane roll cuts

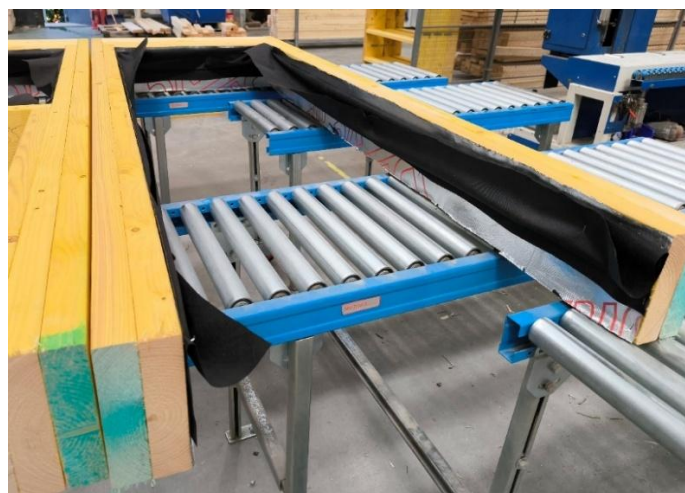


Figure 5.30: Fitted opening overlap membrane strip

5.3.9 Summary - Factory B

This section provided a detailed analysis of how, how much, and why material waste is generated in Factory B. This factory is part of a medium-sized firm producing timber-frame wall panel products, primarily serving residential and educational projects. Material waste was particularly observed and recorded during cutting and fitting activities. During cutting activities, varying amounts of offcuts were recorded, due to discrepancies between the designed cut sizes and standard material sizes. By conducting factory observations, design document analysis and semi-structured interviews, the root causes of this issue included limited alignment of designs with standard material sizes, lack of custom size ordering, and inadequate material nesting. In fitting activities, waste was observed in two key ways: 1) full membrane-based materials (e.g., vapour barriers and breather membranes) were applied directly over openings, and the sections covering these openings were later cut out, resulting in substantial offcuts amounting to 14-18% of the material used; 2) excess quantities of materials, particularly rockwool insulation, breather membrane, and vapour barrier, were used, resulting in waste ranging from 3-9% of total material usage. The root causes behind these issues were identified as the absence of precision-based material application methods and the imprecision associated with manual labour.

5.4 Factory C

The third case study is a timber frame manufacturer based in the UK, mainly producing for residential and commercial projects. The production line of this factory is considered one of the most automated in the UK, with some stations are fully operated by robotic arms. The main structural materials of the manufactured products are engineered wood products. Each design is broken down into a defined number of panels that need to go through several assembly steps before being ready to be transported to the site for final assembly.

The subject of the case is the assembly process of timber frame wall panels with material waste generation/avoidance represent the object under examination. The construction materials used in the assembly process are considered as a unit of analysis to study material waste generation and avoidance in OSC. Figure 5.31 shows the activities of producing a wall panel in this factory.

The production process includes four major materials, including timber framing, OSB sheathing, rigid insulation, and breather membrane. The activities highlighted in yellow represent material application activities where material waste can be generated. Activities marked with a worker symbol are manual and performed using basic tools (e.g., hand saw, knife). In contrast, activities marked with a worker-and-gear symbol are semi-automated, involving the use of mechanical tools (e.g., powered saw). Additionally, activities marked with a gear symbol are automated and require only minimal human intervention. Each one of these activities was directly observed in the factory to identify how, how much, and why material waste is generated or avoided. The following subsections analyse waste generation/ avoidance for each material, explaining the practices, quantities, and root causes.

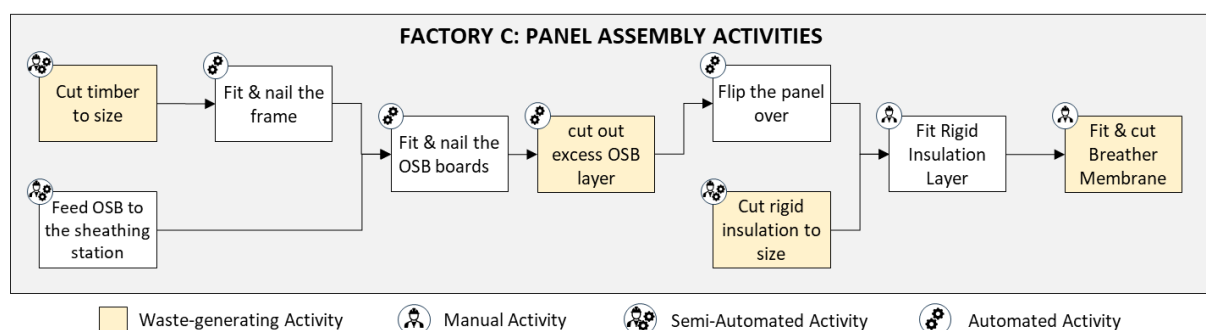


Figure 5.31: Factory C - Timber frame wall panel assembly activities

5.4.1 Cutting Timber Frame Sections

The timber frame sections represent the major structural material of the panel. The standard timber sections used are 4800 and 5400 mm, highly popular timber lengths in the UK market.

The observations of the cutting activities of the timber frame sections covered eight panels. The cutting activities were observed to understand how timber is being cut, and then the saw operator was interviewed to validate the observations. Based on the observations and interview results, the offcuts generated from the cutting activities were estimated.

Using the provided drawings, the total required length of timber for the eight panels was calculated as 339 m. In comparison, the total timber used was 372 m. This resulted in a total offcut waste of 33 m, accounting for approximately 9% of the material. Of this, 8% was sent for recycling, while 1% was stored for potential future reuse (refer to Table 10 at Appendix C for detailed timber waste calculations). Based on the factory practice, any timber offcut below 600 mm is thrown directly in the recycling bin. Observations and interviews with the saw operator reveal three categories of offcuts, which can be explained as follows:

5.4.1.1 430 mm Offcuts

This offcut is associated with timber studs' cutting process, contributing to nearly 6% of the total timber use and 71% of the total generated timber offcuts. Based on the observation notes and the interview with the saw operator, these offcuts were generated from cutting two studs' of 2180 mm out of the 4800 mm standard length of timber. For precise calculation, nearly 5 mm was wasted in the saw cuts, leaving a piece of 430 mm offcut. Some of these offcuts were reused as transportation props (see Figure 5.32), whereas the remaining was planned to be discarded into the recycling bin. For detailed analysis, a structured RCA method was applied using the What-How-Why reasoning chain, as shown in Table 5.40.

Table 5.40: 430 mm offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts measuring 430 mm in length were generated from cutting timber studs
2	How?	By using a timber section that spans more than two stud spaces
3	Why?	Because cutting two studs, each 2180 mm long, from a 4800 mm timber section leaves a remaining piece of approximately 430 mm
4	Why?	Because 4800 mm timber is a popular standard length readily available in the market, while 4500 mm timber is uncommon and require a special order
5	Why?	Because 4500 mm is a non-standard length, ordering it would result in higher costs and longer lead times

Hence, the technical root cause behind these offcuts is the absence of custom-length ordering for 4400 mm timber sections. At the factory level, this practice is reinforced by the potentially higher costs and longer lead times associated with sourcing non-standard lengths (e.g., 4500

mm), which discourages bespoke procurement despite the material inefficiency it creates. This interpretation is supported by observation notes recorded during Observation Session C01 (refer to Appendix F), which documented repeated cutting of standard timber lengths to achieve the required dimensions (see Figure 5.32), as well as by the design document analysis showing the mismatch between used and designed timber sizes.

This conclusion is further confirmed by Interviewee C03, who highlighted the commercial constraints associated with bespoke orders:

‘If you want a bespoke product—say 2178—they’ll want you to hit a minimum volume... If it’s only 200 or 300 pieces, they’d charge an inordinate amount. It wouldn’t be worth it.’

Collectively, the observational, design, and interview evidence confirm that procurement constraints around minimum order quantities and lead times are the primary drivers of these timber offcuts.



Figure 5.32: Timber offcuts being repurposed as transportation props

5.4.1.2 25 mm Offcuts

These offcuts were consistently generated across all newly processed timber sections to produce the required cuts for the eight wall panels under investigation. As a result, these offcuts were repeated 77 times, contributing to 0.5% of the total timber usage. Based on observation notes and an interview with the saw operator, all these offcuts were directly discarded into the

recycling bin as part of standard factory practice. For detailed analysis, a structured RCA method was adopted using What–How–Why reasoning chain as shown in Table 5.41.

Table 5.41: 25 mm offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts measuring about 25 mm were generated at the start of each new timber section
2	How?	By conducting a trim cut to the new timber sections
3	Why?	To ensure a clean, square, and structurally sound edges
4	Why?	Because the mass cutting of raw timber is likely to be uneven and timber drying is likely to cause defected edges.
5	Why?	Because achieving consistently square cuts and protecting edges is time-consuming and costly, making factory trimming more feasible.
5	Why?	Because prefabricators rely on supplier tolerances to avoid extra inspection, ensuring a uniform and efficient production process.

The technical root cause of these offcuts lies in the inconsistent quality of supplied timber edges, which are frequently uneven due to mass-cutting processes at the supplier and cracking caused by natural timber drying. At this factory, all timber edges are trimmed by default, without prior inspection, to ensure dimensional uniformity and maintain production efficiency. In addition, suppliers typically deliver timber with positive tolerances, which further necessitates squaring all edges before use. This interpretation is supported by observation notes recorded during Observation Session C01 (refer to Appendix F), which documented routine initial trim cuts applied to all incoming timber regardless of visible edge condition.

5.4.1.3 Other Offcuts

These offcuts are associated with the cutting process of other timber sections, such as rails and headers. They were generated in varying lengths, accounting for 24% of the total offcuts and 2.1% of the total timber use. Based on observation notes and an interview with the saw operator, these offcuts were consistently produced despite the saw operator’s experience in maximising material use. For thorough analysis, a structured RCA approach was conducted using What–How–Why reasoning chain as presented in Table 5.42.

Table 5.42: Different length timber offcuts generation - root cause analysis

#	Questions	Explanations
1	What?	Offcuts in various lengths are generated
2	How?	By cutting different lengths of different timber sections
3	Why?	Because the cutting process was not optimised across the panels included in the production patch.
4	Why?	Because the current practice favour panel-by-panel cutting practice.
5	Why	Because of the need to adhere to strict production schedule, necessitating a panel-by-panel cutting practice.

Hence, the technical root cause behind these offcuts is the absence of an effective nesting practice that integrates cuts across multiple wall panels. Instead, cutting activities are organised on a panel-by-panel basis to align with the production schedule, reflecting the factory's prioritisation of time efficiency and workflow continuity over material optimisation. This interpretation is supported by observation notes recorded during Observation Session C01 (refer to Appendix F), which documented sequential cutting in line order without cross-panel coordination resulting in various timber offcuts (see Figure 5.33), as well as by the design document analysis showing a lack of planned nesting of timber cuts. It is further reinforced by input from Interviewee C09, who confirmed this production logic by stating: *'I'd say that's right. We cut in panel order for the line.'*



Figure 5.33: Various timber offcuts resulting from limited nesting

5.4.2 Cutting OSB Boards

The OSB boards are used as a sheathing layer to enhance timber frame rigidity and structural integrity. The fitting and cutting activities of this layer were performed using robotic arms.

These robots pick one of three OSB widths, including 597, 797, and 1197 mm and fit it on the designated timber frame position. Although 597 and 797 mm wide OSB are not an industry standard, the procurement team managed to source them with main focus on maximising material efficiency at limited cost implications. Due to the large volume and regular ordering, the OSB supplier found it feasible to supply these custom sizes. However, the lengths of the used OSB boards are kept at the industry standard at 2397 and 2697 mm. Therefore, OSB boards were fed into the robotic OSB sheathing station with three widths: 597, 797, and 1197 mm at either 2397- or 2697-mm length. Once the required OSB boards are positioned according to the preset locations, the robots start to nail the OSB layer into their exact positions. After that, the robots cut out the excess OSB from both edges of the panel, as well as at the openings' locations, generating offcuts. Figure 5.34 illustrates a sample panel in this factory where these offcuts were generated.

The observations of the OSB cutting activities covered eight panels. Based on the drawings provided for these panels, the total required area of OSB boards was calculated as 56.54 m². In comparison, the total processed area of the same boards was 76.96 m². This means that the total offcuts generated is 20.42 m², making about 26.5% of the total material use (refer to Table 11 at Appendix C for detailed OSB offcuts calculations). To understand how and why these offcuts were generated, three categories of offcuts can be identified as explained in the following subsections:

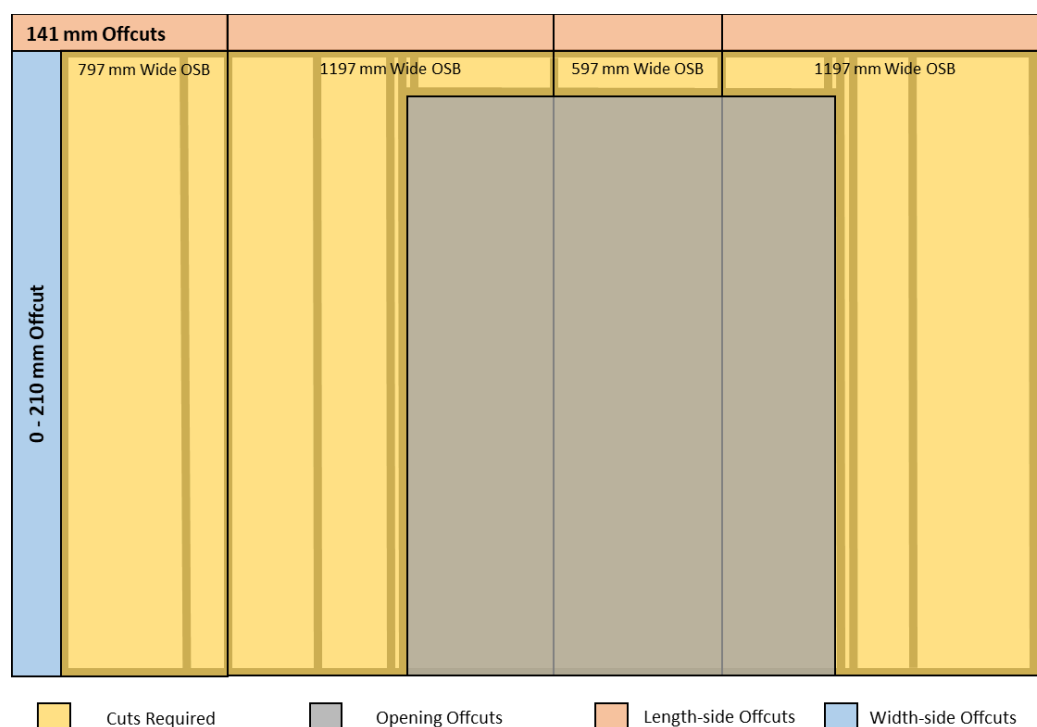


Figure 5.34: OSB required and observed offcuts categories

5.4.2.1 Length-side OSB Board Offcuts

These offcuts were generated by the robotic arms cutting 141 mm strip from the 2397 mm side of the OSB boards, contributing to 6% of total OSB use and 22% of the total OSB offcuts (see the light red strip at Figure 5.28). Based on the observation notes and the interview with the production team, OSB offcuts bigger than 170 mm were stored for further reuse in the manual production of complex panels, offcut strips 170-150 mm wide were repurposed as transportation props (see Figure 5.35), while the smaller offcuts are discarded in the recycling bin. For comprehensive analysis, a structured RCA method was employed using What-How-Why reasoning chain as explained in Table 5.43.

Table 5.43: Length-side OSB board offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts associated with the length-side of the OSB boards were generated
2	How?	By using OSB boards larger than the required panel height
3	Why?	Because the closest standard OSB length is 2400 mm, which is 141 mm longer than the required panel height
4	Why?	Because of the limited design consideration to the standard OSB size
5	Why?	Because design customisation is prioritised over material efficiency and production flow

Hence, the technical root cause of the 141 mm OSB offcuts is the limited consideration of standard OSB sheet sizes during the design stage. This practice reflects a clear prioritisation of design customisation over material efficiency and production production flow, resulting in the repeated generation of narrow OSB strips. This interpretation is supported by observation notes recorded during Observation Session C02 (refer to Appendix F), which documented the frequent generation of 141 mm OSB strips, subsequently cut into small squares, as shown in Figure 5.35. It is further reinforced by the design document analysis comparing used versus designed OSB sizes, which highlights the dimensional mismatch driving these offcuts (the light red strip in Figure 5.34). In addition, Interviewee C09 explicitly confirmed the design-led nature of this issue, stating that *‘the wall height is customer-driven.’* Collectively, the observational, design, and interview evidence confirm that insufficient design alignment with standard OSB sizes is the primary driver of the 141 mm OSB offcuts.



Figure 5.35: OSB offcuts being repurposed as transportation props

5.4.2.2 Width-side OSB Boards Offcuts

These offcuts were generated by the robotic arms when trimming the width-side of the last OSB board fitted onto the frame to precisely match the panel's end (see the light blue strip in Figure 5.34). Because custom-width OSB boards were specially sourced to improve OSB efficiency, only a limited number of OSB offcuts were produced, with an average of 72 mm across the eight panels studied. As a result, these offcuts accounted for only 2% of total OSB use and 6% of total OSB offcuts. Like the length-side OSB offcuts, OSB strips larger than 170 mm were stored for potential future reuse, while those between 150 mm and 170 mm were repurposed as transportation props (see Figure 5.35). Offcuts smaller than 150 mm were discarded in the recycling bin. For thorough analysis, a structured RCA approach was adopted using What-How-Why reasoning chain as presented in Table 5.44.

Table 5.44: Width-side OSB offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts associated with width-side OSB boards were minimal
2	How?	By cutting the last OSB board in each panel only
3	Why?	Because the timber studs were positioned to align with standard OSB board widths (full, half, and two-thirds).
4	Why?	To streamline robotic operations by minimising cutting during assembly
5	Why?	Because simplifying robotic tasks increases production speed, reduces the risk of errors, and improves overall assembly line efficiency

Therefore, the root cause behind OSB width-side offcut reduction is the design alignment with standard OSB width multiples (half, and two-thirds). In doing so, there is no need to cut every OSB board except the last board to meet the required panel width. This practice is supported at factory level since it streamlines the robotic operations to fit the OSB layer.

This interpretation is supported by observation notes recorded during Observation Session C02 (refer to Appendix F), which documented a marked reduction in width-side OSB offcut generation, with offcuts limited to the final board only, as illustrated in Figure 5.36. It is further reinforced by the design document analysis, which shows that OSB widths were deliberately specified using three standardised sizes including full board, two-thirds, and half boards (see Figure 5.34).

Additional confirmation is provided by Interviewee C06, who noted that *'cutting from standard boards into 500 mm-type pieces was creating too much waste, so this approach helps reduce waste on the width side.'* Moreover, Interviewee C08 explained how this design logic is operationalised through robotic placement, stating that *'the robot will pick the most efficient arrangement... place full boards first... and then use a smaller board at the end, usually a 597 or 797, with a small overhang, which the machine routes off.'* Collectively, the observational, design, and interview evidence demonstrate how alignment with standard OSB width multiples, combined with robotic optimisation, effectively minimises width-side offcuts.



Figure 5.36: Width-side OSB offcut generation

5.4.2.3 OSB Opening Offcuts

These offcuts were generated when the robotic arms cut out the OSB layer covering the designated areas for window and door openings. They account for a significant 19% of total OSB use and 71% of the generated OSB offcuts. Based on observation notes, after cutting out these OSB offcuts, the robots pick them from the panel and stock them aside. According to an interview with the production staff, these offcuts are reused in the manual production of more complex panels that the robotic station cannot process. However, no data was available to determine the actual reuse rate. For detailed analysis, a structured RCA approach was followed using What-How-Why reasoning chain as shown in Table 5.45.

Table 5.45: OSB opening offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts are generated in significant amounts at the openings
2	How?	By cutting out the OSB layer fitted over the openings
3	Why?	Because full OSB board were firstly fitted over the openings
4	Why?	Because no pre-cutting activity is performed to plan the required cuts around the openings.
5	Why?	Because it is considered more efficient and precise to use full OSB and cut out openings as needed
6	Why?	To streamline the robot operations in fitting the OSB layer in efficient and timely manners.

Hence, the technical root cause of the opening offcuts is the lack of cut planning around panel openings. This approach is maintained at the factory level to maximise the production flow and timeliness of robotic operations, primarily to adhere to the production schedule. While the robotic system successfully reduced width-side offcuts to just 2% of total OSB usage, it simultaneously resulted in significant offcuts around openings. This reveals a trade-off in using robotic systems for cutting and fitting the OSB layer, raising important questions about the environmental implications of such automation strategies.

This interpretation is supported by observation notes recorded during Observation Session C02 (refer to Appendix F), which documented significant OSB offcut generation at openings, as well as by the design document analysis presented in Figure 5.34, where full boards are specified across opening locations. It is further reinforced by interview evidence, with Interviewee C09 explaining that:

‘Where openings exist, significant opening-related offcuts are generated because full boards are installed first and then cut out,’

While Interviewee C08 highlighted the systemic nature of this issue, noting that:

‘There’s a lot of waste there, because of the way the robotic system works.’

Collectively, the observational, design, and interview evidence confirm that the lack of opening-specific cut planning within robotic workflows is the primary driver of opening-related OSB offcuts, despite gains achieved elsewhere in the system.

5.4.3 Cutting Rigid Insulation Panels

This insulation layer comes in 80 mm thick, 1200 mm wide, and 2400 mm long panels. The main function of using rigid insulation is to improve the thermal and acoustic insulation capacity of the panels. The observations of the cutting activities of the rigid insulation covered eight panels. Using the provided drawings, the total required area of rigid insulation has been calculated as 44.83 m². In comparison, the observed quantities of the insulation used were 54.72 m². This means that the total offcuts make up to 18% of the total rigid insulation use (refer to Table 12 at Appendix C for detailed rigid insulation offcuts calculations). For detailed analysis, two categories of rigid insulation offcuts can be identified as explained in the following subsections:

5.4.3.1 Length-side Rigid Insulation Offcuts

These offcuts were generated from cutting 222 mm out of 2400 mm rigid insulation panels to fill the interior height of the panel of 2178 mm (i.e., the height of the cavities). These offcuts contribute to 8% of the total rigid insulation use and 46% of the total rigid insulation offcuts. For thorough analysis, a structured RCA approach was conducted using What-How-Why reasoning chain as presented in Table 5.46.

Table 5.46: Length-side rigid insulation offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts associated with the length-side of rigid insulation are generated in significant amounts
2	How?	By using full-length panels of 2400 mm which more than the required 2178 mm
3	Why?	Due to the lack of a custom-length rigid insulation panels sourcing
4	Why?	Because custom-length panels are not usually produced by manufacturers and so ordering them can be costly and entail longer lead times

Thus, the technical root cause can be identified as the absence of custom-length ordering, which would be required to eliminate these offcuts by sourcing materials in the exact lengths needed. At the organisational level, this option is not pursued due to the perceived higher costs and longer lead times associated with custom-size orders, resulting in a compromise in material efficiency. This interpretation is supported by observation notes recorded during Observation Session C03 (refer to Appendix F), which documented repeated trimming of standard-length materials and the generation of consistent offcuts. It is further reinforced by the design document analysis comparing used versus designed cut sizes, which highlights the dimensional mismatch driving this waste. In addition, Interviewee C03 confirmed the procurement constraint, noting that: *'Rigid insulation is fairly fixed at this point. The flexibility isn't there to buy pre-cut unless volumes are large enough—hundreds of sheets,'* While also acknowledging that: *'We have brought bespoke sizes in the past when volumes were big enough.'* Collectively, the observational, design, and interview evidence indicate that minimum order quantities and lead-time considerations are the primary barriers to custom-length procurement and the key drivers of these offcuts.

5.4.3.2 Width-side Rigid Insulation Offcuts

These offcuts were generated from the need to cut different sections from the width side of the rigid insulation panels (i.e., the 1200 mm side) mainly to match the required widths of the panel cavities. Since the required cuts widths vary largely, the cutting activity being optimised based on the saw operator experience to maximise material use. However, offcuts are still generated in significant quantities. The total amount of width-side offcuts makes up to 10% of the total rigid insulation area used and about 54% of the total rigid insulation offcuts. For detailed analysis, a structured RCA approach was adopted using What-How-Why reasoning chain as shown in Table 5.47.

Table 5.47: Width-side rigid insulation offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts associated with the width-side are generated in significant amounts
2	How?	By cutting various widths required to fit the varying panel cavity sizes
3	Why?	Because the cutting process was not optimised across the panels included in the production patch.
4	Why?	Because the current practice favour panel-by-panel cutting practice.
5	Why	Because of the need to adhere to strict production schedule, necessitating a panel-by-panel cutting practice.

Hence, the technical root cause of these offcuts is the absence of an effective nesting practice that integrates cutting patterns across multiple wall panels. Instead, cutting activities are organised on a panel-by-panel basis to align with the production schedule, reflecting a deliberate emphasis on time efficiency and workflow continuity over material optimisation.

This interpretation is supported by observation notes recorded during Observation Session C03 (refer to Appendix F), which documented sequential cutting of panels without cross-panel coordination or reuse planning. It is further reinforced by the design document analysis comparing used versus designed cut sizes, which highlights the dimensional mismatches that arise when cuts are not optimised across multiple panels. In addition, Interviewee C09 explicitly acknowledged the unrealised optimisation potential, stating that *'if you optimised across 20 panels, you'd definitely reduce waste further.'*

Collectively, the observational, design, and interview evidence confirm that the lack of cross-panel nesting, driven by scheduling priorities, is the primary contributor to these offcuts.



Figure 5.37: Rigid insulation cuts being prepared in required sizes

5.4.4 Fitting and Cutting Breather Membrane

This is a permeable, yet waterproof protective layer fitted to the external side of the panels, allowing moisture to escape from the building fabric while preventing water from leaking into the internal panel components. The observed width of the membrane used to cover the eight panels under research is 2700 mm. Based on the drawings provided, the total required area of membrane was calculated as 79.15 m², while the actual use was 91.86 m². This means that about 12.71 m² area is wasted, making about 13.8% of total membrane use (refer to Table 13

at Appendix C for detailed breather membrane waste calculations). This waste can be explained in detail on how, how, much and why they are generated in the following subsections:

5.4.4.1 Length-side Breather Membrane Overuse

This area of breather membrane was wasted when the length-side membrane was cut with more than the necessary overlapping width (which is normally 150 mm). The average overlap width across the eight panels was about 300 mm. This means that each panel had an excess of 150 mm in membrane length for the vertical overlaps. This waste accounted for 3% of the total breather membrane waste (see Figure 5.38). For thorough analysis, a structured RCA approach was conducted using What-How-Why reasoning chain as presented in Table 5.48.

Table 5.48: Length-side breather membrane overuse - root cause analysis

#	Questions	Explanations
1	What?	Excess membrane length was added to the vertical overlap
2	How?	By using more membrane overlap than required
3	Why?	Because the membrane layer was intentionally cut larger
4	Why?	To ensure meeting the minimum overlap quickly
	Why?	Because manual measurement, cutting, and fitting are time-consuming and prone to errors
5	Why?	Because speed and convenience are prioritised over precision and material efficiency during installation

Therefore, the technical root cause of this excess membrane use can be attributed to inaccuracies inherent in manual work, where precise measuring and cutting are often regarded as time-consuming. This waste-generating practice is reinforced at the factory level by a strong emphasis on speed and production flow over material efficiency. This interpretation is supported by observation notes recorded during Observation Session C04 (refer to Appendix F), which documented repeated instances of oversized membrane overlaps and trimming during installation, , as illustrated in Figure 5.39.

It is further reinforced by the design document analysis comparing used versus designed cut sizes, which highlights the dimensional mismatch driving this waste, as shown in Figure 5.38. In addition, Interviewee C09 explicitly confirmed the role of manual imprecision, stating that *‘manual cutting introduces imprecision, so overlaps can exceed the standard 150 millimetres.’* Collectively, the observational, design, and interview evidence confirm that production flow-driven manual practices are the primary driver of excess membrane use.

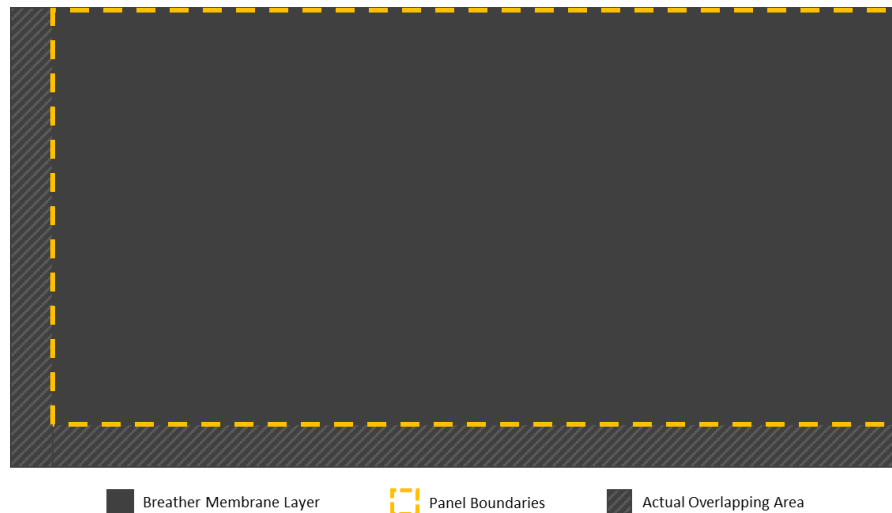


Figure 5.38: Breather membrane layer, panel boundaries, and actual overlapping area

5.4.4.2 Breather Membrane Width-side Overuse

This portion of the breather membrane was wasted because the standard membrane width used exceeded the actual required width. Particularly, the required membrane width is 2,406 mm (including a 150 mm overlap), while the membrane used was 2,700 mm. This resulted in an excess of nearly 300 mm of membrane per panel, consistently across all eight panels studied. In total, this overuse wasted approximately 10 m² of raw material, accounting for 11% of total breather membrane consumption (see Figure 5.38). For detailed analysis, a structured RCA approach was conducted using What-How-Why reasoning chain as shown in Table 5.49.

Table 5.49: Width-side breather membrane overuse - root cause analysis

#	Questions	Explanations
1	What?	Excess overlap associated with width-side of the breather membrane layer is left in significant amount
2	How?	By using a standard membrane width bigger than required
3	Why?	Because the used membrane roll is a standard size, that is more readily available and cost-effective to source.
4	Why?	Because sourcing custom-size membrane rolls is likely to be more expensive and require longer time to source.

Hence, the technical root cause of the width-side excess membrane overlap is the absence of custom-width membrane roll sourcing (e.g., 2500 mm), which would allow the membrane to more closely match panel dimensions. At the factory level, this option is not pursued due to the perceived longer lead times and higher costs associated with sourcing bespoke membrane widths, resulting in a deliberate trade-off that favours procurement efficiency over material optimisation. This interpretation is supported by observation notes recorded during

Observation Session C03 (refer to Appendix F), which documented systematic use of excess membrane along panel widths due to dimensional mismatch, as illustrated in Figure 5.39.

It is further reinforced by the design document analysis comparing used versus designed cut sizes, which highlights the discrepancy between available roll widths and required panel dimensions, as illustrated in Figure 5.38. In addition, Interviewee C04 confirmed the supplier-side constraints underpinning this decision, stating that:

‘They don’t want to stop a plant making standard size to produce 50 of this, 50 of that—it’s uneconomical. If they do it, the price becomes ridiculous.’

Collectively, the observational, design, and interview evidence confirm that procurement and supplier constraints are the primary drivers of width-side excess membrane overlap.

5.4.4.3 Breather Membrane Opening Offcuts

These offcuts were generated from the need to cut the membrane layer covering the door/window openings. The total number of openings recorded across the observed panels are eight, making more than 14.59 m² offcuts. These offcuts contribute to 16% of the total breather membrane use. For detailed evaluation, a structured RCA approach was conducted using the What–How–Why reasoning chain, as shown in Table 5.50.

Table 5.50: Breather membrane opening offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts of breather membrane are generated in significant amounts at panel openings
2	How?	By cutting out the membrane layer that was initially fitted over the openings.
3	Why?	Because full membrane sheet is fitted over the entire panel, including openings
4	Why?	Because the membrane must be continuous to ensure weather resistance, vapour permeability, and thermal performance.
5	Why?	Because applying a full sheet is the most feasible and time-efficient assembly method known
6	Why?	Due to the lack of advanced material application technology capable of producing custom-shaped membranes that precisely match required panel geometries

Therefore, the technical root cause lies in the absence of precision-adaptive material application technology capable of producing custom-shaped sheets that accurately match the required panel geometries. In the absence of such technology, standard membrane sheets are manually applied and cut to fit, resulting in systematic trimming and associated waste. This interpretation is supported by observation notes recorded during Observation Session C04 (refer to Appendix

F), which documented repeated fitting and cutting of membrane around openings, as illustrated in Figure 5.39. It is further reinforced by the design document analysis comparing used versus designed cut sizes, which highlights the persistent dimensional mismatch between standard membrane formats and the actual panel geometries, thereby explaining the inevitability of these offcuts under current production practices.



Figure 5.39: Fitting and cutting breather membrane

5.4.5 Summary - Factory C

This section provided a detailed analysis of how, how much, and why material waste is generated in Factory C. This factory is part of a large-scale firm producing timber-frame wall panel products with some level of automated assembly, primarily serving residential and commercial projects. Material waste was particularly observed and recorded during cutting and fitting activities. During cutting activities, varying amounts of offcuts were recorded, due to discrepancies between the designed cut sizes and standard material sizes. By conducting factory observation, design analysis, and semi-structured interviews, the root causes of included lack of custom size ordering and inadequate material nesting. In fitting activities, waste was observed in two key ways: 1) full membrane-based (e.g., vapour barriers and breather membranes) and board-based (e.g., OSB) materials were applied directly over openings, and the sections covering these openings were later cut out, resulting in substantial offcuts amounting to 16-19% of the material used; 2) excess quantities of materials, particularly breather membrane were used, resulting in waste of 3% of total material usage. The root causes behind these issues were identified as the lack of cut planning, the limited accuracy of manual work, and the absence of precision-adaptive material application methods.

5.5 Factory D

The fourth case study is a timber frame manufacturer based in the UK, mainly producing for educational projects. The main structural materials of its products are engineered wood products. Each design is broken down into a defined number of panels, that need to go through few assembly steps before being ready to be transported to the site for final assembly.

The subject of the case is the assembly process of open timber frame wall panels with material waste generation/avoidance represent the object under examination. The construction materials used in the assembly process are considered as a unit of analysis to study material waste generation and avoidance in this factory. Figure 5.40 shows the activities of producing a wall panel in Factory D.

The production process includes three major materials, including timber framing, OSB sheathing, and rockwool insulation. The activities highlighted in yellow in Figure 5.40 represent material application activities where material waste can be generated. Activities marked with a worker symbol are manual and performed using basic tools (e.g., handsaw, knife). In contrast, activities marked with a worker-and-gear symbol are semi-automated, involving the use of mechanical tools (e.g., powered saw). Each one of these activities were directly observed in the factory to identify how, how much, and why material waste is generated or avoided. The following subsections analyse waste generation/ avoidance for each material, explaining the practices, quantities, and root causes.

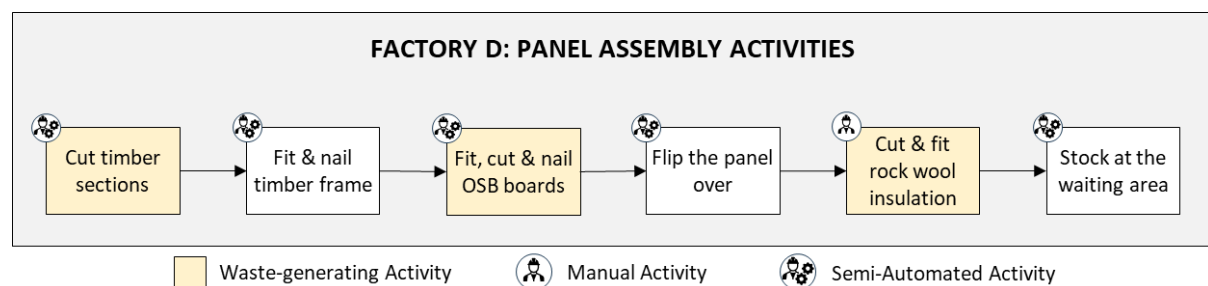


Figure 5.40: Factory D - Timber frame wall panel assembly activities

5.5.1 Cutting and fitting Timber Frame Sections

The timber frame sections represent the main structural material of the wall panel. The standard timber section used is 3600 mm. The observations of the cutting activities of the timber frame sections covered 10 panels. The cutting activities were observed to understand how timber is being cut, and then the production team was interviewed to validate the observations. Based on

the observations and interview results, the offcuts generated from the cutting activities were estimated.

Using the drawings provided, the total required length of timber for the 10 panels was calculated as 156,021 mm. In comparison, the total used length of timber was 176,400 mm, making up to 12% of the total material use (refer to Table 14 at Appendix D for detailed timber offcuts calculations). Based on the factory practice, any timber offcut below 300 mm is thrown directly in the recycling bin. To relate back different offcuts to their causing practices, three categories of offcuts were identified and analysed. The following subsections explain each category of these wastes in more detail.

5.5.1.1 646 mm Offcuts

This offcut was repeated 20 times, contributing to 7.4% of the total timber use and 64% of the total generated timber offcuts. Based on the observation notes and the interview with the production team, these offcuts were generated from cutting one studs of 2949 mm out of the 3600 mm standard length of timber. For precise calculation, nearly 5 mm were wasted in the saw cuts, leaving a piece of 646 mm offcut. All these offcuts were stored for further reuse as timber frame noggins. For thorough evaluation, a structured RCA approach was conducted using the What-How-Why reasoning chain, as shown in Table 5.51.

Table 5.51: 646 mm offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts associated with timber studs cutting are generated
2	How?	By cutting 2949 mm stud out of 3600 mm timber
3	Why?	Due to the lack of closest-size ordering (i.e., 3000 mm lengths),
4	Why?	Because 3600 mm timber is believed as the most material-efficient size for the production process
5	Why?	Because a significant portion of the 646 mm offcuts can be reused as noggins, reducing material waste

Hence, the technical root cause of these offcuts is the lack of appropriate size ordering, specifically, the non-adoption of 3000 mm timber lengths. Instead, the factory opted to procure 3600 mm timber, based on the assumption that the resulting offcuts could be reused as noggins. However, no systematic analysis or quantitative comparison has been undertaken to assess whether sourcing 3000 mm lengths would have been more material-efficient overall or would have resulted in lower net waste generation.

This interpretation is supported by observation notes recorded during Observation Session D01 (refer to Appendix F), which documented the excessive accumulation of 646 mm offcuts, as illustrated in Figure 5.41. It is further reinforced by the design document analysis comparing used versus designed cut sizes, which shows that offcut generation exceeds the actual noggin requirements within the same design package. This practice is also reflected in input from Interviewee D05, who justified the procurement choice by stating:

'It wouldn't be worth buying 3 m timber, because you still need that excess for the noggin. If you bought 3 m timber, you'd have to buy excess material for the noggins anyway.'

Collectively, the observational, design, and interview evidence indicate that procurement decisions are driven by assumed reuse potential rather than validated material efficiency outcomes, leading to systematic offcut generation.



Figure 5.41: Excessive accumulation of 646 mm offcuts

5.5.1.2 20 mm Offcuts

These offcuts were regularly generated across all newly processed timber sections to produce the required cuts for the eight wall panels under investigation. As a result, these offcuts were repeated 49 times, contributing to 0.6% of the total timber usage. Based on observation notes and an interview with the saw operator, all these offcuts were directly discarded into the recycling bin as part of standard factory practice. For detailed evaluation, a structured RCA approach was conducted using the What-How-Why reasoning chain, as shown in Table 5.52.

Table 5.52: 20 mm offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts measuring about 20 mm were generated at the start of each new timber section
2	How?	By conducting a trim cut to the new timber sections
3	Why?	To ensure a clean, square, and structurally sound edges
4	Why?	Because the mass cutting of raw timber is likely to be uneven and timber drying is likely to cause defected edges.
5	Why?	Because achieving consistently square cuts and protecting edges is time-consuming and costly, making factory trimming more feasible.
6	Why?	Because prefabricators rely on supplier tolerances to avoid extra inspection, ensuring a uniform and efficient production process.

Hence, the technical root cause of these offcuts is the inconsistent quality of supplied timber edges, which are frequently uneven due to mass-cutting processes at the supplier and cracking caused by natural timber drying. To ensure dimensional uniformity and maintain production efficiency, the factory routinely performed trim cuts on all timber edges without prior inspection. In addition, timber is typically delivered with positive length tolerances, which further necessitates squaring all edges before use. This interpretation is supported by observation notes recorded during Observation Session D01 (refer to Appendix F), which documented the consistent removal of approximately 20 mm from timber edges as a standard practice, regardless of visible edge condition.

5.5.1.3 Other Offcuts

These offcuts were generated in different lengths, starting from 70 mm and can reach 822 mm. These offcuts contribute to 31% of the total generated timber offcuts and 3.6% of the total timber use. Based on the observation notes and the interview with the production team, these offcuts were generated as by-product of cutting timber, despite the production team efforts to reduce offcuts. For detailed analysis, a structured RCA approach was adopted using the What-How-Why reasoning chain, as shown in Table 5.53.

Table 5.53: Different length offcuts' generation root cause analysis

#	Questions	Explanations
1	What?	Offcuts in various lengths are generated
2	How?	By cutting different lengths of different timber sections
3	Why?	Because the cutting process was not optimised across the panels included in the production patch.
4	Why?	Because the current practice favour panel-by-panel cutting practice
5	Why	Because of the need to adhere to strict production schedule, necessitating a panel-by-panel cutting practice.

Hence, the technical root cause behind these offcuts is the absence of an effective nesting practice that integrates cutting operations across multiple wall panels. Instead, cutting is undertaken on a panel-by-panel basis to align with the production schedule, reflecting a deliberate prioritisation of time efficiency and workflow continuity over material efficiency. This interpretation is supported by observation notes recorded during Observation Session D01 (refer to Appendix F), which documented the generation of multiple offcut lengths during panel fabrication, as illustrated in Figure 5.42. It is further reinforced by the design document analysis, which shows no design detailing or guidance to support efficient material nesting across panels.

This production logic is explicitly confirmed by Interviewee D02, who stated, *'We do it panel by panel,'* and further explained that cross-panel optimisation would generate unmanageable complexity:

'Yes. You'd end up with thousands of different timber bits—you couldn't manage it.'

Similarly, Interviewee D03 acknowledged the theoretical benefits of project-wide optimisation but highlighted its practical limitations, noting that:

'A project-wide approach might choose a different timber size to reduce waste across several panels, but that creates tracking headaches: multiple elements cut at different times.'

Collectively, the observational, design, and interview evidence confirm that the lack of cross-panel nesting, driven by manageability concerns and production scheduling priorities, is the primary contributor to these offcuts.



Figure 5.42: Various offcuts generated because of limited nesting practice

5.5.2 Fitting and Cutting OSB Boards

The OSB boards are used as a sheathing cover to improve timber frame rigidity and structural integrity. The cutting activity of this layer is performed manually using electrical saws. Different from Factory B, this factory does not pre-cut OSB boards before assembly but fit full boards first and then cut out the excess OSB material. This factory uses only one size OSB boards of 1200 mm by 2400 mm.

The observation window of the cutting activities of the OSB boards covered 10 panels. Based on the drawings provided for these panels, the total required area of OSB boards is calculated as 29.58 m². In comparison, the total processed area of the same boards was 37.44 m². This means that the total offcuts generated is 7.86 m², making about 21% of the total material use (refer to Table 15 at Appendix D for detailed calculations). To understand how and why these offcuts being generated, three categories of offcuts are identified as explained in the following subsections:

5.5.2.1 Length-side OSB Board Offcuts

These offcuts were generated from cutting 625 mm piece from the 2400 mm side of the OSB board. The 625 mm cut is needed along with full board length of 2400 to cover the full panel length of 3025 mm (see Figure 5.43). This length-side cut contributes to the generation of 2.95 m² offcuts, making up to 8% of total OSB use and 38% of the total generated OSB offcuts. For thorough analysis, a structured RCA method was followed using the What–How–Why reasoning chain, as explained in Table 5.54.

Table 5.54: Length-side OSB board offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcut associated with length-side of OSB boards are generated
2	How?	By cutting the second OSB board at 625 mm, generating 1775 mm offcut pieces that are not fully reusable
3	Why?	Because the 1775 mm offcut can only be reused to produce two 625 mm cuts, it leaves one remaining 525 mm piece that is unusable
4	Why?	Because of the limited design consideration to the OSB board length multiples (i.e., quarters)
5	Why?	Because of the excessive prioritisation of the design customisation over material efficiency

Hence, the technical root cause behind these offcuts is the limited consideration of standard OSB board length multiples (e.g., quarters) during the design process. Specifically, designing wall heights to require a secondary cut of 600 mm rather than 625 mm would allow a single full OSB board to be reused four times without generating offcuts. However, the current practice is justified by a clear prioritisation of design customisation over material efficiency.

This interpretation is supported by observation notes recorded during Observation Session D02 (refer to Appendix F), which documented repeated cutting of OSB boards into non-standard lengths, resulting in consistent residual strips, as illustrated in Figure 5.43. It is further reinforced by the design document analysis, which shows wall height specifications that do not align with standard OSB length fractions, as illustrated in Figure 5.45. In addition, Interviewee D04 explicitly confirmed the design-driven nature of this issue, stating that:

‘That’ll be down to design, depending on the end user.’

Interviewee D01 further contextualised this decision from a client perspective, noting that:

‘From the client side, I don’t think they ask for more sustainable layouts in terms of reducing offcuts... they ask for other sustainability measures—solar, net zero ambitions, etc.—but reducing offcuts might not be something they request directly.’

Collectively, the observational, design, and interview evidence confirm that client- and design-led priorities, rather than material optimisation, are the primary drivers of these OSB offcuts.



Figure 5.43: Length-side OSB offcut accumulation

5.5.2.2 Width-side OSB Boards Offcuts

These offcuts were generated only when the designed panel width falls below the standard OSB width, which is 1200 mm. This necessitates cutting from the width side of the OSB boards, generating 4.9 m² offcuts. This makes up to 13% of total OSB use and 62% of total OSB offcuts. For detailed analysis, a structured RCA approach was adopted using the What–How–Why reasoning chain, as shown in Table 5.55.

Table 5.55: Width-side OSB board offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts associated with the width-side of the OSB boards were generated
2	How?	By cutting from the width side to fit varying panel widths
3	Why?	Because of the automated design tool that auto-generates random ranges of panel widths below 1200 mm
4	Why?	Because the design tool does not account for standard OSB width multiples to allow for complementary cuts (e.g., halves, thirds, quarters)

Therefore, the technical root cause of the excessive width-side OSB offcuts is the limited consideration, within the design tools, of standard OSB width multiples. Restricting required cuts to predictable fractions of a board, such as quarters, halves, or thirds, would enhance material efficiency and streamline the cutting process. This interpretation is supported by observation notes recorded during Observation Session D02 (refer to Appendix F), which documented repeated non-standard width cuts and the accumulation of width-side offcuts, as illustrated in Figure 5.44.

It is further reinforced by the design document analysis, which shows panel layouts that do not align with standard OSB width multiples, thereby necessitating irregular width cuts, as illustrated in Figure 5.45. In addition, Interviewee D03 highlighted limitations in the current optimisation logic, stating that:

‘The computer will attempt to optimise too, but—strangely—it doesn’t work as efficiently.’

Collectively, the observational, design, and interview evidence indicate that insufficient design-tool alignment with standard OSB width multiples is the primary driver of excessive width-side OSB offcuts.



Figure 5.44: Width-side OSB offcut accumulation

5.5.2.3 OSB Opening Offcuts

These offcuts were totally avoided at the 10 observed wall panels which have only two window openings. Thanks to the pre-cutting list produced in advance, offcuts of about 5% of the total OSB use at the openings were avoided. For detailed analysis, a structured RCA method was pursued using What-How-Why reasoning chain as shown in Table 5.56.

Table 5.56: OSB opening offcuts - root cause analysis

#	Questions	Explanations
1	What?	Offcuts associated with the OSB wall openings are avoided
2	How?	By cutting and fitting the required OSB cuts around the openings
3	Why?	Because the required OSB cuts were pre-planned around the openings in a cutting list
4	Why?	Because the cuts pre-planning comes as part of an automated design tool that produces shop drawings
5	Why?	Due to the perceived feasibility of adopting the automated cutting output in terms of both material efficiency and production flow

Thus, the technical root cause behind the avoidance of opening-related offcuts is the use of pre-planned cutting around openings, enabled through an automated design tool that generates cutting layouts while explicitly excluding door and window areas. This design practice is adopted by the factory because it is perceived as a feasible means of enhancing both production flow and material efficiency by eliminating cutting around openings. This interpretation is supported by observation notes recorded during Observation Session D02 (refer to Appendix F), which documented the installation of OSB panels with openings already accounted for in the cutting patterns, resulting in no additional trimming at opening locations.

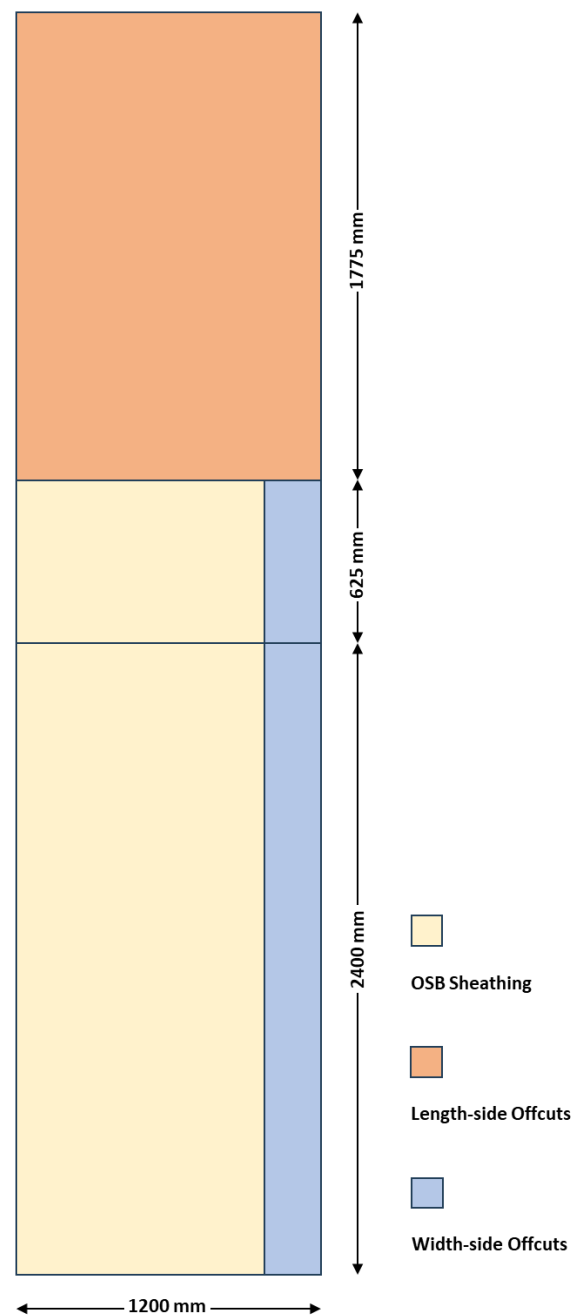


Figure 5.45: OSB sheathing assembly plan and offcuts

5.5.3 Cutting & Fitting Rockwool Insulation

These insulation blocks come in 100 mm thick, 1200 mm wide, and 3700 mm long, primarily to enhance the thermal and acoustic insulation capacity of the wall panels. The observations of cutting and fitting activities of the rockwool insulation covered 10 panels.

Using the drawings provided for that panel, the total required volume of rockwool of insulation is calculated as 25.26 m². In comparison, the total processed volume of insulation was recorded as 27.79 m². This means that the total waste is 2.53 m², making about 9% of the total material use. This insulation material is wasted when more insulation is packed into a space than required. This happens when the workers put the insulation layers over the spaces required to be filled and cut the needed pieces using a knife. However, the cuts are never perfect with many cuts being slightly bigger than required. For detailed analysis, a structured RCA approach was adopted using the What-How-Why reasoning chain, as shown in Table 5.57.

Table 5.57: Rockwool insulation over-stuffing - root cause analysis

#	Questions	Explanations
1	What?	Loss of rockwool insulation volumes
2	How?	By slightly overfilling the cavities with more insulation than required
3	Why?	Because insulation pieces are intentionally cut slightly larger than the cavity size
4	Why?	To ensure a complete fill with no gaps
5	Why?	Because manual measurement and cutting lack precision
6	Why?	Because speed and convenience are prioritised over precision during installation

Hence, the technical root cause behind the overstuffing of rockwool insulation is the limited precision inherent in manual cutting, combined with operational pressure to fill cavities as quickly as possible. This practice reflects the factory's prioritisation of assembly flow over precise measurement and cutting, thereby compromising material efficiency.

This interpretation is supported by observation notes recorded during Observation Session D03 (refer to Appendix F), which documented insulation pieces being cut oversize and compressed into cavities, as illustrated in Figure 5.46. It is further reinforced by the design document analysis, which shows a consistent dimensional mismatch between used insulation widths and the actual cavity sizes. In addition, Interviewee D03 explicitly acknowledged this trade-off, stating that:

‘We’re building quickly, in a controlled environment, standardised, quality is higher—you’d expect waste generation to be minimal. But time matters too: when you build quickly, accuracy can reduce and waste might increase.’



Figure 5.46: Overstuffing practice of rockwool insulation

5.5.4 Summary - Factory D

This section provided a detailed analysis of how, how much, and why material waste is generated in Factory D. This factory is part of a small-sized business producing timber-frame wall panel products, primarily serving educational projects. Material waste was particularly observed and recorded during some cutting and fitting activities. During cutting activities, varying amounts of offcuts were recorded, due to discrepancies between the designed cut sizes and standard material sizes. By conducting observations, design analysis, and semi-structured interviews, the root causes of this issue were identified as limited design consideration to the standard material sizes, poor choice of material sizes, and inadequate material nesting. In fitting activities, excess volumes of rockwool insulation were stuffed into wall cavities, accounting for approximately 9% of total insulation material used. The root causes behind this overuse issues were identified as the limited accuracy of manual work.

5.6 Chapter Summary

This chapter presented micro-level material waste analysis, mainly to understand how, how much, and why material waste is generated at source in OSC (refer to Table 16 in Appendix E for detailed summary of the analysis). The production processes of four OSC products were

directly observed across four factories with interviews and design documents analysis employed to enrich the analysis, promote data reliability, and perform validation. Nine root cause themes can be identified. Five of them are supported through literal replication, while the remaining four are supported through theoretical replication. Specifically, manual work inaccuracies, poor choice of material size, waste transfer by outsourcing, inconsistent material quality, and lack of precision-adaptive material application were consistently associated with either material waste generation or avoidance/reduction. In contrast, custom-size ordering, standard size alignment, cut planning adoption, and material nesting were linked to material waste avoidance/reduction when present, and to material waste generation when absent, demonstrating theoretical replication. Table 5.58 presents the identified root cause themes, the type of replication logic (literal or theoretical) associated with each, and the specific instances in which they were observed across the four cases. The next chapter synthesises these findings to develop a higher-level understanding of material waste generation at source in OSC.

Table 5.58: Case study replication across the identified root cause themes

Root Cause Theme	Replication Logic	Factory A			Factory B			Factory C			Factory D			Grand Total
		Generation	Avoidance/ Reduction	Total	Generation	Avoidance/ Reduction	Total	Generation	Avoidance/ Reduction	Total	Generation	Avoidance/ Reduction	Total	
Custom-Size Ordering	Th	1	2	3	3		3	3		3				9
Manual Work Inaccuracies	Lt	1		1	3		3	1		1	1		1	6
Poor choice of material size	Lt				1		1				1		1	2
Standard Size Alignment	Th		5	5	5	1	6	1	1	2	2		2	15
Waste transfer by outsourcing	Lt		2	2										2
Cut Planning adoption	Th	2		2		2	2	1		1				5
Material Nesting	Th		2	2	4	2	6	2		2	1		1	11
Inconsistent Material Quality	Lt				1		1	1		1	1		1	3
Lack of precision-adaptive application	Lt				2		2	1		1				3
Grand Total		4	11	15	19	5	24	10	1	11	6	0	6	56

Th: Theoretical Replication; Lt: Literal Replication

Chapter Six: Material Waste Categories in Offsite Construction: A Thematic Analysis of Root Causes and Influencing Conditions

6.1 Introduction

This chapter builds on the micro-level analysis presented in the previous chapter to develop a higher-level, thematic understanding of material waste generation in OSC. Drawing on evidence from the four case studies, it moves beyond individual waste instances to identify broader patterns in how material waste emerges in relation to underlying root cause practices. The chapter employs thematic analysis to classify material waste into distinct categories and to map each category to its associated root causes. In doing so, it develops a conceptual structure for understanding how material waste is generated, reduced, or avoided under different production conditions. Five distinct categories of material waste are identified: Standard Size-Induced Waste, Suboptimal Nesting Offcuts, Opening-Induced Offcuts, Inaccuracy-Induced Waste, and Edge-Squaring Offcuts. By identifying and defining these categories and linking them to their root causes, this chapter addresses the fourth research question: What distinct categories of material waste emerge in OSC? In addition, the chapter interprets these categories in relation to the role of automated technologies and differing operational priorities, particularly the tension between production flow and material efficiency. The findings indicate that automation was not consistently applied in ways that supported waste reduction and that production flow was frequently prioritised over material efficiency. Minimal waste was observed only where these priorities were aligned. These insights provide an explanatory basis for understanding the conditions under which waste is generated, and they lay the conceptual foundation for the quantitative comparisons presented in the following chapter.

6.2 Material Waste Categories in OSC

In the previous chapter, material waste generation instances were identified and analysed to determine how, how much, and why material waste is generated at source in OSC. In this chapter, thematic analysis was employed to identify distinct categories of material waste, each explained by its root-cause practices. Notably, the identified waste categories were predominantly observed in the form of offcuts, while overuse was less common. No waste in the form of damaged materials was identified. Overuse was mainly observed in flexible

materials (e.g., membranes), whereas offcuts were more commonly associated with rigid materials (e.g., OSB). This distinction is largely attributable to the ability of flexible materials to be slightly compressed or folded without compromising the geometric integrity of the designed product. As a result, overuse represents a form of waste that remains embedded within built components and contributes subtly to increased material consumption.

Figure 6.1 summarises the thematic analysis in a Sankey diagram, showing the origins of different categories of material waste, from the observed cases to different materials, and root cause practices. The width of the lines reflects the number of component assembly activities observed across different cases in relation to materials, root cause practices and waste categories. The following subsections provide detailed explanations of how and why different categories of material waste are generated at source in OSC.

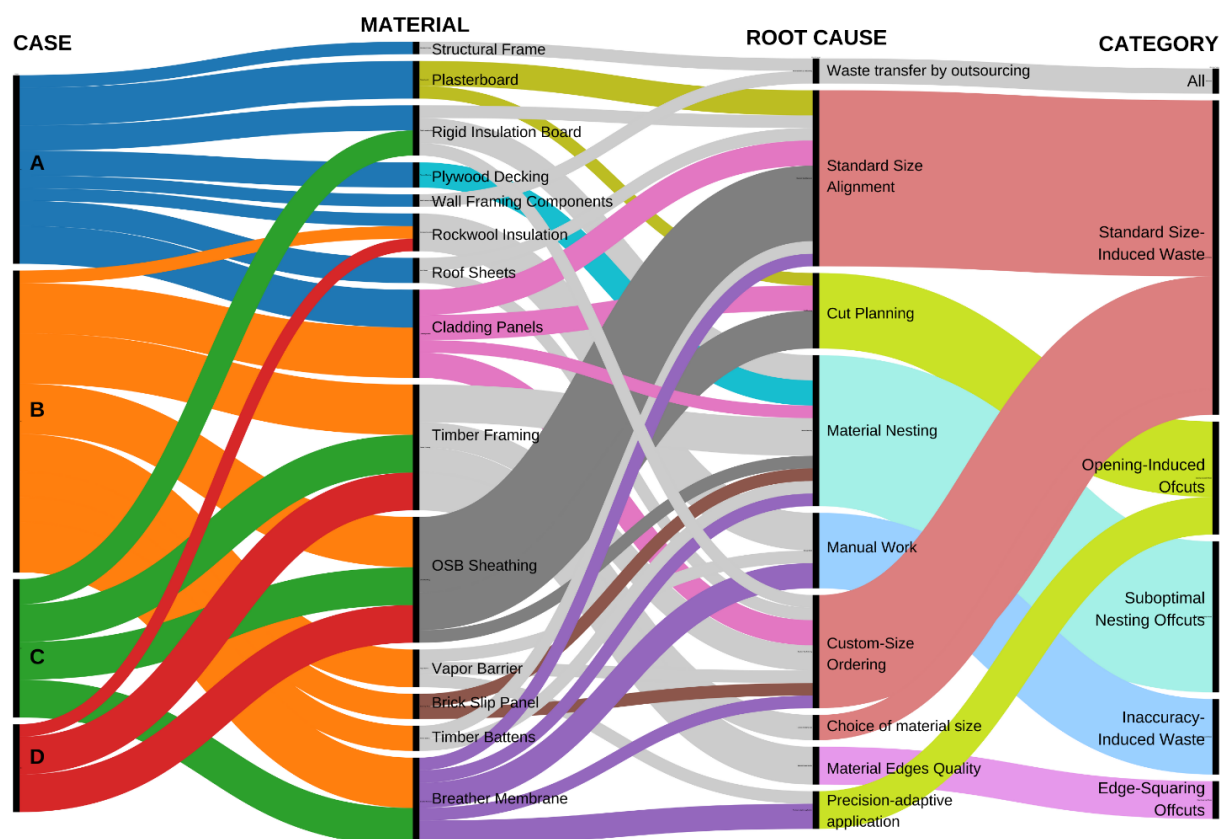


Figure 6.1: The origins of different material waste categories in relation to the materials and root causes

6.2.1 Standard Size-Induced Waste

When the required cut size in design is smaller than the standard material size being used, standard size-induced waste is likely to be generated. The root cause practices behind the generation of this category of waste can be explained in the following subsections and in the flowchart shown in Figure 6.2:

6.2.1.1 Lack of Standard Size Alignment

This is the most straightforward root cause practice for offcuts generation, identified repeatedly across the four cases. In principle, any designed cut size that does not align with standard material sizes is likely to produce offcuts. However, blaming the design for overlooking the standard material sizes is only reasonable when the difference between the designed and available material sizes is insignificant. In such cases, a slight adjustment to the design could eliminate offcuts with minimal impact on the required level of customisation (i.e., required customer sizing). Therefore, the lack of alignment with standard sizes is often driven by an overly rigid approach to design customisation, which necessitates additional cutting steps and generates offcuts, ultimately compromising both production flow and material efficiency. This is especially evident in the length-side of the OSB boards at Factories B and C, where slight discrepancies between the wall panel design and standard board sizes remain unaddressed due to the rigid floor-level design.

However, when the design is aligned with standard material sizes, both production flow and material efficiency are enhanced. Matching the required cut sizes to standard material dimensions eliminates the need for trimming, thereby preventing the generation of offcuts. Instead, the materials fit directly into their designated positions smoothly and efficiently. This approach was particularly evident at Factory A, where the design team had the flexibility to adjust the geometry of the walls and ceilings to align with standard plasterboard and roof sheet sizes, promoting both material efficiency and overall production flow.

6.2.1.2 Lack of Custom-Size Ordering

When the required cut size does not align with standard material sizes, often due to rigid design customisation, there is still an opportunity to avoid material waste caused by this mismatch. This can be achieved by sourcing custom-sized material cuts that precisely match the design requirements. Such an approach is particularly viable when the difference between the designed cut size and standard material size is substantial and/or when design flexibility is limited. In these cases, the failure to order custom-sized materials is a key factor behind the generation of standard size-induced offcuts. This decision is often influenced by the perceived higher cost and lead time associated with sourcing custom sizes, which compromises both material efficiency and production flow due to the added cutting step. This issue was evident at the width-side of the cladding panels at Factory A, the vapour barrier at Factory B, and the breather

membrane at Factory C (among others), where significant mismatches between required and used material sizes led to excessive material waste generation.

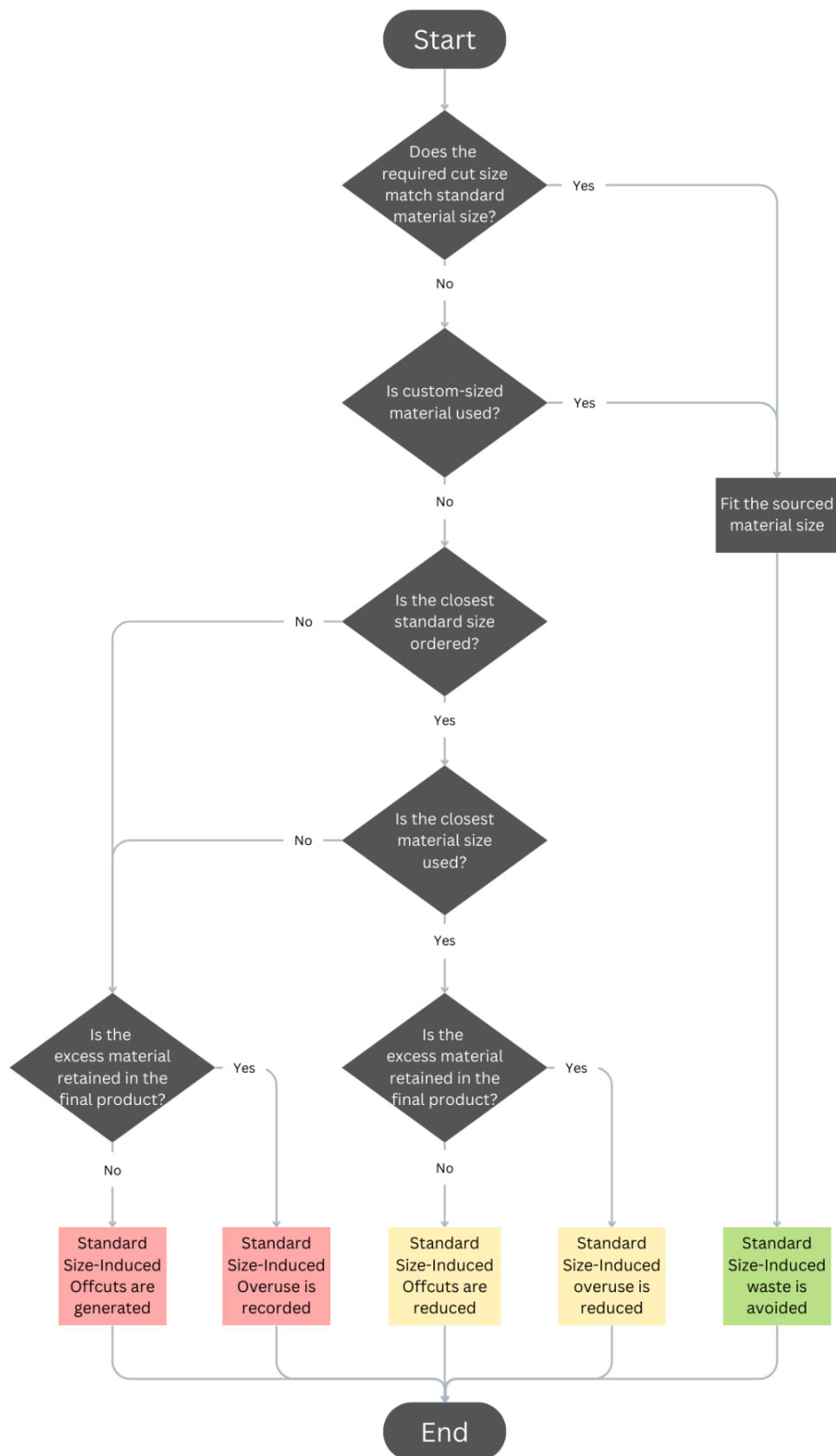


Figure 6.2: Standard size-induced waste generation, reduction, and avoidance

However, when custom-sized materials are sourced to fit directly without the need for cutting or generating offcuts, both production flow and material efficiency are promoted. This was evident in the lengths-side of the cladding panels and the length-side of the roof sheets at Factory A, where long-term supply chain relationships enabled the factory to obtain custom-sized materials at competitive prices and within suitable timeframes. As a result, the production team managed to both streamline production activities and minimise material waste.

6.2.1.3 Poor Choice of Material Size

When both standard size alignment and custom-size ordering are lacking, selecting the closest standard material size to the required cut can only help reduce offcuts to the minimum possible. However, if even the closest standard size is not used, excessive offcuts are likely to be generated due to the significant size mismatch.

According to the analysed data, this issue was observed in two instances, both associated with human error. At Factory B, timber sections that would have produced fewer offcuts were not transported near the saw due to a lack of coordination between the logistics and production teams. As a result, an unsuitable timber size was used to produce the required cuts mainly to avoid production line disruption, resulting in excessive offcuts generation. Similarly, at Factory D, a larger-than-required timber section was consistently used based on the assumption that the resulting offcuts could be reused as noggins. However, the analysis revealed that the volume of the generated offcuts far exceeded the noggin demand, leading to significant offcut accumulation.

6.2.2 Suboptimal Nesting Offcuts

These offcuts are generated due to the lack of effective material nesting, which involves integrating different cuts within and across various OSC units with the aim of maximising material efficiency and reducing waste. The main driver behind this waste category is the excessive focus on production flow in OSC, which encourages cutting materials in line with the production schedule rather than according to an optimal layout that would minimise offcuts. In doing so, offcuts are likely to accumulate, signalling suboptimal material nesting practice.

Based on the detailed activity-level analysis, three key variables determine whether suboptimal nesting offcuts are generated, reduced, or avoided. The first variable is *the use of a cutting plan*, which specifies the exact cuts required for assembly. The cutting plan includes a cutting list, which serves as a critical input for *nesting-enabled cutting machinery*, the second key variable.

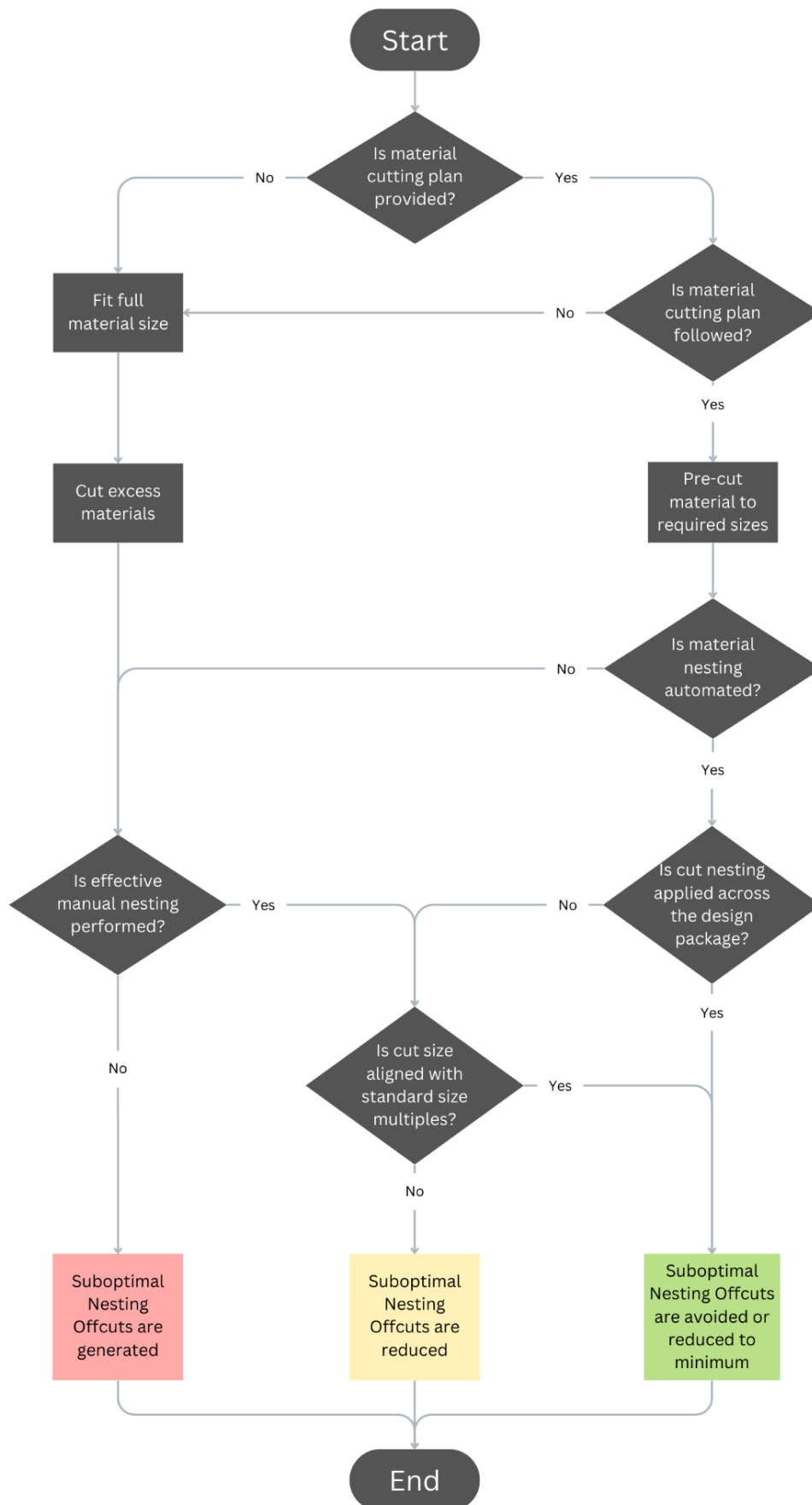


Figure 6.3: Suboptimal nesting offcuts generation, reduction, and avoidance/ reduction to minimum.

However, although both the cutting list and nesting capability were available in Cases B, C, and D (particularly in timber cutting), the nesting feature was not activated. Interviews revealed that when the nesting feature is enabled, the resulting cuts are produced in a random sequence based on material efficiency rather than the production schedule. This sequencing causes significant disruption to production flow, and for this reason, the automated nesting feature is not utilised. Accordingly, material nesting is carried out manually, relying heavily on workers' experience.

However, when a cutting plan is followed, the flexibility to perform manual nesting is reduced, often resulting in excessive offcut generation. This is particularly evident in the cutting and fitting of brick slip panels at Factory B and rigid insulation boards at Factory C. In contrast, when no cutting plan is followed, manual nesting tends to yield better outcomes by reducing the amount of generated offcut. This is clearly demonstrated in the cutting and fitting of rigid insulation boards at Factory A.

Regardless of whether a cutting plan is followed, when the required cuts are *aligned with size multiples of the standard material* (the third variable), effective manual nesting was observed. This is particularly evident in the cutting and fitting of plywood decking at Factory A and breather membrane at Factory B. Figure 6.3 presents a flowchart illustrating how suboptimal nesting offcuts are generated, reduced, or avoided/minimised.

6.2.3 Opening-Induced Offcuts

These offcuts are generated at the opening areas (e.g., windows, doors) because of fitting full material sizes over the openings and then cutting out the layer covering the openings. The generation or avoidance of this category of offcuts can be associated with two key practices discussed in the following subsections and illustrated in the flowchart shown in Figure 6.4.

6.2.3.1 Lack of Cut Planning

This practice refers to the absence of design detail or production step to pre-cut the required material sizes of two-dimensional rigid materials (e.g., OSB, rigid insulation, cladding panels) that can be joined and do not need to be continuous. Instead, full-size materials were fitted over openings and then trimmed to expose those areas, resulting in excessive opening-induced offcut generation. This issue was particularly evident in plasterboard assembly at Factory A and the OSB application at Factory C, where full sheets were placed over openings, leading to

significant amounts of offcuts. According to the activity-level analysis, the primary driver behind this practice is production flow, primarily to eliminate the pre-cutting step.

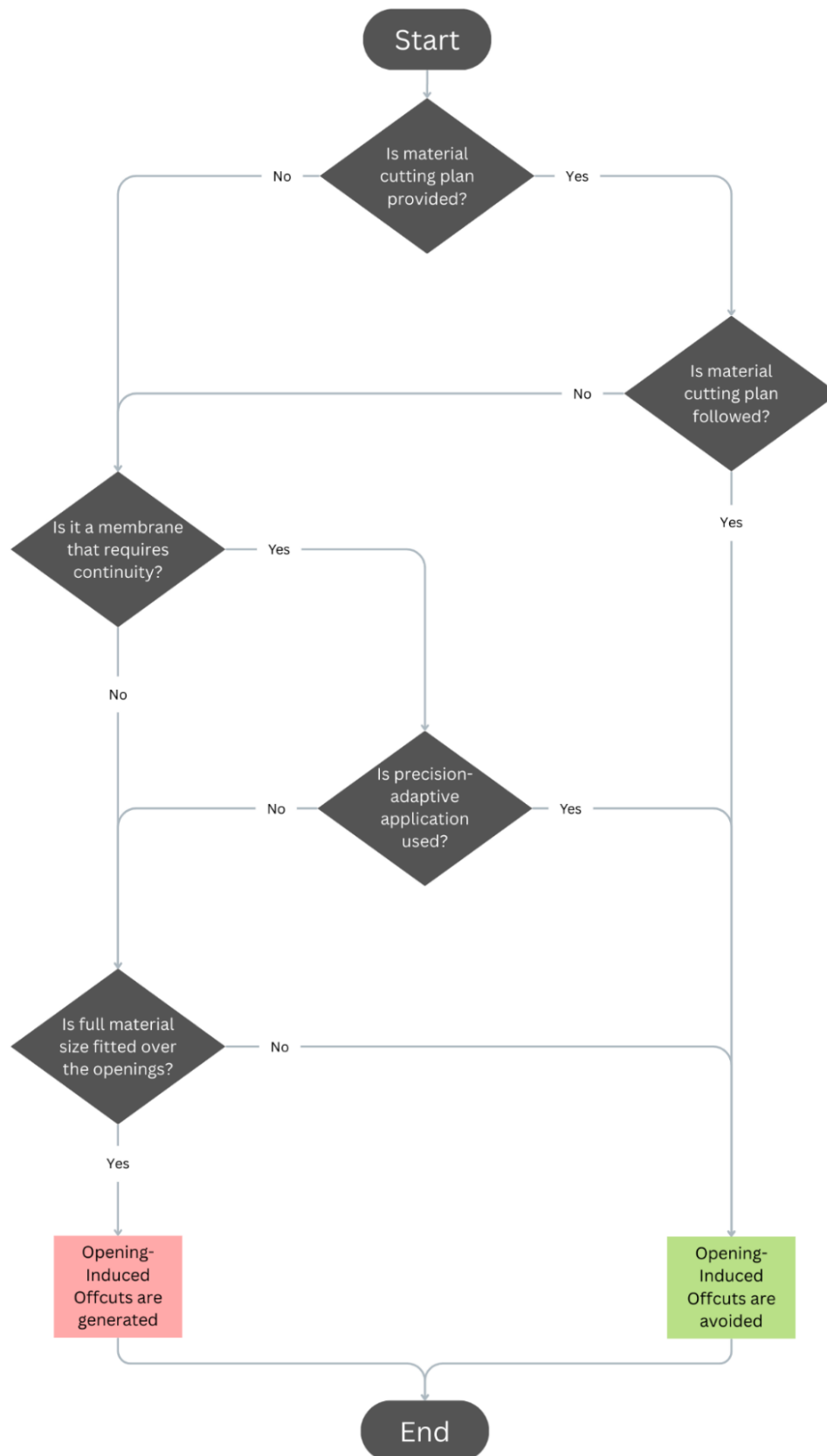


Figure 6.4: Opening-induced offcut generation and avoidance.

6.2.3.2 Lack of Precision-Adaptive Material Application

This practice reflects the absence of a precise and adaptive material application method capable of producing highly customised shapes, while ensuring high-quality fitting that preserves essential functions such as airtightness, thermal insulation, and water resistance. This could involve, for example, the in-house production of highly customised membranes that exclude opening areas. The absence of such a practice is particularly evident with flexible materials (e.g., breather membranes, vapour barriers) that require continuity to deliver the required functionality. Consequently, full rolls were applied across surfaces, and the sections covering openings were cut out, leading to significant offcut generation. The main driver behind this approach is the emphasis on production flow, which comes at the expense of material efficiency.

6.2.4 Inaccuracy-Induced Waste

This category of waste is associated with *manual work inaccuracies*, where rough measurement, fitting, and cutting are carried out to assemble flexible materials. This includes, rockwool insulation, vapour barriers, and breather membranes across the four cases investigated. Unlike rigid materials such as OSB or cladding panels, no efficient precision tools were observed for measuring, cutting, and fitting flexible materials.

According to the interviews conducted, accurate manual measurement is generally viewed as time-consuming and unnecessary given that flexible materials can be slightly folded, stuffed, or cut manually using basic tools. To that reason, a tendency to add positive tolerance was consistently observed to ensure the minimum required size is met efficiently and consistently, without investing additional time in precise measurement.

According to the root cause analysis, this practice is driven by a prioritisation of production flow and speed over material efficiency. In most cases, the excess flexible material was retained within the product. This is particularly the case for rockwool insulation and the length-side of the breather membrane across the investigated cases. However, only in one instance, the excess material was cut and discarded into recycling bins. This was the case for the length-side of the vapour barrier at Case B. Figure 6.5 presents a flowchart illustrating how inaccuracy-induced waste are generated or avoided.

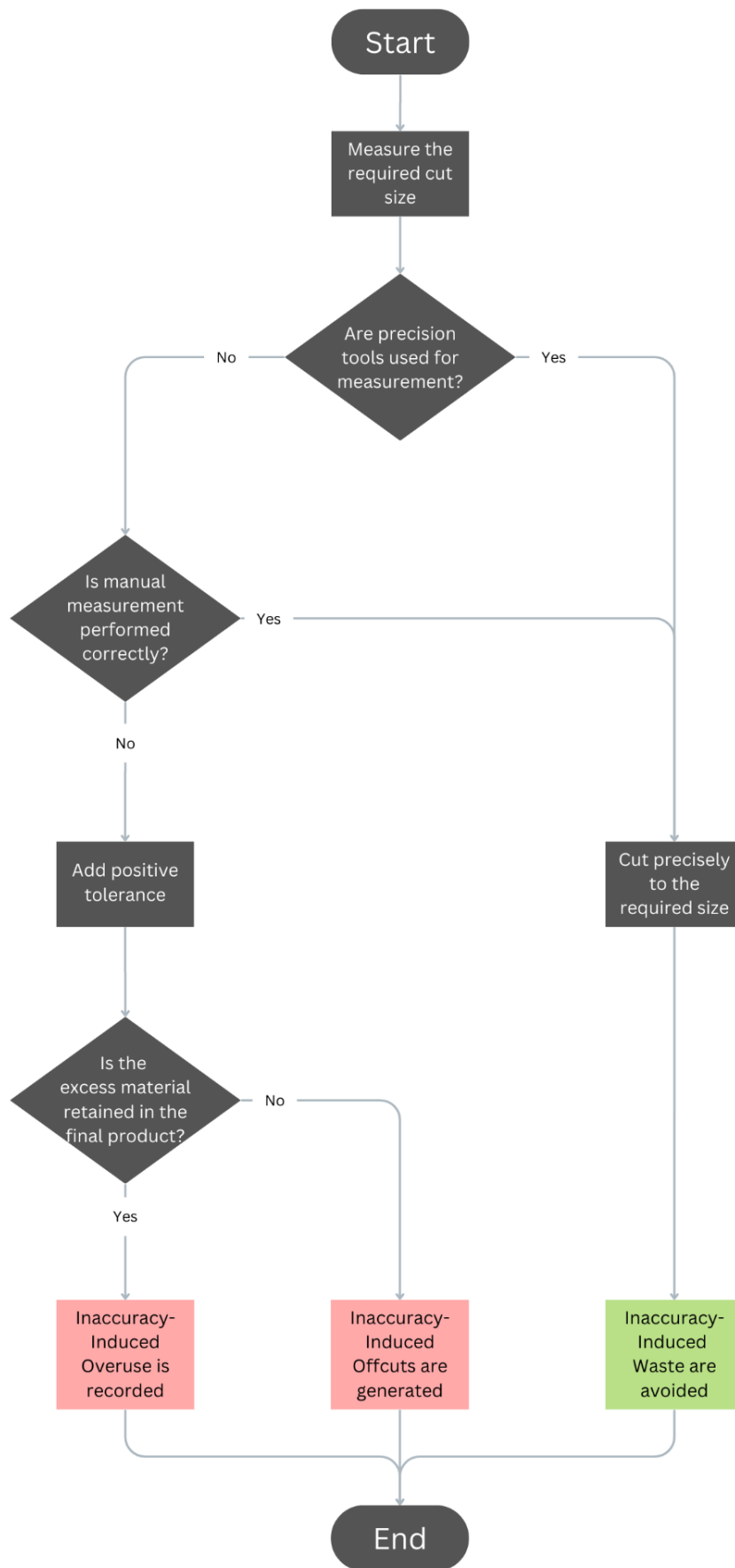


Figure 6.5: Inaccuracy-induced waste generation and avoidance.

6.2.5 Edge-Squaring Offcuts

These offcuts are generated due to the need to slightly trim material edges to ensure a square, clean start that is both even and structurally sound for assembly. This is particularly common with standard timber framing sections, which are typically processed at the supplier facility using limited precision tools for mass cutting. In addition, timber sections are prone to defects caused by the natural drying process. Hence, these factors increase the likelihood of uneven or cracked timber edges when standard timber sections arrive to the OSC facility.

Timber suppliers generally do not use precision tools for mass cutting, nor apply excessive protective treatments to timber edges. Instead, they typically add a positive tolerance beyond the nominal length, allowing manufacturers to trim potentially uneven and defective ends. As a result, sacrificing 20-50 mm of timber from each edge is considered more practical and feasible than investing in precision mass cutting and/or protective treatments, both of which are viewed as costly and time-consuming for producing unnecessary protected and square edges at this stage. Consequently, trimming 20-50 mm from each edge has become standard practice across Factory B, C, and D, regardless of the actual quality of the timber. Notably, no quality checks were performed to identify the defective edges. While this approach is driven by the desire to ensure accuracy and quality, it comes at the expense of material efficiency. Figure 6.6 presents a flowchart illustrating how edge-squaring offcuts are generated or avoided.

6.2.6 Discussion

The identified categories of material waste and their associated causal practices demonstrate that material waste in OSC primarily arises from making-do practices across the design, procurement, and production processes. Consistent with lean construction theory, making-do refers to situations in which work proceeds despite incomplete, inadequate, or misaligned input information (Koskela, 2004; Formoso *et al.*, 2011; Formoso *et al.*, 2020). Across the investigated OSC factories, making-do was not accidental but systematically embedded, reflecting deliberate trade-offs in which production flow, among other priorities, was frequently prioritised over material efficiency.

At the design stage, making-do was observed through incomplete or inadequate design input, particularly the failure to align design specifications with standard material sizes and the absence of explicit cut-planning information. This form of design-related making-do aligns with Formoso *et al.* (2002), who identified poor standardisation and insufficient detailing as key drivers of material waste in traditional construction. Extending this evidence to OSC, the

findings demonstrate that dimensional misalignment and incomplete design detailing persist even within factory-based production environments.

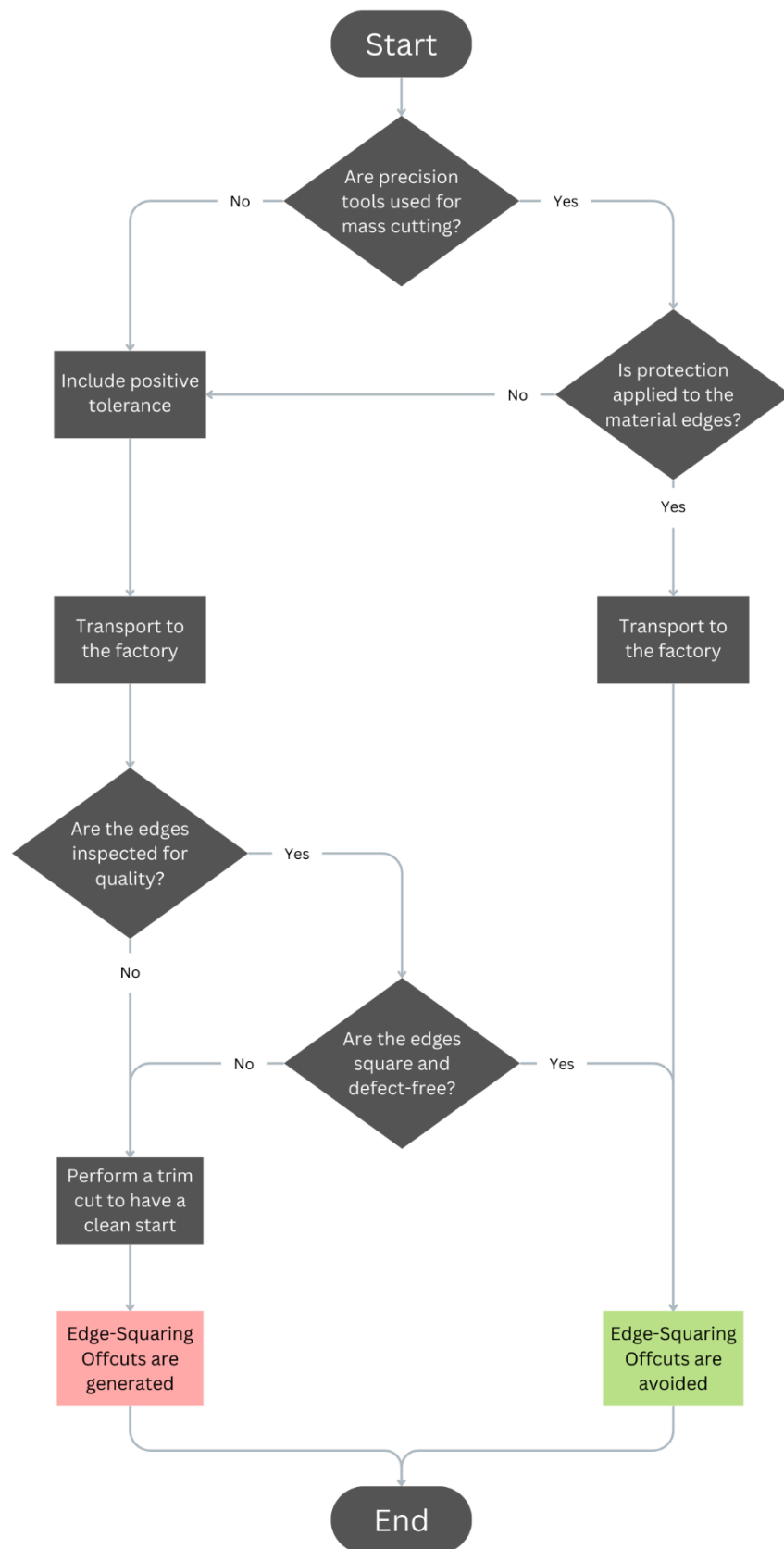


Figure 6.6: Edge-squaring offcuts generation and avoidance

These design-level material inefficiencies propagate into procurement, where making-do arises through the failure to order custom-sized materials that match the design requirements. Prior research attributes procurement inefficiencies to late design finalisation, which compels procurement activities to proceed with incomplete input information (Koskela, 2004; Elfving, 2003). The present findings extend this understanding by demonstrating that procurement-related making-do in OSC is predominantly a conscious and rationalised decision. Standard material sizes are selected to avoid perceived risks associated with longer lead times, higher costs, or supply uncertainty linked to custom orders. While such decisions preserve procurement reliability and schedule certainty, they transfer dimensional misalignment into production, where additional cutting becomes unavoidable.

At the production stage, making-do becomes operationally visible through the use of unsuitable material sizes, inadequate tools, and simplified execution methods aimed at maintaining production flow. These practices align with Formoso et al. (2017) categorisation of making-do arising from unavailable or inadequate resources, tools, and information. The findings indicate that production workers frequently rely on manual cutting, rough measurement, ad hoc material nesting, routine trimming of material edges without prior inspection, and full-sheet application followed by trimming around openings. While similar issues have been reported in conventional construction by Formoso's et al. (2002) work which linked imprecise measurement to excessive consumption of concrete and cement, this study identifies comparable making-do inefficiencies in OSC and demonstrates that such practices are systematic rather than exceptional in controlled factory settings.

Hence, these findings show that making-do in OSC spans different stages where design incompleteness, procurement rigidity, and production flow prioritisation interact to generate systematic material waste. Rather than isolated inefficiencies, these practices reflect a coherent organisational logic in which production flow and stability consistently favoured over material efficiency considerations. These results therefore extend lean construction theory by empirically showing how making-do becomes institutionalised across design, procurement, and production in OSC, transforming avoidable material waste into a normalised outcome.

6.3 Waste Outcomes of Automated Technologies

Automation is widely believed to facilitate significant waste reductions in OSC. However, no prior studies evaluated the validity of this claim in practice. Hence, this research has investigated the how different categories of automated technologies contributed to material

waste generation. Three key categories of automated technologies were identified and investigated as discussed in the following subsections:

6.3.1 Automated Design Modularisation Tools

These automated design tools are BIM-integrated, used to breakdown design into modules, sections, and detailed cutting lists of different materials to facilitate the cutting and fitting activities of different components in OSC. These tools are typically programmed with a set of parameters, such as geometric design (e.g., wall length), structural requirements (e.g., min-max stud spacing), transportation considerations (e.g., weight, size), and standard material sizes. When this automated tool is firstly applied, design detail is expected to generate based on the set specifics of the parameters. The generated detail is then manually audited by production team to ensure they are workable and there are no detailing errors.

The more the standard material sizes or their multiples are considered by the automated design modularisation tool, the more chance for cut integration by design and the less chance for offcut generation later in production. However, when no consideration is made to the standard material sizes, Standard Size-Induced Waste is likely to generate (see Section 6.2.1).

Based on the activity level analysis conducted, the parameter of standard size consideration was only considered in one instance across the four cases. This instance observed at Case C, where the panel stud location design is aligned with the OSB board width multiples (i.e., halves, two-thirds). However, standard material sizes or their multiples were not considered across Case B and D. Particularly, the width-side cut design of OSB in Case B and D was highly random, impeding effective integration of different cuts. Hence, significant OSB offcut generation was observed along the width side, totalling 7% and 13%, respectively. Figure 6.7 illustrates how this automated technology contributes to material waste generation.

From a lean perspective, the automated design modularisation tools observed primarily support conversion efficiency rather than flow efficiency. Lean theory emphasises that improving conversions alone does not necessarily reduce waste unless flow is also considered (Koskela, 2000; Koskela, 2004). In the researched factories, the BIM-integrated tools were configured to satisfy geometric, structural, and logistical parameters, but standard material sizes or their multiples were not embedded as governing design constraints. As a result, automation frequently generated randomised cutting patterns, hindering cut integration and embedding standard size-induced offcuts at the production stage, as observed in Factory B and D. By contrast, Factory C demonstrates that when automated design explicitly aligns component

layout with standard material dimensions, flow efficiency is enhanced and material waste is reduced. This finding extends lean discussion on design modularisation (Økland et al., 2017b; Choi et al., 2020b; Zhang et al., 2022) by demonstrating that automated design technologies reduce material waste only when deliberately configured to support production flow.

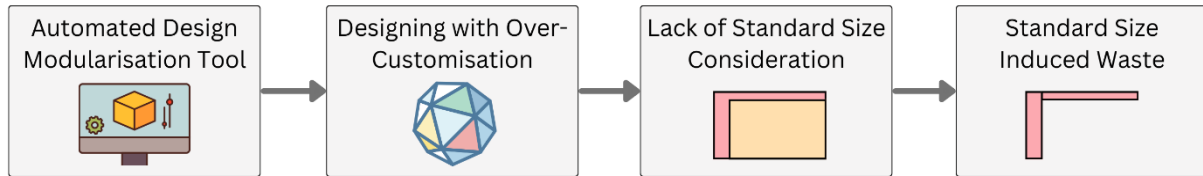


Figure 6.7: Automated design modularisation tool and associated inefficiencies behind waste generation

6.3.2 Automated Nesting-Enabled Saws

These saws include the automated crosscut saws observed in Cases B, C, and D, and the automated panel saw observed in Case C. Across these cases, the automated saws have the capability to read material cutting lists, generate optimised cutting layouts, and execute the required cuts. This is achieved using optimisation algorithms integrated into the saw software, enabling them to produce the required cuts in a sequence that maximises material efficiency. In doing so, Suboptimal Nesting Offcuts can be avoided (see Section 6.2.2).

However, when the nesting feature at these saws was enabled, the generated cuts were produced according to best layout that yields the best material utilisation. This means that the generated cuts are not aligned with the required sequence of the production schedule, posing a significant threat to the production flow. As a result, the material nesting feature of these saws were largely underutilised. While the nesting feature could save material, it generated random cuts that require time-consuming and error-prone manual labelling and sorting. Therefore, in the observed OSC cases, the nesting function of automated saws was largely overlooked, as maintaining production flow was prioritised over maximising material efficiency, resulting in the generation of significant amount of Suboptimal Nesting Offcuts (see Section 6.2.2). Figure 6.8 illustrates how this automated technology contributes to material waste generation.

From a lean perspective, the findings on automated nesting-enabled saws expose a clear misalignment between conversion efficiency and flow efficiency. Lean theory emphasises that improving individual conversion activities, such as optimising cutting layouts to minimise offcuts, does not necessarily improve overall system performance if production flow is disrupted (Koskela, 2000, 2004). While the observed automated saws effectively enhance conversion efficiency through algorithm-based nesting, the generated cut sequences are poorly

aligned with production schedules and downstream assembly needs, thereby undermining flow. As a result, enabling nesting introduces additional wastes related to sorting, labelling, and coordination, leading production teams to prioritise flow stability over material optimisation.

This finding extends the automation literature (Liu *et al.*, 2019; Gbadamosi *et al.*, 2019; Malik *et al.*, 2021; Shafiee *et al.*, 2025) by demonstrating that technologies optimised solely for conversion-level material efficiency are likely to be underutilised in practice when they conflict with production flow requirements. This reinforces the lean principle that effective waste reduction in OSC depends on system-level flow alignment rather than isolated technological optimisation.

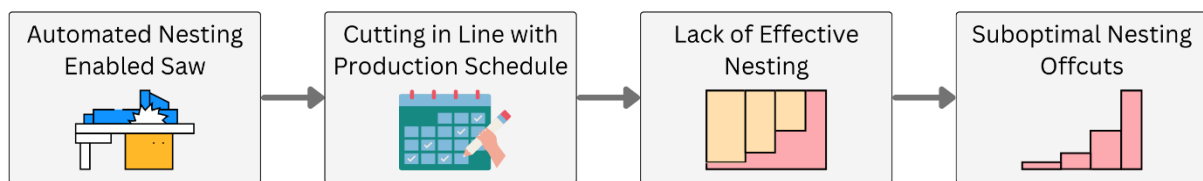


Figure 6.8: Automated nesting enabled saw and associated inefficiencies behind waste generation

6.3.3 Robotic Arms for Automated Assembly

Particularly, these automated assembly arms were observed at Case C which represents one of the most advanced assembly tools known in OSC. These arms are typically used to process board-based material cutting, fitting, and fastening, such as OSB and plasterboards. These arms have the capability of pick a wide range of cut sizes using vacuum cup system and place them onto their designated positions according to CAD files.

However, at Case C, only three OSB sizes (i.e., full boards, halves, and two-thirds) were used to be handled by the robotic arms and no cutting planning was adopted to precisely pre-cut only the required sections. This resulted in full OSB size fitting even over the openings and beyond the edges, which then cut out by the robotic arms, leading to excessive Opening-Induced Offcuts and Standard Size-Induced Offcuts generation (see Sections 6.2.3 and 6.2.1). Although the robotic arms are clearly featured with significant capability to handle even smaller cut sizes, no pre-cut OSB sections were produced or assembled in practice.

According to the interviews conducted, pre-cutting the OSB boards to only cover the required areas, although promotes material efficiency, it was found to affect production flow in two ways. First, it is considered as an extra activity where materials are placed nearby the saw, pre-cut to the planned sizes, transported to final assembly station, and assembled onto their designated positions. These steps are seen as a waste of time and labour, compromising overall

production flow. Second, having significantly various cut sizes to be precisely fitted onto their designated positions, means significantly slower and more complex robotic operations. The more complex tasks are delegated to the robotic arms to sort, handle, and fit different cut sizes, the more probability of errors and disruptions, threatening the production flow.

Hence, although the robotic arms theoretically have the capability to handle different cut sizes and so assist better material efficiency, they were not employed as such in practice. This is explained by the clear prioritisation of production flow over material efficiency, primarily to streamline the robotic operations. To that reason, no OSC pre-cutting was performed at Case C, to avoid complex, error prone, and slower robotic operations. This resulted in excessive offcut generation at the openings (i.e., Opening-Induced Offcuts) and the edges (i.e., Standard Size-Induced Offcuts) making about 25% of the total use of OSB material at Case C. Figure 6.9 illustrates how this automated technology contributes to material waste generation.

From a lean perspective, the robotic assembly arms at Case C reflect a flow-dominant configuration of automation, where production flow and stability are prioritised over material conversion efficiency. Lean theory distinguishes between conversion efficiency, concerned with minimising input losses, and flow efficiency, which emphasises continuity and reliability of production (Koskela, 2000, 2004). Although the robotic arms are technically capable of handling variable and smaller cut sizes, their operation was deliberately constrained to a limited set of standard board sizes to avoid pre-cutting, complexity, and disruptions to flow. As a result, material losses in the form of Opening-Induced and Standard Size-Induced Offcuts were accepted as a trade-off for maintaining smooth robotic operations. This finding extends lean discussions on automation (Gusmao Brissi *et al.*, 2022) by empirically showing that advanced OSC technologies do not inherently reduce waste. When configured to optimise flow alone, automation can institutionalise conversion losses and embed material waste.

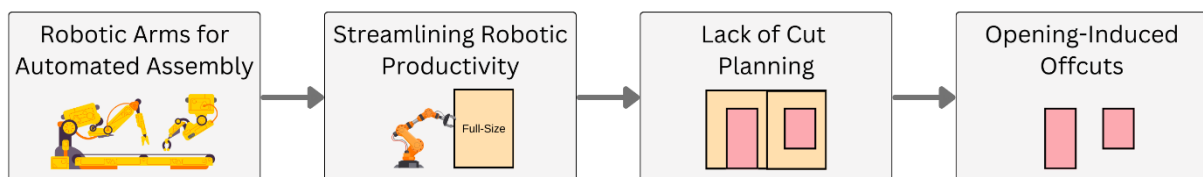


Figure 6.9: Robotic arms for automated assembly and associated inefficiencies behind waste generation

6.4 Waste Outcomes and Operational Priorities

Across the observed assembly activities in various cases, two core operational priorities were identified, including production flow and material efficiency, alongside two process-dependent

priorities, including design customisation and procurement time and cost. The analysis shows that potential tension or synergy between production flow and material efficiency is a primary factor influencing whether material waste was generated, reduced, or avoided. These dynamics are reflected in four distinct scenarios: 1) flow-driven tension, where production flow is prioritised over material efficiency, resulting in increased waste generation; 2) material efficiency-driven tension, where material efficiency is prioritised over flow, potentially slowing production processes; 3) third-priority dominance, where both production flow and material efficiency are compromised in favour of a third process-dependent priority, such as design customisation or procurement time and cost; and 4) synergistic alignment, where production flow and material efficiency are simultaneously optimised, promoting flow and saving material waste. Each scenario is shaped by specific practices that determine overall waste outcomes, whether waste is generated, reduced, or avoided. Figure 6.10 summarises these scenarios, linking them to associated practices and waste categories. The following subsections discuss each category of scenarios in detail:

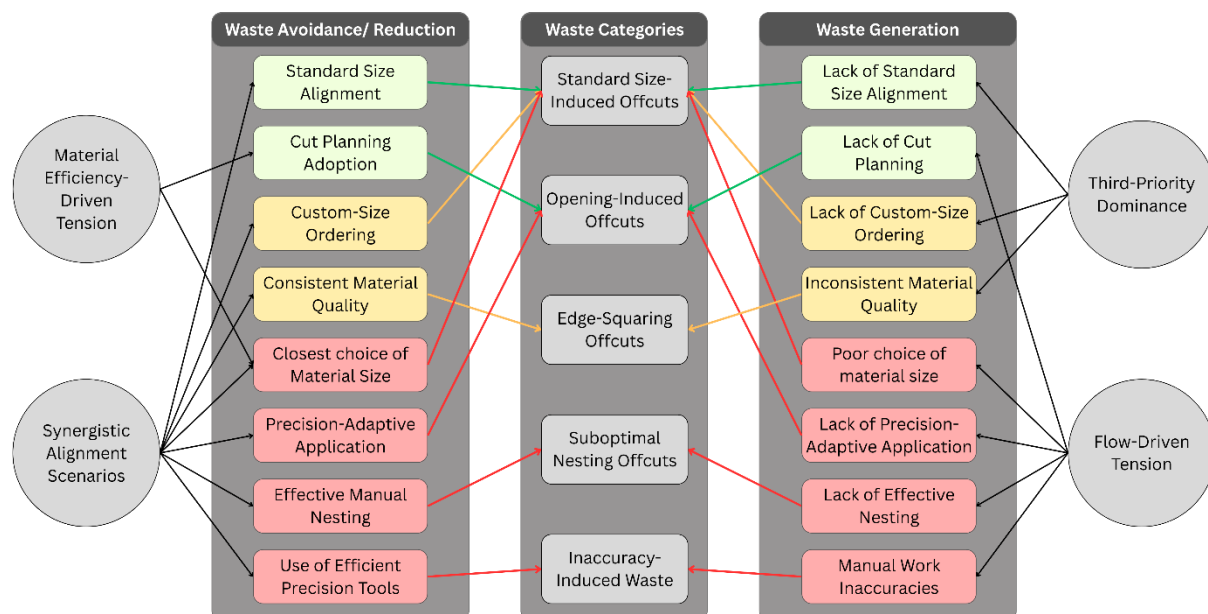


Figure 6.10: Interaction scenarios between production flow and material efficiency and their impact on material waste (Note: red, green and yellow colours refer to design, procurement, and production practices, respectively)

6.4.1 Production Flow-Driven Tension Scenarios

These scenarios involve instances where material waste is generated because of clear prioritisation of production flow over potential material savings. These scenarios can be explained in the following wasteful practices.

6.4.1.1 Lack of Cut Planning

The absence of cut planning detail provided as part of the shop drawing is observed across the assembly activities of the plasterboards and cladding panels in Case A and OSB in Case C. In these instances, no material pre-cutting activity was performed, motivating full material sizes to be fitted over the openings. The material covering the openings then was cut out, generating excessive offcuts, defined as Opening-Induced Offcuts in this study (see Section 6.2.3). Eliminating the pre-cutting activity is a boost to production flow because it saves the activity time, and the time needed to fit wide range complex cuts potentially planned around the openings. However, this flow improvement comes at the expense of material efficiency, where excessive material offcuts were generated at the openings.

6.4.1.2 Lack of Effective Nesting

When the cutting process does not include an effective and feasible approach to material nesting, the generated amount of offcut is expected to increase (defined as Suboptimal Nesting Offcuts in Section 6.2.2). This is especially true across timber framing sections over Case B, C, and D, OSB sheathing, brick slips, and cladding boards at Case B, and rigid wool insulation at Case C. In these instances, limited manual and no automated material nesting were performed. This is because cutting the required material sections according to the best layout that delivers the best for material efficiency means that the cuts would be produced in a random sequence and not in line with the production schedule. In this case, significant disruption to production flow is likely. To that reason, material nesting was not performed across these cases, clearly prioritising production flow over material efficiency.

6.4.1.3 Lack of Precision-Adaptive Material Application

When membrane-based materials, which require continuity, are fitted in full sizes and then the layer covering the openings are cut out, significant offcuts are likely to be generated at the openings (defined as Opening-Induced Offcuts in Section 6.2.3). These materials require continuity to provide functions like water resistance and airtightness (e.g., breather membranes and vapour barrier). This means that no cut planning is possible to only plan the required sections around the openings. The absence of efficient material application approach that can produce customised membrane-based sections avoiding the openings, is a key reason for these offcuts. However, using full size membrane over the openings is although a quick and productive, it generates significant offcuts. Hence, there is a clear prioritisation of production flow over material efficiency observed across membrane-based materials.

6.4.1.4 Manual Work Inaccuracies

When no precision tools are available to measure and cut flexible materials (e.g., membranes, rockwool insulation) precisely and efficiently, manual work is likely to be adopted, resulting in material overuse (defined as Inaccuracy-Induced Waste in Section 6.2.4). This issue was observed across flexible material that can bend or fold, including breather membranes, vapour barrier, and rock wool insulation across the observed cases. In these instance, positive tolerance of material was consistently added to ensure meeting the required size quickly and efficiently without excessive measurement. Although adding the positive tolerance compromised material efficiency, it avoided excessive measurement which in turn promoted production flow.

6.4.2 Third-Priority Dominance Scenarios

These scenarios involve the instances where material efficiency and production flow are both compromised in favour of a third priority, including design customisation and procurement cost and time. These scenarios can be explained in the following wasteful practices.

6.4.2.1 Limited Standard Size Alignment

When the required sizes of the designed OSC components are not aligned with standard material sizes, both material efficiency and production flow are compromised. In most cases, this practice is justified by the excessive prioritisation of design customisation, where the architectural geometries are largely impacted by customer requirements. This results in compromising material efficiency as the difference between the designed and the standard material sizes results in offcut generation. Similarly, production flow is compromised as an extra activity to cut the difference between design and raw material sizes is needed. Hence, excessive material waste was generated (defined as Standard Size-Induced Waste in Section 6.2.1).

6.4.2.2 Lack of Custom-sized Ordering

When the required sizes of the designed OSC components are not aligned with standard material sizes, ordering custom-sized material is likely to mitigate the potential compromise of material efficiency and production flow. However, this comes at the expense of procurement cost and time, as the custom-sized materials are likely to require both longer lead times and higher cost to source. Hence, the absence of custom-sized materials is similar to the lack standard size alignment, both require an extra cutting activity where significant offcuts are

likely to generate (defined as Standard Size Induced Waste in Section 6.2.1), compromising material efficiency and production flow.

6.4.2.3 Inconsistent Material Quality

When the sourced materials are identified with quality issues, consistent trimming may be required to eliminate the defected parts, generating some offcuts (defined as Edge-Squaring Offcuts in Section 6.2.5). This is especially the case for timber framing sections, which due to the natural drying process, they are prone to cracks and defects. In this case, a trim cut is consistently performed to ensure the accuracy and quality of the used materials, compromising both material efficiency and production flow. This is explained by the trim cut required, which both waste some material and impede production flow.

6.4.3 Material Efficiency-Driven Tension Scenarios

Only one scenario was identified where material efficiency is prioritised over production flow. This scenario can be explained in the following design practice.

6.4.3.1 Cut Planning Adoption

When the cutting process is conducted separately according to a pre-planned cutting list, only the material cuts required at the OSC component is produced, saving considerable amounts of offcuts (defined as Opening-Induced Offcuts in Section 6.2.3). This is observed across OSB assembly at Case B and D and the cladding boards at Case B, where offcuts generation is avoided. Although this practice saves significant materials that could have been wasted at openings (as seen in the plasterboards and cladding panels in Case A and OSB in Case C), it compromises production flow. This is explained by the need to a pre-cutting activity, which takes time and efforts, compromising overall production flow.

6.4.4 Synergistic Alignment Scenarios

These scenarios involve the instances where material and production flow coincide. These scenarios can be explained in the following efficient practices.

6.4.4.1 Standard Size Alignment

When the designed cut sizes are aligned with standard material sizes, both material saving and production flow are promoted. Although this might come at the expense of design customisation, this practice was observed across several materials including, the plasterboard, rigid insulation, and roof sheets in Case A, breather membrane in Case B, and OSB sheathing

in Case C. Particularly, raw materials can be directly fitted with no need to prior cutting, streamlining production and avoiding offcut generation (defined as Standard Size Induced Waste in Section 6.2.1).

6.4.4.2 Custom-Sized Ordering

When custom-sized materials are ordered to match the required cut sizes in the design, both material savings and production flow are enhanced. Although this practice may incur higher procurement costs and lead times, it was observed in Factories A and C, where long-term supplier relationships facilitated the cost-effective procurement of certain custom-sized materials. Specifically, this practice was noted for roof sheets and cladding boards in Case A. By sourcing materials in the required sizes, components can be directly fitted without the need for prior cutting, thereby streamlining production and eliminating offcut generation (defined as Standard Size Induced Waste in Section 6.2.1).

6.4.4.3 Effective Manual Nesting

When the required cut sizes are partially aligned with standard material sizes (i.e., either the length-side or the width-side), manual nesting can be performed in a more efficient manner. This is because performing material nesting from one side is far less complex than two-sided materials. This is observed across Case A rigid insulation and plywood decking, and Case B breather membrane and timber battens. Particularly, the offcut generated to produce the required cut is likely to be integrated into the next, promoting both material efficiency and production flow.

6.4.5 Discussion

The four categories of scenarios identified represent different configurations of OSC systems, each associated with distinct material waste outcomes. Lean theory conceptualises production as the concurrent management of transformation, flow, and value, and posits that waste emerges when these dimensions are treated separately or prioritised at the expense of one another (Koskela, 1992; Koskela, 2000). The flow-driven tension scenarios empirically substantiate lean theory's warning that accelerating flow without stabilising conversion processes leads to waste generation. Practices such as the lack of cut planning and ineffective nesting illustrate how process continuity is maintained through making-do, thereby institutionalising systematic inefficiencies (Koskela, 2004; Formoso *et al.*, 2011).

By contrast, the material-efficiency-driven tension scenarios exhibit the opposite condition, whereby conversion efficiency is prioritised through detailed cut planning to reduce material waste, but at the expense of production flow. Lean theory explicitly cautions against such conversion-focused optimisation when pursued in isolation, as it can introduce batching, delays, and reduced system responsiveness (Ohno, 1988; Koskela, 1992). The empirical evidence presented here corroborates this theoretical position by showing that material savings achieved through pre-cutting activities compromise flow when not embedded within an integrated production system. This highlights that waste reduction alone does not constitute lean performance, reinforcing the lean argument that improvements must be evaluated at the system level through the balanced management of conversion and flow activities.

The third-priority dominance scenarios extend existing lean theory by demonstrating how narrowly defined value objectives, such as customer-driven design customisation or procurement-related constraints can override both flow and conversion considerations. Lean theory emphasises that value should be defined systemically, incorporating downstream production implications rather than isolated customer or economic preferences (Ballard and Howell, 1994; Koskela, 2000). The observed misalignment between design dimensions and standard material sizes, the absence of custom-sized ordering, and the need for trimming due to inconsistent material quality illustrate how waste can be structurally embedded upstream at the design and procurement stages. These findings align with prior empirical work highlighting fragmented decision-making as a key driver of material waste (Formoso *et al.*, 2002), while extending it to the context of OSC.

Only the synergistic alignment scenarios reflect a fully integrated lean configuration, where flow, conversion, and value are jointly considered and aligned through upstream design and procurement decisions. Lean theory proposes that such alignment enables waste prevention by design rather than waste control through downstream correction (Koskela, 2000). The empirical results demonstrate that practices such as standard size alignment, custom-sized ordering supported by long-term supplier relationships, and effective manual nesting allow both smooth production flow and high material efficiency while still delivering required value. These findings are consistent with lean principles of design for production, standardisation as a prerequisite for flow, and supply chain integration (Ballard and Howell, 1994), and they empirically substantiate lean theory's claim that waste reduction is primarily a function of how production systems are designed and managed rather than a consequence of operational errors.

Hence, this synthesis demonstrates that material waste in OSC is not an accidental by-product, but a systemic outcome of how production objectives are prioritised, traded off, or aligned across different operational priorities. By empirically mapping waste outcomes to specific priority configurations, these findings advance lean theory by showing how different forms of misalignment between flow, conversion, and value manifest as distinct and predictable material waste patterns in OSC.

6.5 Summary

Building on micro level material waste analysis presented in the previous chapter, this chapter employed thematic analysis to identify five distinct categories of material waste in OSC. Each category was explained and mapped to its associated root cause practices to illustrate how waste is generated, reduced, or avoided, thereby addressing the study's second research question. In addition, material waste outcomes were analysed in relation to the adoption of automated technologies and varying operational priorities. The findings highlight the suboptimal utilisation of automation for waste reduction and a predominant emphasis on production flow as the primary operational priority. Notably, material waste was only reduced when production flow and material efficiency were aligned. These insights address the third research question. The next chapter presents cross-case analysis of material waste variability across different factories, materials, waste categories, and root cause practices.

Chapter Seven: Cross-Case Analysis of Material Waste Variability at Source in Offsite Construction

7.1 Introduction

The previous chapter presented an interpretive synthesis of the distinct material waste categories identified through micro-level analysis of construction components across the four factories and mapped these categories to their associated root cause practices. Building on that conceptual foundation, this chapter undertakes a cross-case quantitative analysis of material waste variability across factories, materials, waste categories, and root cause practices. In doing so, it addresses the research question concerned with how material waste varies across key analytical dimensions by examining relative severity, variability, and patterns of occurrence. The findings show that Factory A, a steel-frame modular system, had the lowest median waste value, whereas Factory C, a timber-frame panelised system, had the highest. From a material perspective, several characteristics were found to influence waste values, including opening-inclusivity, flexibility, cut variability, standard size variety, and consistent near-fit, with materials exhibiting more of these characteristics tending to generate higher waste values. From a waste category perspective, Opening-Induced Offcuts had the highest median waste value at 16%, whereas Edge-Squaring Offcuts were the least significant at less than 1%. Finally, the most significant root cause practices were the lack of cut planning and the lack of precision-adaptive material application, mainly associated with Opening-Induced Offcuts across rigid and flexible materials, respectively. By quantifying how waste varies across different production conditions, this chapter helps address the limited empirical understanding of how much material waste is generated at source in OSC and provides a basis for prioritising improvement efforts to enhance material efficiency.

7.2 Waste Quantification by Factory

This section compares material waste values initially generated at source across different factories (refer to Section 1.7 for detailed scope definition). Box plot chart is adopted to visualise waste values because of its powerful visualisation elements that illustrate spread, centre, and outliers, allowing for detailed waste value analysis and comparisons (refer to Table 16 - Appendix E for detailed waste quantification data). Figure 7.1 shows a box plot illustrating the variability and central tendency of waste values across different factories. The following sub-sections provide a quantitative, case-by-case analysis of these waste values.

7.2.1 Factory A

This factory, which involved a steel frame modular system, showed the lowest median value of material waste at 2.5%, with most waste levels falling below 10%, reflecting remarkable material efficiency across several materials (see Figure 7.1). This favourable performance can be attributed to the efficient design, procurement, and production practices adopted in this factory.

In terms of design, several materials were fully or partially specified to align with standard material sizes, such as ceiling and wall plasterboards, the length side of rigid insulation panels, and the width side of roof sheets. Aligning standard material sizes with the required dimensions in the design allows for direct fitting, eliminating the need for cutting and hence offcut generation. Altogether, this leads to significant improvements in material efficiency and production flow by design.

For procurement, waste associated with the structural frame and wall frame components was completely avoided as the manufacturing of these components were outsourced to external suppliers. As a result, the associated material waste was shifted to the supplier factories, meaning no waste was technically generated at this factory for these components. Additionally, custom-sized material ordering was implemented for the length side of roof sheets and cladding boards. Ordering materials in sizes that align with design requirements not only prevents offcuts but also enhances production flow by eliminating the need for additional cutting.

For production, efficient manual nesting practices were observed along the width-side of rigid insulation panels and in both directions of the plywood boards. This approach relies on the production team's experience to integrate and optimise cuts, aiming to enhance material efficiency and boost production flow wherever possible.

However, some higher values and outliers were also observed in Factory A. Based on activity-level analysis, these significant material waste levels are attributed to the lack of cut planning for wall plasterboards and cladding panels. In these instances, full-size materials were fitted directly over openings (e.g., windows and doors), and the sections covering the openings were cut out, resulting in excessive offcuts. Additionally, the absence of custom-sized ordering for the width side of the cladding panels further contributed to substantial offcut generation. These issues led to few of high material waste values, some of which appeared as outliers.

7.2.2 Factory B

This factory, which involved a timber frame panelised system, demonstrated a significant spread in material waste values, ranging from 10% to 30%, with a notably high median of 18% (see Figure 7.1). Both the median and variability indicate medium to high severity of wasteful practices across design, procurement, and production stages. From a design perspective, there was limited alignment with standard material sizes across OSB, cladding boards, and timber battens. In other words, neither standard sizes nor their multiples were considered during design development. As a result, small but consistent size discrepancies required cutting, which cumulatively led to substantial material waste.

In terms of procurement, custom-sized material ordering was absent across several components in this factory, including timber framing sections, the width side of the vapour barrier, and corner-type brick slip sections. This lack of tailored sourcing for commonly used non-standard sizes resulted in a substantial amount of offcuts. Additionally, inconsistent material quality was observed, particularly at the edges of the timber framing sections. This was attributed to natural drying effects and inaccuracies in supplier mass-cutting processes, which consistently necessitated trim cuts; however, their contribution to overall material waste was only minor.

For production, several wasteful practices were identified, including the lack of effective material nesting, absence of precision-adaptive material application, manual work inaccuracies, and poor choice of material sizes. In this factory, material nesting was largely absent, as cutting operations were prioritised according to the sequence of production schedule rather than material efficiency. This was evident across timber framing sections, OSB & cladding infill sections, and brick slip panels. Similarly, the absence of a material application method capable of processing membrane-based materials into highly customised sections without generating offcuts at openings led to substantial waste. This issue was particularly observed with vapour barriers and breather membranes in this factory.

Moreover, manual work, often performed with limited accuracy and driven by the pressure to complete tasks quickly, led to overuse of rockwool insulation, breather membranes, and vapour barriers in this factory. This approach prioritised speed over precision, with slightly more material used to meet the required sizes without extensive measurement. Finally, delays in logistics impeded the use of the closest material sizes to the required size, resulting in excessive offcuts generation in some timber framing sections.

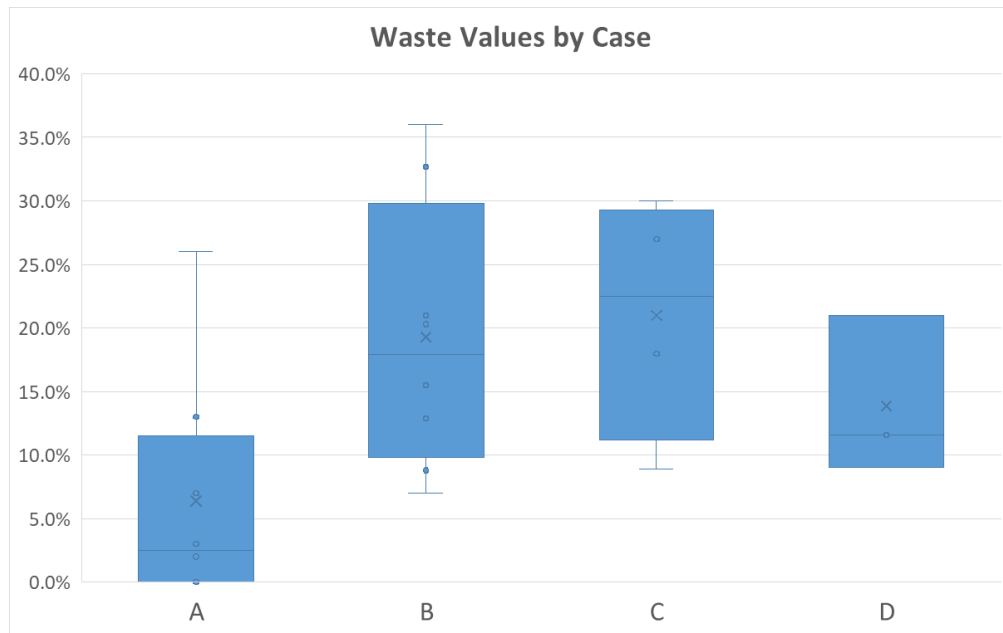


Figure 7.1: Distribution of waste values by factory

7.2.3 Factory C

This factory, which involved a timber frame panelised system, exhibited the highest median value of material waste among the four factories (approximately 22%), along with significant value variability (11-29%), indicating consistently high and uneven material waste generation across different materials (see Figure 7.1). These results reflect significant inefficiencies across design, procurement, and production practices.

From a design perspective, the lack of cut planning of OSB material around openings led to significant offcuts generation at the openings. That is, full size OSB layer was fitted and then the excess at the openings was cut out, which although generated significant offcuts at the openings, it reduced task complexity to the robotic arms. Particularly, this practice was promoted by the need to streamline the automated assembly operations of the robotic arms used in this factory for automated OSB fitting and cutting activities. Additionally, there was limited alignment with standard material sizes, specifically on the length side of OSB panels, where neither standard sizes nor their multiples were considered, resulting in repeated trimming that cumulatively produced high offcut volumes in this factory.

From a procurement standpoint, the absence of custom-sized materials was evident in this factory, across timber framing sections, the length side of the rigid insulation boards, and the width side of the breather membrane. The failure to match frequently needed non-standard sizes of these materials contributed substantially to material waste. Like Factory B, inconsistent material quality was noted at the timber frame edges due to natural drying and supplier mass-

cutting inaccuracies, which required trim cuts; however, their contribution to material waste was minor.

From a production perspective, several wasteful practices were identified, including the lack of effective nesting, absence of precision-adaptive material application, and manual work inaccuracies. In this factory, material nesting was largely absent, as cutting operations were performed in line with the production schedule rather than material efficiency, particularly across timber framing sections and the width side of rigid insulation boards. Similarly, the lack of a material application method capable of processing membrane-based materials into customised sections without generating offcuts at openings resulted in substantial material waste, especially with breather membranes. Furthermore, manual work, often performed under time pressure and with limited accuracy, led to the overuse of breather membranes. This practice prioritised speed over precision, with additional material used to meet size requirements without careful measurement.

7.2.4 Factory D

This factory, which involved a timber frame panelised system, showed the second lowest median at 12% with narrow spread (9-21%), indicating consistent data and systematic issues (see Figure 7.1). This reflects the impact of the adopted practices across design, procurement, and production on material waste generation. For design, limited standard size alignment was common across OSB boards in this factory, where neither standard material sizes nor their multiples were considered in design. This resulted in the slight difference in size being cut out consistently and accumulated contributing to material waste generation. For procurement, like Factories B and C, inconsistent edge quality in timber framing, caused by natural drying and supplier mass-cutting inaccuracies, necessitated frequent trim cuts, but their contribution to waste was minor.

For production, several wasteful practices were identified, including the lack of effective material nesting, manual work inaccuracies, and poor choice of material sizes. That is, material nesting was absent as cutting operations were performed according to the sequence of the production schedule rather than material efficiency, particularly across timber framing sections. Similarly, manual work, often performed under time pressure and with limited accuracy, led to the overuse of rockwool insulation. This practice prioritised speed over precision, with additional material used to meet size requirements without careful measurement. Finally,

human error impeded the use of the closest material sizes to the required size resulted in excessive waste generation in several timber framing sections.

7.3 Waste Quantification by Material Category

This section compares material waste values across different categories of construction materials. Bar chart is used to visualise waste values across different materials because of its powerful visualisation of single value variables, facilitating both classification and comparison (refer to Table 16 - Appendix E for detailed waste quantification data). Figure 7.2 compares material waste values across different construction materials.

Based on the design, procurement, and production practices, these materials can be defined with five interrelated characteristics, including opening-inclusive, flexible, high-cut variability, limited size variety, and consistent near-fit materials (See Venn diagram in Figure 7.3). The more characteristics are identified with the material, the more waste value is expected. Table 7.1 illustrates the identified characteristics and estimated waste values against different materials of different factories. Hence, five categories of material characteristics in relation to waste values can be identified as follows:

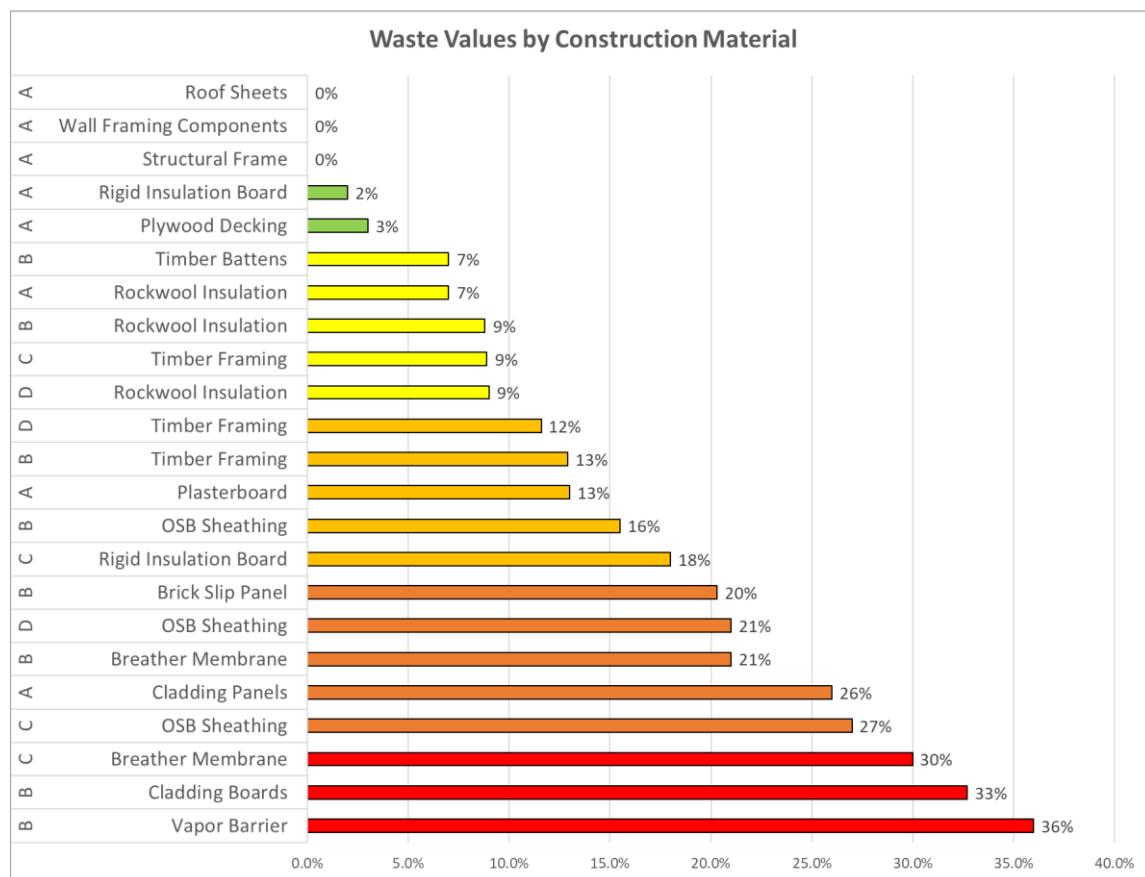


Figure 7.2: Distribution of waste values by construction materials

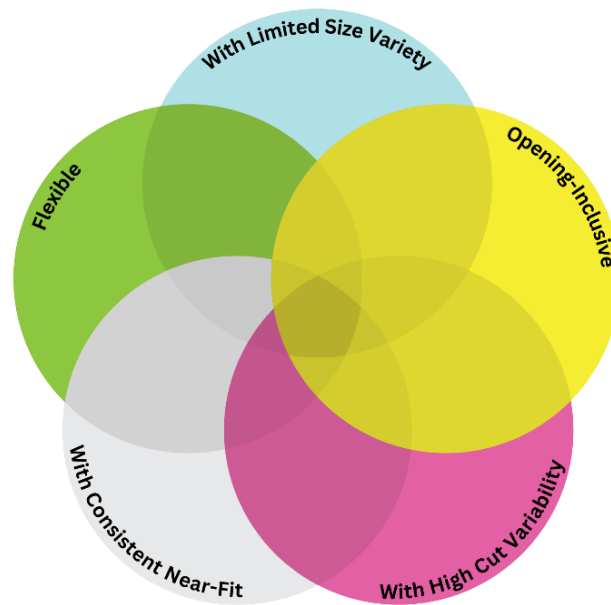


Figure 7.3: Overlapping material characteristics contributing to material waste generation in OSC

7.3.1 Opening-Inclusive Materials

This category includes materials designed with openings (e.g., for windows and doors) that are often installed without a prior cut-planning step. When no cuts are pre-cut to fit around the openings, full-size materials are likely to be fitted even over the opening areas, requiring the material layer covering the openings to be cut out afterwards. This process results in significant offcut generation. Therefore, materials identified as opening-inclusive are more likely to produce excessive offcuts, especially when coincide with other wasteful characteristics, resulting in some of the highest waste generation values across different materials. This issue is clearly observed with the vapour barrier and breather membrane in Factory B, OSB sheathing and breather membrane in Factory C, and cladding panels in Factory A.

7.3.2 Flexible Materials

This category includes materials that are foldable and compressible, which are often associated with limited measurement and cutting precision. This limitation arises from the restricted capability of production tools to accurately measure and cut flexible materials with the required precision and speed, as these tasks are typically performed manually. Hence, consistent material overuse was observed primarily to ensure coverage of the minimum required dimensions quickly, without extensive measurement. When such overuse is combined with other wasteful material characteristics, the resulting waste values can be severe. Hence, materials identified as flexible are more likely to be overused. This is notably observed with vapour barriers and breather membranes, which already generate significant offcuts due to

openings. However, when material overuse occurs in isolation, the resulting waste values tend to be lower, as seen in the application of rockwool insulation across various factories.

Table 7.1: Material characteristics in relation to the total generated waste across different materials

Case Factory	Material	Quantity	Opening-Inclusive	Flexible	High Cut Variability	Limited Size Variety	Consistent Near-Fit (Side 1)	Consistent Near-Fit (Side 2)	Total
B	Vapour Barrier	36.0%	x	x		x			3
B	Cladding Boards	32.7%			x		x	x	3
C	Breather Membrane	30.0%	x	x		x			3
C	OSB Sheathing	27.0%	x				x	x	3
A	Cladding Panels	26.0%	x			x			2
B	Breather Membrane	21.0%	x	x					2
D	OSB Sheathing	21.0%					x	x	2
B	Brick Slip Panel	20.3%			x	x			2
C	Rigid Insulation Board	18.0%			x	x			2
B	OSB Sheathing	15.5%			x		x		2
A	Plasterboard	13.0%	x				x		2
B	Timber Framing	12.9%			x	x			2
D	Timber Framing	11.6%			x				1
D	Rockwool Insulation	9.0%		x					1
C	Timber Framing	8.9%			x	x			2
B	Rockwool Insulation	8.8%		x					1
A	Rockwool Insulation	7.0%		x					1
B	Timber Battens	7.0%			x		x		2
A	Plywood Decking	3.0%							1
A	Rigid Insulation Board	2.0%							0
A	Structural Frame	0.0%							0
A	Wall Framing Components	0.0%							0
A	Roof Sheets	0.0%							0

Note: The colour coding is used to emphasise both material waste rates and the frequency of wasteful material characteristics. For material waste rates, red denotes values exceeding 20%, dark yellow represents values between 10% and 20%, light yellow represents values between 5% and 10%, and green denotes values below 5%. For the number of wasteful characteristics, red indicates three or more characteristics, dark yellow indicates two characteristics, light yellow indicates one characteristic, and green indicates none.

7.3.3 Materials with High Cut Variability

This category of materials is designed with significantly varied cut sizes. Due to the limited adoption of material nesting across the factories, this cut variance is likely to result in significant offcut generation. Particularly, offcuts are generated because of missed opportunities of integrating different cut to deliver better material utilisation. Hence, materials identified with high cut variability are likely to generate additional offcuts. This was observed across different materials, including timber framing across different factories, brick slips, OSB

sheathing, timber battens in Factory B, rigid insulation boards in Factory C, and cladding boards in Factory B.

7.3.4 Materials with Limited Size Variety

This category of materials is only supplied in the market with limited options of standard sizes. This limits the potential of design alignment with standard material sizes and hence the generation of excessive offcuts. Although ordering custom-sized materials can eliminate potential offcut generation, this was mostly avoided due to the high cost and time associated with this option. Hence, having limited standard size variety is likely to generate excessive material offcuts. This was observed across several materials, including vapour barrier in Factory B, breather membrane in Factory C, OSB sheathing in Factory D, and cladding panels in Factory A.

7.3.5 Materials with Consistent Near-Fit

This category includes frequent material cuts designed to closely match standard material sizes. Although the slight size difference may appear to generate only negligible strips of offcuts, the high frequency of such cuts can significantly increase the total volume of waste produced. This results from limited design consideration to rounding material dimensions to align with standard material sizes. The issue may affect one or both dimensions of raw materials (i.e., length and/or width). When it occurs on both sides, the amount of offcut generated can become substantial, especially when combined with other waste categories. Therefore, frequent near-fit cut sizing often leads to excessive offcut accumulation. This was particularly evident in the cladding boards of Factory B and the OSB sheathing in Factory C and D.

7.4 Waste Quantification by Waste Category

This section compares different material waste categories in terms of the quantity of waste generated in percentages. Due to the large volume of the observations of different materials, box plot chart is adopted to allow detailed analysis and comparisons (refer to Table 16 - Appendix E for detailed waste quantification data). Figure 7.4 shows a box plot chart illustrating the variability and central tendency of waste values across different material waste categories.

7.4.1 Opening-Induced Offcuts

This category of material waste refers to the material offcuts being generated because of full-size material fitting over the openings and cutting out the layer covering the openings. This category recorded the highest and most consistent waste values, with percentages ranging from approximately 13% to 18%, and a median value of nearly 16% (see Figure 7.4). These consistent values suggest that material waste generation at openings (e.g., windows and doors) is a systematic issue. At the design level, the absence of material cut planning around the openings encouraged ad-hoc cutting and fitting. That is, full size materials were fitted even over openings and then trimmed, resulting in substantial offcuts.

At the production level, the lack of precision-adaptive material application that can produce highly customised membrane-based material sections (which require continuity) necessitated the use of full-size materials over openings, leading to significant offcut generation. The absence of these practices leads to consistent material fitting and cutting over openings, which account for a fixed proportion of the total panel area. Hence, the slight variability within this waste category can be attributed to differences in the opening areas specified in the design packages across the four factories.

7.4.2 Inaccuracy-Induced Waste

This category of material waste refers to the flexible material overuse (e.g., membranes, rockwool insulation) as a result of consistent manual application of positive size tolerance to ensure meeting the minimum required size without excessive measurement. This category of waste shows a moderate median value of around 7.5%, with a moderate spread indicating some variability across the factories (see Figure 7.4). While greater inaccuracy-induced waste is observed with rockwool insulation, a much lower range is noted for vapour barriers and breather membranes. The variation in waste levels can be explained by the application context: rockwool insulation is fitted between multiple cavities within each panel, whereas membranes are typically applied as a single continuous layer. This means that material overapplication in rockwool insulation occurs repeatedly within a single panel, while membranes require extra tolerance only once to ensure full coverage in a timely and efficient manners. Therefore, the frequency of adding extra tolerance contributes to the variation in waste rates, even though both factories are associated with manual work inaccuracies.

7.4.3 Standard Size-Induced Waste

This category of material waste refers to the consistent mismatch between designed versus standard material sizes, necessitating significant offcut generation. This category of waste shows a moderate median value of around 7.5%. This comes with some waste value variability ranging between 5% and 11% (see Figure 7.4). This variation highlights the strong influence of design on the quantity of waste generated, with this sensitivity largely driven by two key factors. First, the difference between the required size and the available standard material size; the greater the difference, the higher the estimated waste. Second, the frequency of size mismatch, which can range from a few instances to many, increasing the total volume of offcuts produced. Therefore, the variability in this waste category is driven by both the magnitude and the repetition of size mismatches between the required and standard material sizes.

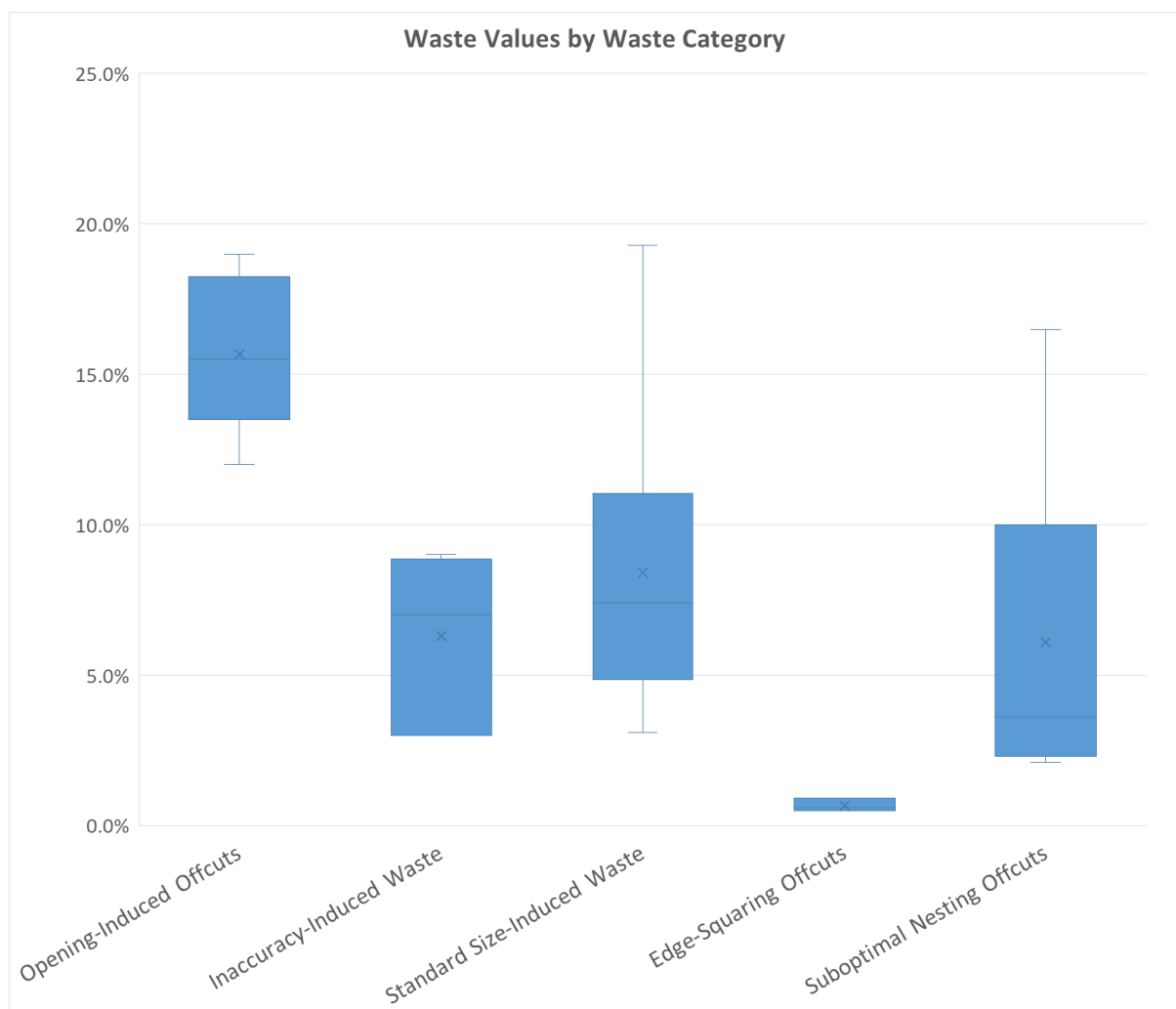


Figure 7.4: Distribution of waste percentages by waste category

7.4.4 Edge-Squaring Offcuts

This category of material waste refers to the consistent trim cutting practice associated with timber sections, to eliminate potentially uneven and cracked edges without excessive inspection. This waste category is both the lowest and most consistent among all quantified material waste categories, with values ranging between 0.5% and 0.9% (see Figure 7.4). The minimal waste is attributed to the small quantity of offcuts generated from trim cuts of 20-50 mm on standard timber sections. However, the limited variability can be explained by the relatively fixed trim cut width in proportion to the timber length (i.e., longer sections may require slightly larger trim cuts). Overall, this waste category reflects a highly predictable and routine practice aimed at ensuring square and clean timber edges before further processing and assembly.

7.4.5 Suboptimal Nesting Offcuts

This category of material waste refers to the offcuts generated because of the missed opportunities to integrate different cuts and in turn increase material utilisation. This category shows a low median of 3.5% yet with significant variability ranging from 2% to 10% (see Figure 7.4). This variation can be attributed to the quality of the material application practices, particularly material nesting. The effectiveness of material nesting directly influences the amount of waste generated. Although automated nesting is expected to result in minimal and consistent waste levels, it was not adopted in the observed factories due to an excessive prioritisation of cutting according to the production schedule rather than optimising material efficiency. Instead, manual nesting was used, leading to highly unpredictable waste quantities. This manual approach is largely dependent on the saw operator's experience and their ability to integrate various cuts without disrupting the production flow. Hence, the variability in waste values in this category of material waste can be explained by the unpredictable manual nesting practice.

7.5 Waste Quantification by Root Cause Practice

This section compares OSC waste values across different root cause practices. Due to the large number of observations for various materials, a box plot chart is used to enable detailed analysis and comparisons (refer to Table 16 - Appendix E for detailed waste quantification data). Figure 7.5 presents a box plot illustrating the variability and central tendency of waste values associated with each root cause practice.

7.5.1 Lack of Precision-Adaptive Application

This is the most wasteful root cause category with waste values median peaking at 16% (see Figure 7.5). This comes with limited variability reflecting the systematic wasteful practice of fitting full size membrane-based materials over the openings and then cut out the layer covering them, generating excessive offcuts. Although pre-cutting membrane-based materials around the openings might seem to be a solution to eliminate these offcuts, this is technically not possible as these materials need to be continuous to provide airtightness and waterproof functions. Hence, the absence of a material application approach that can produce customised membrane-based sections avoiding the openings is likely to cause severe waste generation.

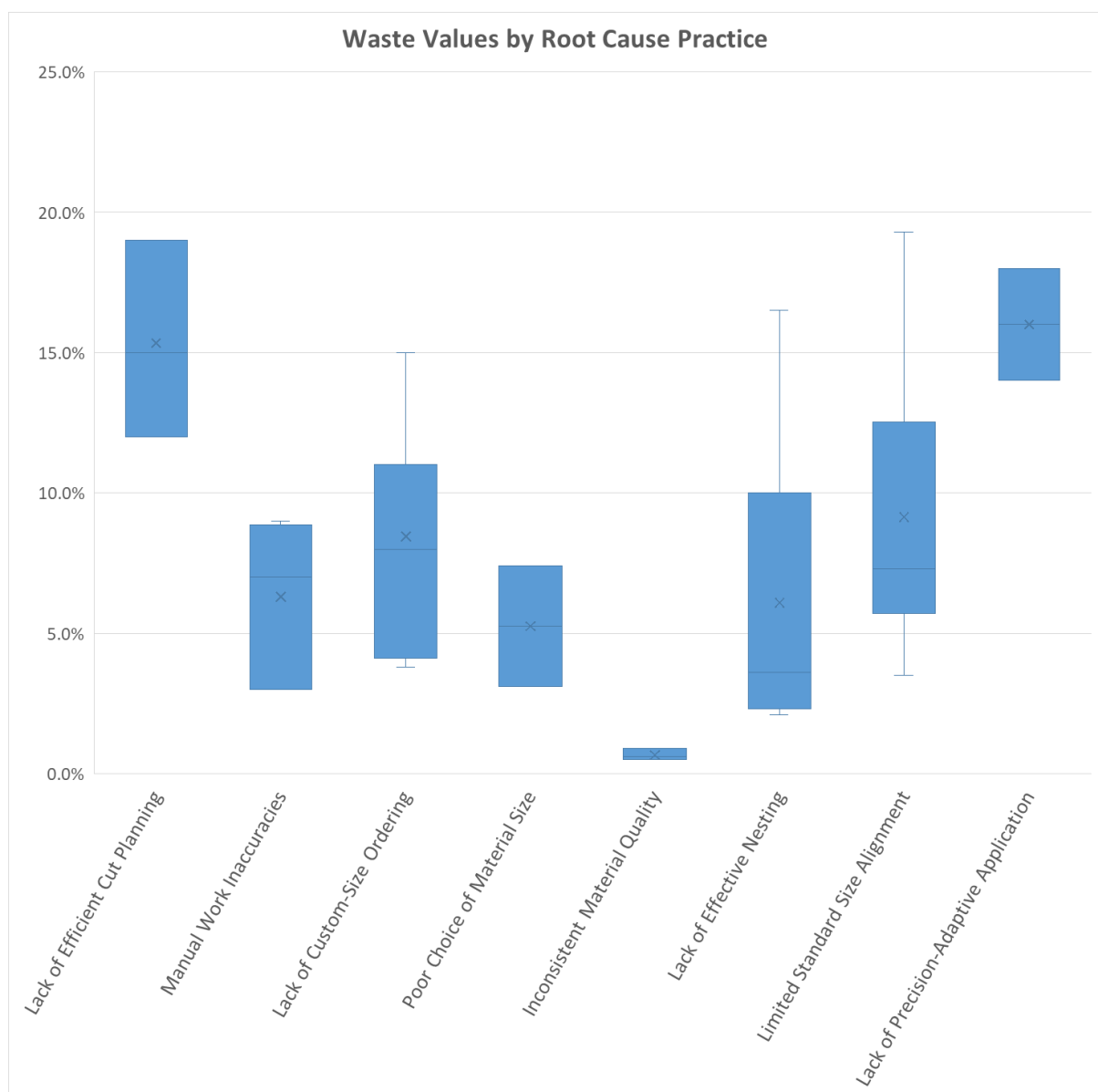


Figure 7.5: Distribution of waste percentages by root cause practice

7.5.2 Lack of Efficient Cut Planning

This category is the second most severe root cause identified across the four factories, with waste values at peaking 15% (see Figure 7.5). This involves the lack of cutting list produced as part of the design detailing to facilitate pre-cutting the required sections around the openings for not membrane-based materials (i.e., rigid materials that can be joined and do not require continuity). Hence, a systematic practice of fitting full size materials over the openings and then cut out the area covering the openings is observed, generating excessive offcuts.

7.5.3 Lack of Custom-Size Ordering

This category of root causes has recorded a median of nearly 8% of waste out of different materials across the observed factories with limited consistency (see Figure 7.5). This reflects the variability of the generated waste which is highly affected by the frequency and difference between the required and used material size. Hence, the absence of the procurement practice of ordering custom sizes results in the difference between design versus material size to generate offcuts.

7.5.4 Limited Standard Size Alignment

This root cause category is responsible for 7% of waste values yet with significant spread (see Figure 7.5). This reflects the amount variability of the generated offcuts which is highly affected by the frequency and difference between the required and used material sizes. Hence, failing to consider standard material sizes in design is likely to resulting the difference between the required versus the standard materials sizes to generate offcuts.

7.5.5 Manual Work Inaccuracies

This root cause category has also recorded at 7%. However, this category comes with moderate variability (see Figure 7.5). This reflects the systematic issue identified of the lack of precision tools to cut and fit flexible materials efficiently. Although manual work can alleviate these offcuts, the need to finish the task quickly and efficiently necessitated inaccurate measurement and cutting, sacrificing extra tolerance of material to ensure meeting the minimum requirement quickly. Hence, manual work adoption is likely to result in material overuse especially across flexible materials.

7.5.6 Lack of Effective Nesting

This root cause category recorded a relatively low median waste value of 3.5% across different materials. However, it is characterised by significant variability (see Figure 7.5), reflecting the inconsistency in material nesting outcomes, ranging from high to less severe nesting inefficiency. Although some cutting tools are equipped with nesting features, these were not utilised due to their incompatibility with the production schedule. These tools generate cuts based on the most material-efficient sequence, which often conflicts with the sequencing required by the production timeline. Therefore, while this root cause category is associated with a relatively low average waste rate, the wide variability suggests that material nesting practices can range from high to less severe nesting inefficiency, depending on how well the required cuts are optimised to minimise offcuts.

7.5.7 Poor Choice of Material Size

This category of root causes recorded a relatively low waste value at 5% with limited variability (see Figure 7.5), indicating a systematic issue. Failure to use the closest standard material size to the required cut size is likely to generate excessive offcuts. Hence, when material sizes are chosen improperly, offcuts are likely to generate in a consistent manner.

7.5.8 Inconsistent Material Quality

This category is the least significant and most consistent root cause across the identified categories, with minor waste value below 1% (see Figure 7.5). When material edges are prone to defect, a trim cut was consistently observed to ensure a square and clean edges, ready for precise assembly. This is especially the factory with timber framing sections which necessitated a trim cut to eliminate potentially defected edges.

7.6 Discussion

Cross-case analysis of material waste variability across factories, components, waste categories, and root-cause practices offers important theoretical insights when contrasted with dominant assumptions in OSC material waste research. Overall, the findings indicate that material waste is shaped primarily by how design, procurement, and production practices are configured and prioritised within each factory. This challenges the common tendency to view OSC as intrinsically ‘waste-saving’ and instead positions waste generation as contingent on system configuration and operational priorities.

The main contribution of these results lies in redefining the boundaries of material waste quantification in OSC. Much of the existing research that claims OSC reduces material waste draws this conclusion from site-based disposal records, such as truckload data (Jaillon *et al.*, 2009; W Lu *et al.*, 2021). However, the quantification boundaries adopted in these studies capture only waste generated on site, while excluding waste generated within OSC factories, thereby overstating OSC's waste-reduction benefits. By quantifying factory-generated material waste and analysing it by factory, material, waste category, and root-cause practices, this study extends the assessment boundary upstream and reframes the central question from whether OSC reduces onsite waste to under which circumstances OSC can eliminate material waste generated offsite.

At the factory level, the contrast between Factory A and Factory C is theoretically informative. Factory A, despite being largely manual, recorded the lowest median waste, whereas Factory C, despite its higher level of automation, recorded the highest median waste. This challenges the prevailing assumption that automation inherently improves material efficiency. Instead, it reinforces lean theory's emphasis that performance depends on system integration and the alignment of upstream decisions with downstream operations, rather than technology intensity alone (Koskela, 1992). In Factory C, high waste levels were associated with an operational preference to protect production flow, relying on reuse and recycling rather than prevention at source. This reflects a flow-dominant optimisation logic that sustains continuity but can obscure avoidable material waste. By contrast, Factory A's lower waste levels were enabled by upstream practices, particularly design alignment with standard material sizes and effective material nesting, demonstrating that preventive design and production choices can significantly improve material efficiency. Overall, these findings support the theoretical proposition that waste reduction is not an automatic outcome of OSC, but a conditional one shaped by systemic process integration and a balanced focus on both conversion and flow activities.

In addition, these results provide a more granular quantification of material waste in OSC. Much of the OSC literature estimates waste at the project level using disposal records (W Lu *et al.*, 2021) or generic waste rates (Loizou *et al.*, 2021; Mirshekarlou *et al.*, 2021). While this approach can report overall waste performance, it rarely identifies which materials, activities, or practices drive waste generation, limiting its value for deeper diagnosis and intervention design. By contrast, this study quantifies material waste by material and links measured waste values to specific waste categories and root-cause practices. This enables waste variation to be interpreted as a practice-dependent phenomenon rather than an aggregated project outcome.

The findings show that waste tends to increase when multiple unfavourable design, procurement, and production conditions coincide around a material, meaning that waste becomes a predictable system outcome rather than an irregular operational deviation.

This is particularly evident in the material-level findings, where breather membranes and vapour barriers were identified as the most waste-prone. This was driven by frequent interruptions caused by openings to meet airtightness and waterproofing requirements, limited precision in cutting and fitting, and the restricted availability of standard size variations. Such outcomes are not adequately explained by generic, onsite waste quantification studies, as their boundaries are typically limited to aggregated, project-level analysis. In this respect, the present study addresses this gap by demonstrating that robust material waste quantification in OSC must extend beyond overall estimations to the material- and practice-level in order to reveal the mechanisms through which waste is generated.

Thus, these findings address concerns regarding data reliability in OSC waste research. Much of the literature reporting substantial waste reductions in OSC relies on secondary data (Hao *et al.*, 2021), expert surveys (Eghbali *et al.*, 2019), or literature-derived rates (Loizou *et al.*, 2021), which limits contextual interpretation and constrains root-cause explanation. By contrast, the present analysis, grounded in empirical quantification and systematic cross-case comparison, provides a more robust foundation for explaining how and why material waste varies in practice.

7.7 Summary

This chapter presented cross-case analysis of material waste across different factories, materials, waste categories, and root cause practices. The results indicated that Factory A (modular steel frame manufacturer) generated significantly lower material waste values compared to Factories B, C, and D (panelised timber frame manufacturer). This can be attributed to the consistent alignment of Factory A's designs with standard material sizes, as well as the outsourcing of certain component manufacturing to external suppliers, which reduces and transfers a significant portion of potential material waste. Materials identified as having more waste-prone characteristics, such as opening inclusivity, flexibility, cut variability, limited standard size variety, and consistent near-fit requirements, were more likely to have higher waste levels. This was especially evident for breather membranes and vapour barriers, which are inclusive of openings (necessitating opening offcuts), highly flexible (encouraging overapplication), and available in limited standard sizes (necessitating perimeter offcuts).

Among the material waste categories, Opening-Induced Offcuts emerged as the most severe, with a median waste value of 16%. This finding is further supported by the analysis of root cause practices, where lack of cut planning and lack of precision-adaptive material application (both generating Opening-Induced Offcuts) were identified as the most waste-generating practices in OSC. Hence, this highlights significant inefficiencies in design detailing and production capacity when addressing OSC products with openings. The next chapter builds on the quantitative findings presented in this chapter, together with the qualitative insights from Chapter Six, to propose a range of targeted interventions aimed at reducing material waste in OSC.

Chapter Eight: The Development of Targeted Interventions for Material waste Reduction in Offsite Construction

8.1 Introduction

This chapter addresses the fifth research question by developing a range of targeted interventions for material waste reduction at source in OSC. By reflecting on the identified root cause practices and employing lean theory, several preventive measures have been proposed across design, procurement, and production processes. In addition, the development of these measures considered potential tensions between material efficiency, production flow, design customisation, and procurement cost & time. Hence, the proposed interventions are grounded in empirical evidence on material waste and guided by lean theory. However, it is beyond the scope of this study to validate these interventions in real-world settings. Where manual activities seemed to affect production flow, automated technologies were suggested to help balance production flow with material efficiency.

8.2 Design-Focused Preventive Measures

This section outlines the proposed interventions aimed at reducing material waste by design. These interventions are developed by reflecting on the design-related root causes identified in Chapter Six. The targeted interventions include: 1) Designing in Line with Standard Material Sizes or their Multiples, and 2) Adopting Cut Planning Around Openings. The following subsections provide a detailed discussion of each.

8.2.1 Designing in Line with Standard Material Sizes or their Multiples

The lack of alignment between design dimensions and standard material sizes was identified as one of the most frequent root causes behind material waste generation in this research. The empirical evidence indicates that whenever specified cut sizes fall outside standard material sizes (or workable multiples), offcuts become systematically unavoidable. Across the observed assembly activities, the median volume of offcuts attributable to this misalignment accounted for approximately 7% of total material usage. This makes dimensional coordination at the design stage a key intervention strategy for reducing waste upstream.

The proposed intervention is therefore to redesign components and sub-assemblies so that their dimensions are either 1) directly aligned with standard material widths/lengths, or 2) based on multiples that can be efficiently nested with minimal remainder. In practice, this necessitates

the design process to consider standard material sizes and factory assembly constraints as explicit design inputs, rather than downstream considerations. Figure 8.1 illustrates this targeted intervention by showing how the integrated approach of designing in line with standard material sizes or their multiples reduces unavoidable offcuts. Implementing this intervention depends on three interrelated design practices discussed as follows:

8.2.1.1 Cross-functional Design Input Integration

To design in line with standard material sizes or their multiples, the design team must systematically integrate three categories of input at the early design stage: 1) currently available standard material sizes and supplier constraints from procurement; 2) acceptable dimensional tolerances of customer sizing from sales (e.g., ceiling heights); and 3) production and assembly constraints from manufacturing (e.g., cutting and nesting capabilities). This integrated approach should enable designers to develop solutions that are simultaneously constructible, procurable, and material-efficient. This intervention is consistent with the DfMA principles of linking design detailing with downstream requirements through cross-process coordination (Boothroyd *et al.*, 2010). It also reflects lean intent by preventing material waste at source and promoting stable flow for downstream processes (Koskela, 2000).

8.2.1.2 Early Exploration and Selection of Size-compatible Alternatives

Once these inputs are available, the design team should explore potential dimensional variations and select those that best reconcile customer requirements with standard material sizes and production constraints. In practice, this involves generating and comparing multiple dimensioning alternatives for major interfaces and high-volume components (e.g., panel widths and sheathing break points), and progressively narrowing the options using transparent decision criteria, including offcut reduction, producibility, procurement feasibility, and compliance with customer requirements. This approach aligns with set-based design logic, which emphasises the early exploration of multiple alternatives and the gradual convergence towards the most feasible solution under competing constraints (Liker, 2020; Ward *et al.*, 2021). The value of this approach lies in reducing late-stage design locking into dimensions that systematically generate offcuts during production.

8.2.1.3 Standardising Modular Design Rules and Dimensional Libraries

To maintain dimensional alignment beyond individual projects, proven design solutions should be formalised into design rules and modular libraries. This involves defining standardised dimensional ‘families’ (e.g., panel or module grids, allowable dimensional multiples, and lining

break rules) that are aligned with standard material sizes and typical nesting logic. By applying these rules consistently across projects, unnecessary design variability can be reduced, thereby lowering the likelihood of material waste generation. This standardisation approach promotes repeatability and limits avoidable design variation, both of which are key enablers of improved process stability and production efficiency (Choi et al., 2020b).

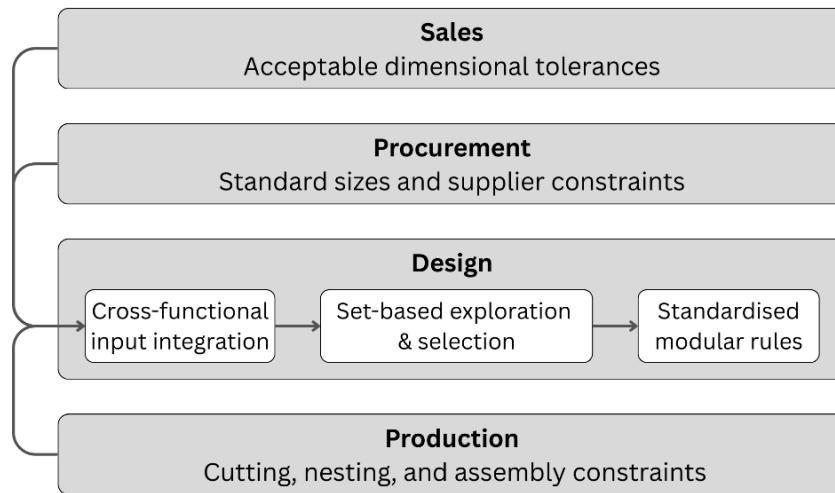


Figure 8.1: Designing in line with standard material sizes or their multiples

8.2.2 Adopting Cut Planning Around Openings

The lack of cut planning around openings (e.g., windows and doors) was identified as another key root-cause practice underlying material waste generation in this study. Across multiple instances in the four factories, workers applied full sheets of material over opening areas and subsequently cut out the material covering the openings. While this approach is perceived as quicker and easier on the production line, it systematically generated substantial offcuts, with a mean value exceeding 15% of total material use.

The proposed intervention is to plan, detail, and assemble sections with openings in a manner that eliminates avoidable cut-outs. This can be achieved by providing explicit design detailing for material layout around openings (i.e., by defining cut sizes such that openings are designed around rather than cut out) and by preparing the required cuts prior to assembly. The primary objective is to replace reactive trimming during production with a pre-planned cutting strategy. Figure 8.2 illustrates this targeted intervention by showing how cut planning around openings eliminate opening-induced offcuts. Executing this intervention requires two interrelated practices, presented as flows:

8.2.2.1 Standardised Opening Cut Layouts and Detailing Rules

This involves establishing a repeatable set of detailing rules for material cut planning around openings. Such rules may include: 1) defining standard break lines and joint locations in relation to openings; and 2) specifying preferred cut dimensions (e.g., to avoid narrow or fragile sections). By standardising this detailing across the entire design package, significant offcut generation at openings can be avoided. This practice reduces reliance on the ad hoc production practice of applying full material sheets over openings and cutting them out during assembly, generating excessive offcuts. This approach is line with the lean principle of standardised work, which involves defining an agreed best practice to stabilise the process and reduce variation, therefore reducing improvisation and supporting continuous improvement (Liker, 2020).

8.2.2.2 Timely Pre-cut Preparation Aligned with Production Sequence

Once cut plans around openings are defined as part of the design detailing, the next step is to plan their timely pre-cutting in alignment with the production schedule. The primary objective is to avoid disruptions to production flow by ensuring that the production team receives the correct cuts, in the correct order, and for the correct openings, thereby eliminating the need for full-sheet installation followed by cut-outs. To support fast and accurate assembly, prepared cuts should be clearly labelled and accompanied by concise assembly sketches. This approach is compatible with JIT logic, as it supports continuity of flow while minimising unnecessary handling, searching, and making-do practices (Kong *et al.*, 2018).



Figure 8.2: Adopting cut planning around openings

8.3 Procurement-Focused Preventive Measures

This section outlines the proposed procurement-focused interventions for reducing material waste. These interventions are developed in response to the procurement-related root causes identified in Chapter Six. The targeted intervention ‘Sourcing a Variety of Standard and Custom Material Sizes’ is discussed in the following subsection.

8.3.1 Sourcing Variety of Standard and Custom Material Sizes

The lack of standard and custom material size variety refers to limited procurement capability to source material sizes beyond those most commonly available in the market. This root cause was associated with high levels of offcut generation, with a mean value exceeding 8% of total material use. The collected data indicate that OSC manufacturers tend to procure widely available standard sizes due to the perceived time and cost implications of sourcing less common dimensions. However, factories with long-term relationships with raw material suppliers were able to access a wider range of both standard and custom material sizes.

The proposed intervention is therefore to enhance procurement capability to source material sizes beyond readily available standard dimensions, in order to more closely align procured materials with design requirements. This can be achieved either by extending the available range of standard sizes or by enabling cost- and time-effective sourcing of custom sizes where necessary. Figure 8.3 illustrates this targeted intervention by showing how sourcing variety of standard and custom material sizes can reduce offcuts. Implementing this intervention requires three interrelated practices, presented as flows:

8.3.1.1 Developing Reliable Supplier Capability for Size Flexibility

The first step towards improving procurement capability is to structure the procurement process around supplier arrangements that can reliably provide size flexibility. This can be achieved by securing access to a broader range of both standard and custom material sizes. The findings indicate that the quality of supplier relationships has a direct impact on practical access to custom material sizes. In particular, factories with long-term supplier agreements were able to negotiate more favourable lead times, pricing, and responsiveness for less common material sizes. Accordingly, the intervention should prioritise supplier segmentation and partnership development by formalising service expectations (e.g., available size ranges, lead times, and minimum order quantities) and by agreeing clear escalation routes when non-standard sizes are required. This approach aligns with the lean concept of ‘keiretsu’, which emphasises long-term, collaboration and mutual reliability within integrated supplier networks (Womack *et al.*, 1990).

8.3.1.2 Making Material-size Procurability Visible to Designers

The capability to source a wider range of standard and custom material sizes depends not only on supplier arrangements but also on the availability of accurate procurability information at the point when design decisions are made. To support this, up-to-date data on which material sizes are readily procurable, and under what conditions they can be sourced (e.g., lead times,

pricing, and minimum order quantities) should be made accessible to the design team. Providing this information enables designers to align design decisions with procurable material sizes in real time, particularly during the early design stages. In doing so, offcuts induced by the lack of standard size alignment and custom size ordering can be minimised. This is consistent with Othman and El-Saeidy's (2024) finding that suppliers' most important contribution to waste reduction during the design process is the provision of technical information on materials and their capabilities, highlighting the need to make procurability information available to designers at the point of decision-making.

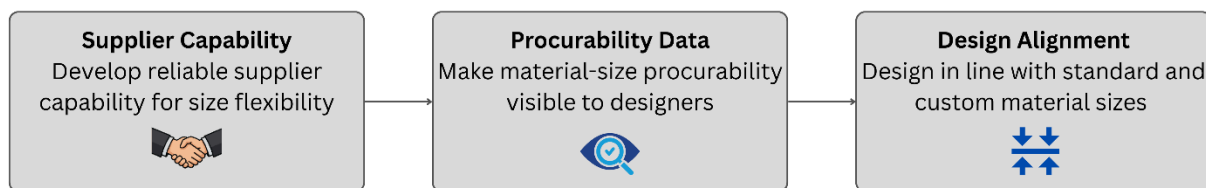


Figure 8.3: Sourcing variety of standard and custom material sizes

8.4 Production-Focused Preventive Measures

This section outlines the proposed interventions aimed at reducing material waste through a range of improved production capabilities. These interventions are developed by reflecting on the production-related root causes identified in Chapter Six. The targeted interventions include: 1) Performing Efficient Material Nesting, 2) Adopting Precision Adaptive Material Application, 3) Employing Precision Tools to Process Flexible Materials, and 4) Selecting the Right Size of Raw Materials. Each of these is discussed in detail as follows:

8.4.1 Performing Efficient Material Nesting

When the designed cut sizes are highly variable, offcuts were generated with a median value of 3.5% of total material use. This is explained by the limited human capability to manually integrate different cuts of different sizes in efficient and timely manners. This is exacerbated by the need to produce the required cuts in the sequence of the production schedule rather than the best layout for material efficiency. Although Factory B, C, and D all have an automated nesting feature as part of their automated saws, this feature was largely neglected. This is because this feature generates the required cuts in a random manner with no labels, making it difficult to the production team to identify and sort different cuts properly to keep aligned with the production schedule. Hence, material nesting was not conducted due to the potential disruptions expected to impede the production flow.

The proposed intervention is therefore to align material nesting with production flow requirements, rather than treating nesting as a separate conversion activity. In practice, the objective is not only to generate optimal nesting patterns but also to ensure that the resulting cut lists can be executed without disrupting production flow. Figure 8.4 illustrates this targeted intervention by showing how performing efficient material nesting can promote material waste reduction. Implementing this intervention requires three complementary practices, which are discussed below:

8.4.1.1 Delivering Complete Cut-list Information to Enable Planned Nesting

The first step is to consistently provide design detailing in which cut sizes and quantities are specified as part of the design package, typically in the form of cut lists. From a lean perspective, this information constitutes part of the complete kit of prerequisites required before production begins; when it is absent, work proceeds under incomplete conditions and production teams are more likely to resort to making-do through ad hoc cutting decisions (Ballard, 1999a; Ballard, 2000). This is supported by the findings of this research, which show that when cut planning was not included in shop drawings, production teams were encouraged to make ad hoc decisions that prioritised production flow and speed over material efficiency. Standardising the provision of material cut lists within design detailing is therefore a key prerequisite for enabling structured nesting and minimising associated offcuts.

8.4.1.2 Activating Nesting Optimisation While Controlling Its Practical Outputs

The second step involves activating the nesting function in a manner that optimises material utilisation without disrupting production flow. This is consistent with Meng et al. (2025), who argue that nesting/layout and cutting scheduling should be optimised collaboratively rather than separately in order to balance material yield with make span and delay performance. The findings of this research similarly indicate that when the nesting feature of automated saws was activated, the required cuts were often produced in a random sequence. This sequencing necessitated additional sorting and classification to realign the cuts with the production schedule, thereby posing a risk to production flow. Accordingly, the nesting function should be planned and configured not only to achieve high material yield but also to maintain a cut sequence that causes minimal or no disruption to production flow.

8.4.1.3 Integrating Nesting with Identification, Labelling, and Sorting

The third step involves supporting the nesting function with complementary mechanisms that enable the timely identification and retrieval of produced cuts. Evidence from this research

shows that automated nesting was often avoided because the resulting cuts were difficult to sort and match with the production sequence. This is consistent with Abdullah et al. (2021), who showed that nesting outputs become more workable when they incorporate embedded identification cues and grouping logic that reduce visual search and facilitate faster downstream assembly. Accordingly, the nesting function should be integrated with cut identification and sorting systems, including automated labelling linked to drawings and a sorting arrangement that groups cut batches in the order required for assembly. By doing so, unnecessary searching and associated human error can be reduced, enabling production teams to benefit from material nesting without disrupting production flow.

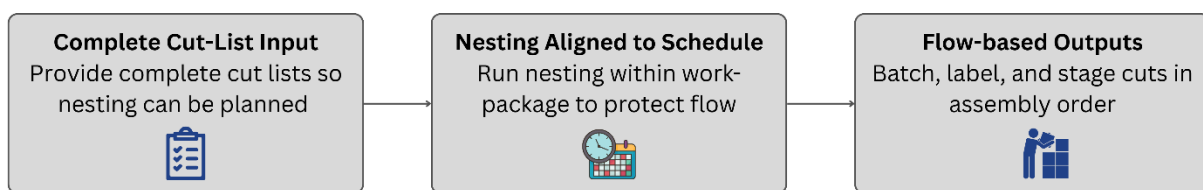


Figure 8.4: Performing efficient material nesting

8.4.2 Adopting Precision Adaptive Material Application

Flexible two-dimensional materials (e.g., vapour barriers and breather membranes) were found to generate substantial offcuts at the openings, with a waste median value of over 16% of total material use. Different from rigid materials (e.g., OSB) which can be planned around the openings, flexible materials need to be continuous to provide functions, such as airtightness and water resistance. This resulted in consistent offcuts generation at openings across the researched cases. Hence, eliminating these offcuts is not possible through improved cut planning alone, because offcuts are embedded in the standard ‘cover-then-cut’ practice.

The proposed intervention is therefore a shift from ‘cover-then-cut’ practice to precision adaptive application: a capability to generate membrane pieces in the required shapes with openings avoided. In theory, this technology resembles additive manufacturing in which only the required geometry is generated, avoiding the generation of cut-out waste. Figure 8.5 illustrates this targeted intervention by showing how adopting precision adaptive material application can reduce opening induced offcuts associated with flexible materials. Two enabling technologies are required to make this intervention feasible as discussed below:

8.4.2.1 Accurate Digital Definition of Required Membrane Geometry

The first step requires precision adaptive application technology to accurately define the required membrane geometry, including width, length, thickness, opening locations and sizes,

and overlap dimensions. These details should be derived from reliable digital inputs rather than manual measurement, which is time-consuming and prone to human error. This is consistent with Guo et al. (2020), who note that traditional manual inspection is inaccurate and time-consuming and propose the use of 3D laser scanning to estimate geometric properties from scanned data through comparison with the as-designed BIM model. Accordingly, rapid capture methods such as laser scanning can support the precise definition of membrane geometry prior to fabrication or application. In lean terms, this can be interpreted as consistent with error-proofing logic, as it reduces reliance on ad hoc measurement and helps eliminate systematic errors at source.

8.4.2.2 Timely Production and Release of Pre-shaped Membranes

The second step involves translating the defined membrane geometry into a production and release process that delivers pre-shaped membrane components. This can be achieved through technologies capable of producing the required membrane shapes in a timely manner while avoiding opening areas. A useful analogue is provided by Bøe et al. (2023), who found that blown-in loose-fill insulation can fill cavities without the need for tailor-made cut pieces and can avoid the time-consuming, less repeatable trimming associated with conventional cut-to-fit solutions. This supports the proposition that, when a material can be delivered directly in the required geometry, both offcuts and secondary fitting work can be reduced. Developing and adopting such technologies would therefore not only eliminate offcuts, but also streamline production by removing the need for secondary trimming around edges or openings during assembly.

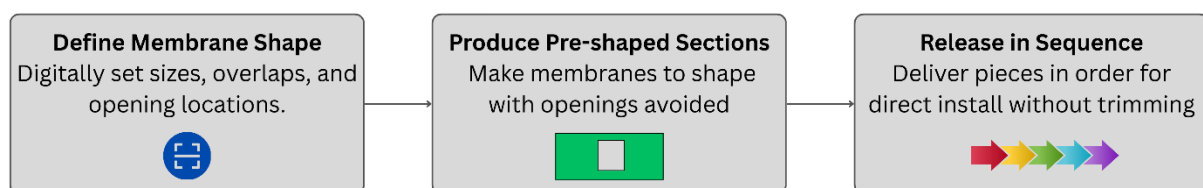


Figure 8.5: Adopting precision adaptive material application

8.4.3 Standardising Manual Work to Minimise Material Overapplication

Manual work inaccuracies were identified as a key factor behind material overapplication across different flexible materials, including breather membranes, vapour barrier, and rockwool insulation. That is, rough measurement, fitting, and cutting practices were widely carried out to assemble flexible materials, resulting significant material overapplication with median waste values of 7% of total material use. Unlike rigid materials, such as OSB or cladding panels, no

efficient precision tools were observed for measuring, cutting, and fitting flexible materials. According to the interviews conducted, accurate manual measurement is generally viewed as time-consuming and unnecessary given that flexible materials can be slightly folded, stuffed, or cut manually using basic tools. To that reason, a tendency to add positive tolerance was consistently observed to ensure the minimum required size is met efficiently and consistently, without investing additional time in precise measurement.

The proposed intervention is therefore to reduce material overapplication by introducing a simple, repeatable approach for measuring and fitting flexible materials. The solution does not involve high-precision measurement, but to standardise accurate practice that achieves required functional performance with minimal material overapplication. Figure 8.6 illustrates this targeted intervention by showing how standardising manual work can minimise material overapplication. To implement this intervention, two key practices are required as follows:

8.4.3.1 Defining a Repeatable Sizing-and-Fitting Procedure

This involves establishing a standard procedure for measuring, cutting, and fitting flexible materials. This procedure should clearly define reference measurement points, specify acceptable tolerances for different types of flexible materials, and outline how cut pieces are handled and assembled to prevent unintended overstuffing. The objective is to minimise variability in measurement decisions by replacing ad hoc practices with a validated approach that is sufficiently rapid to support production flow. This practice aligns with the principle of standardisation, which aims to reduce variation, stabilise task execution, and limit repeated ad hoc decisions (Liker, 2020), that often lead to oversizing under time pressure.

8.4.3.2 Physical and Visual Cues for Consistent Sizing

This involves reinforcing the standardised procedure with simple physical aids and visual cues that guide production workers in cutting materials precisely and efficiently. This is consistent with Tommelein (2008), who argues that lean mistake-proofing (poka-yoke) can be achieved through simple, low-cost physical devices and visual cues that prevent errors at source rather than relying on inspection or worker vigilance alone. This includes the use of physical templates or fixtures that eliminate the need for repeated manual measurements, thereby reducing the risk of overapplication. These aids should be complemented by clear visual cues, such as reference lines for common material sizes, marked zones for different material types, step-by-step guidance on the cutting sequence, and clear indications of required overlaps. Together, these measures remove the conditions that promote material overstuffing, minimise

ambiguity during cutting and fitting, and support consistency across varying skill levels, thereby systematically reducing overapplication.

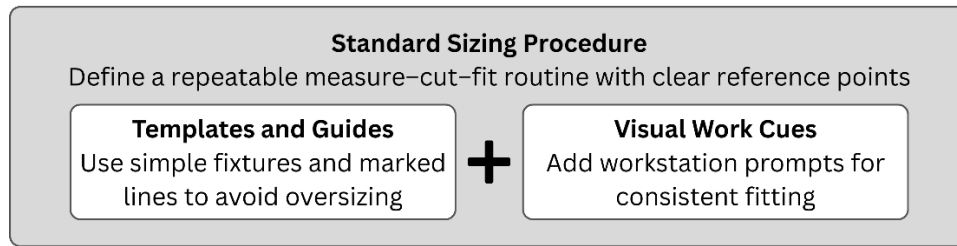


Figure 8.6: Standardising manual work to minimise material overapplication

8.4.4 Selecting the Right Size of Raw Materials

Designing in line with standard material sizes or sourcing custom sized materials were identified as key strategies to reduce offcuts and streamline production flow. At OSC facility, production teams can take straightforward decisions in selecting and fitting those materials into their designated positions. However, when both standard material size alignment and custom-size ordering are lacking, selecting the closest standard material size to the required cut might be more difficult and prone to subjective judgements. This resulted in two instances of taking inadequate decisions on material selection which yielded more offcuts than necessary, with waste rate median of just over 5% of total material use.

The proposed intervention is therefore to reduce ad hoc size selection routine by making the ‘right size’ explicit, verifiable, and available at the point of use. Figure 8.7 illustrates this targeted intervention by showing how selecting the right size of raw materials can reduce material waste. To implement this intervention, two key steps are required as follows:

8.4.4.1 Specifying Raw-material Size Selection within the Production Package

The first step involves providing production information that specifies the raw material sizes to be processed for each work package. This includes identifying preferred material sizes as well as next acceptable size alternatives. This is consistent with Ballard (1999b), who argue in lean work structuring that product and process design should be integrated and that the flow of design information and materials to downstream production units should be deliberately structured to support workflow. By embedding material size selection within the design-to-production information flow, uncertainty associated with size choice is reduced and decision-making is shifted upstream to the design level, where options can be evaluated in terms of material efficiency and feasibility rather than being made reactively on the factory floor. This

results in more predictable cutting activities and fewer ad hoc size substitutions that generate avoidable offcuts.

8.4.4.2 Controlling Material Release So the Correct Sizes Arrive When Needed

The second step is to control material release in alignment with the production schedule, thereby facilitating correct material size selection. Rather than relying on large, mixed stocks at workstations, materials should be issued in batches that correspond to scheduled production tasks. This reflects lean supply system principles, which emphasise reducing unnecessary inventories, using pull-based release mechanisms such as just-in-time and kanban, and linking material management directly with production control (Arbulu and Ballard, 2004). By limiting the range of materials available at the point of use, this approach reduces confusion during processing and lowers the likelihood of size substitution or the use of less suitable dimensions. In addition, controlled batch release supports more efficient inventory management by avoiding overstocking and unnecessary handling, which is consistent with lean materials management strategies that seek to organise material flow to match production or installation rates (Tsao and Lidelöw, 2017).

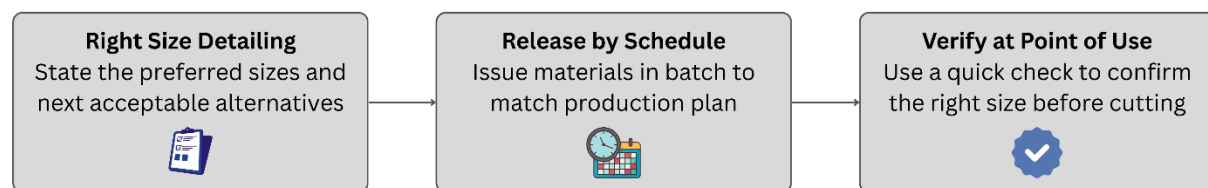


Figure 8.7: Selecting the right size of raw materials

8.4.5 Automating Material Edge Inspection to Minimise Offcuts

Material offcuts were also generated due to the need to slightly trim material edges to ensure a square, clean start that is both even and structurally sound for assembly. This is particularly common with standard timber framing sections, which are typically processed at the supplier facility using limited precision tools for mass cutting. In addition, timber sections are prone to defects caused by the natural drying process. Hence, these factors increased the likelihood of uneven or cracked timber edges when standard timber sections arrived to the OSC facility.

Due to the limited quantities of this root cause category (a median value of less than 1%), suggesting a manual mitigation procedure to inspect and separate defected material edges can have significant implications on production flow. Hence, any improvement intervention should balance production flow against material efficiency. To that reason, the researched cases found it more feasible to trim a slight piece of material across all timber sections rather than go

through lengthy manual quality checks to save insignificant amount of waste. Alternatively, an efficient solution may involve developing an automated technology integrated to the saws, capable of scanning each material section and determining whether, and how much, a trim cut is required. This automated tool can be implemented as illustrated in Figure 8.8 and is discussed below.

8.4.5.1 Built-in Edge Quality Control at the Cutting Point

The first step is to embed an automated quality inspection function within the cutting machinery rather than treating inspection as a separate manual activity. The objective is the timely detection of uneven or defective edges and immediate decision-making while the timber is already positioned for cutting. In practice, this requires: 1) a scanning capability to assess edge squareness and identify visible defects that may compromise fit (e.g., splitting or uneven fibre tear-out); and 2) decision rules that classify edges as either acceptable or trim required. The machine should therefore intervene only when trimming is necessary. This approach aligns with the concept of built-in quality, whereby inspection is integrated into the production process (Liker, 2020), eliminating unnecessary trimming of undamaged edges. More specifically, it reflects the principle of source inspection, which emphasises detecting abnormalities at the point of processing and enabling immediate corrective action only where required, thereby avoiding unnecessary trimming of undamaged edges (Ghinato, 1998).

8.4.5.2 Data Capture to Improve Supplier Performance and Handling Practices

The second step involves systematic data capture and analysis of the frequency, type, and severity of edge damage. This is consistent with Alarcón et al. (1999), who, from a lean perspective, emphasise the use of performance indicators, nonconformity analysis, and cause-effect analysis to diagnose procurement-related problems and support continuous improvement across suppliers, logistics, and quality processes. Such data helps the identification of whether damage is primarily attributable to supplier cutting imprecision, material handling, or storage conditions. In turn, this evidence supports informed, cross-functional decision-making across procurement and logistics to minimise trim cuts by eliminating the conditions that necessitate them. Potential responses may include revising supplier agreements, modifying packing requirements, or adjusting storage practices. This feedback-based approach aligns with the lean principle of continuous improvement, as it enables recurring damage patterns to be identified and addressed at their source rather than being repeatedly corrected through trimming at the factory.

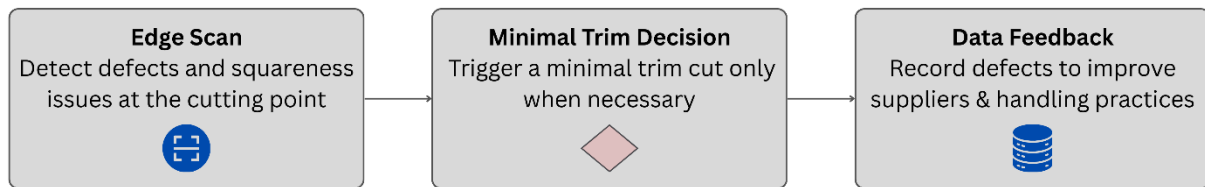


Figure 8.8: Automating material edge inspection to minimise offcuts

8.5 Summary

This chapter has proposed a range of targeted interventions aimed at reducing material waste at source in OSC. Informed by the root-cause practices and waste quantities identified in Chapters Six and Seven, and guided by key manufacturing principles, the chapter outlines a set of interventions and enabling technologies to mitigate material waste generation. Importantly, the proposed interventions explicitly recognise the need to balance conversion efficiency across individual processes with flow efficiency across the production system, a defining feature of lean theory. This balance is achieved by aligning material efficiency objectives with production flow requirements. For example, aligning design dimensions with standard material sizes reduces both cutting activities and offcut generation, thereby supporting smoother production flow. Similarly, integrating labelling and sorting technologies with automated saws across the studied factories enables automated nesting to be used for material savings without disrupting production flow. However, testing the effectiveness of these interventions in practice lies beyond the scope of this research and represents an important direction for future work. This chapter addresses the eighth and final research question and, in doing so, concludes the empirical analysis.

Chapter Nine: Conclusion

9.1 Introduction

This final chapter synthesises the study's findings to fulfil the research aim: *'to develop an empirical understanding of material waste generation at source in OSC by quantifying waste, identifying its root causes, and proposing targeted interventions to support waste reduction'*. Drawing on evidence generated across the case study factories, the chapter reflects on the key findings and highlights their theoretical and practical implications. It begins by providing concise answers to the five research questions raised earlier in this research (see Section 1.5), followed by a focused synthesis of the study's main findings. The chapter then outlines the research's theoretical contributions to understanding material waste in OSC and discusses its practical implications for manufacturers and industry stakeholders. Next, it critically reflects on the methodological and practical limitations encountered. The chapter concludes by summarising the study's original contributions and emphasising the importance of adopting leaner practices to reduce material waste in OSC.

9.2 Answers to the Research Questions

This section provides brief and direct answers to the research questions posed at the beginning of this study. These answers are supported by the research findings and augmented by reflective statements on their significance.

9.2.1 Research Question 1

The first research question asked, *'How, how much, and why material waste is generated at source in OSC?'*. The findings show that material waste is predominantly generated in the form of offcuts and, to a lesser extent, as material overuse (e.g., overstuffing). In contrast to material waste research in traditional construction (Formoso *et al.*, 2002), almost no waste was identified in the form of damage in this study. This reflects a key advantage of the controlled OSC environment, where more standardised logistics and handling practices limit damage-related waste. Despite this advantage, substantial quantities of material waste (mostly offcuts) were generated at source across multiple components, with values reaching up to 36% of total material use (see Figure 7.2). This finding challenges the widespread assumption that OSC is inherently material-efficient. The analysis identified multiple root causes to underpin waste generation across the four factories, spanning design, procurement, and production processes.

These findings emphasise that material waste in OSC is not an incidental by-product, but a systematic outcome of upstream and production-level inefficiencies embedded within current practices.

9.2.2 Research Question 2

The second research question asked, ‘*What distinct categories of material waste emerge in OSC?*’. The findings of the thematic analysis identified five material waste categories, including Standard Size-Induced Waste, Suboptimal Nesting Offcuts, Opening-Induced Offcuts, Inaccuracy-Induced Waste, and Edge-Squaring Offcuts. Each material waste category was mapped to its associated root causes to clarify how waste is generated, reduced, or avoided. In doing so, this research presented the first known categorisation of material waste in OSC. This research extends earlier work of Formoso and colleagues (Formoso *et al.*, 2017; Formoso *et al.*, 2002) by researching material waste quantities and root causes in the context of OSC. Theoretically, identifying and defining material waste categories into their root causes opens the doors for well-defined research issues that attract further research both to explore solutions or build upon. Practically, understanding the root causes behind different waste categories is instrumental in shaping manufacturers strategies towards material efficiency and environmental performance.

9.2.3 Research Question 3

The third research question asked, ‘*How do automation-related waste generation instances and varying operational priority configurations shape material waste outcomes in OSC?*’. The findings indicate that automation was often used inefficiently for material waste reduction due to the dominant prioritisation of production flow. From a lean perspective, automated conversion activities were not optimised for material efficiency where doing so was perceived to threaten production flow. For example, activating material nesting at automated saws resulted in cuts being produced in random sequences that were difficult to identify and stage in line with the production schedule, thereby risking disruption to production flow (see Subsection 6.3.2). This challenges the existing studies (Gbadamosi *et al.*, 2019; Liu *et al.*, 2019; Liu *et al.*, 2017; Liu *et al.*, 2018; Banihashemi *et al.*, 2017; Shafiee *et al.*, 2025; Malik *et al.*, 2021) which often propose and evaluate automated technologies in isolation, using limited samples and controlled settings that do not fully capture flow-related constraints in real production environments.

With respect to operational priorities, the findings show that production flow is frequently prioritised over material efficiency, and that material waste is reduced only when material efficiency improvements do not compromise production flow. These findings highlight the practical complexity of material waste generation, particularly the way interactions between competing operational priorities shape waste outcomes. From a lean perspective, the results reflect a strong flow-oriented focus in OSC, in which production flow is consistently prioritised over conversion efficiency (represented in this study by material efficiency), thereby contributing to significant material waste generation.

9.2.4 Research Question 4

The fourth research question asked, *‘How does material waste vary by factory, component, waste category, and practice?’*. The findings show that Factory A, recorded the lowest median level of material waste, while Factory C, had the highest. Despite Factory C’s significantly higher level of automation, substantial offcuts were generated due to its excessive focus on production flow and reliance on reusing and recycling waste rather than preventing it. In contrast, Factory A, although largely manual, achieved the lowest waste median owing to consistent design alignment with standard material sizes and efficient manual nesting conducted across different components. For components, several design, procurement, and production characteristics were found to influence material waste levels. The more of these characteristics associated with a material, the higher the waste value it tended to be. Breather membranes and vapour barriers were identified as the most waste-prone materials, due to limited precision in cutting, limited availability of standard size variations, and the necessity to cut at openings. From a waste category perspective, Opening-Induced Offcuts emerged as the most severe, with a median waste value of 16%, while Edge-Squaring Offcuts were the least significant, at under 1%. The most critical root cause practices were identified as the lack of cut planning and the absence of precision-adaptive material application, which primarily contributed to Opening-Induced Offcuts in both rigid and flexible materials. Waste generation at the openings underscore the significant impact of inadequate design detailing and limited production capabilities.

9.2.5 Research Question 5

The last research question asked, *‘What targeted interventions can be proposed to reduce material waste at source in OSC?’*. Informed by the root-cause practices and waste quantities identified in Chapters Six and Seven, and guided by key manufacturing principles, this research

proposed a set of targeted interventions and enabling technologies to mitigate material waste generation. These interventions are grounded in the diagnosis of underlying root causes, rather than addressing superficial symptoms, therefore providing a more targeted and sustainable approach to waste reduction. They include aligning design decisions with procurement, production, and customer requirements; enhancing procurement flexibility to meet design specifications; and strengthening production capabilities to process materials with high precision and minimal waste. A unifying theme across these interventions is the explicit recognition of the need to balance material efficiency (i.e., conversion efficiency) with production flow efficiency, which represents a critical condition within lean theory.

9.3 Synthesis of Key Findings

The findings indicate that although the controlled environment helped eliminate material waste in the form of damage, other forms were found to arise in significant amounts. Waste in the form of offcuts and overuse was reported across several components, peaking at 36% of total material use and signalling hidden inefficiencies that warrant deeper exploration. The analysis identified several root-cause practices behind these material inefficiencies, spanning design, procurement, and production processes. Further thematic analysis helped identify five distinct categories of material waste, each mapped to its underlying root-cause practices to explain how waste is generated, reduced, or avoided. Developing such a high-level conceptualisation of waste categories is vital to facilitate understanding and, in turn, manage material waste in OSC.

Further analysis revealed that the OSC production system is primarily designed to support production flow. Material efficiency across different conversion activities was pursued only when it aligned with, or did not impede, production flow. This tension was found to overshadow the potential of automated technologies, such as robotic assembly and material nesting, to deliver material efficiency. In practice, these technologies were either underutilised or programmed to accelerate conversion activities to promote production flow, often at the expense of material efficiency.

Quantitatively, the findings reveal that the largely manual factory performed significantly better than the highly automated one, with median material waste rates of 2.5% and 22%, respectively. This can be largely explained by the earlier finding that automation was primarily employed to boost production flow rather than material efficiency. Membrane-based materials were also associated with substantial material waste, peaking at 36% of total material use, due to their design and production characteristics. These include the inclusion of openings, which

necessitates cut-outs; material flexibility, which encourages consistent overstuffing; and frequent near-fit conditions, which generate smaller but recurrent offcuts. In addition, opening-induced offcuts were identified as the most severe material waste category in OSC, with a median waste rate of 16%. This category is primarily explained by two root-cause practices: a lack of cut planning and a lack of precision-adaptive material application. In practice, these involve installing full boards/sheets over openings (e.g., windows, doors) and then cutting out the opening areas. Such practices were frequently observed across the studied factories, reflecting a clear prioritisation of production flow over material efficiency.

To develop targeted interventions that mitigate the identified root causes, the balance between material efficiency and production flow was critically considered. Accordingly, a set of interventions and enabling technologies was proposed across design, procurement, and production processes. At the design level, the proposed approach emphasises integrating customer sizing requirements with procurement and production capabilities to maintain smooth production flow while minimising material waste. At the procurement level, greater flexibility in sourcing a wide range of standard and custom material sizes is proposed as a key strategy to accommodate design complexity, reduce size discrepancies, and enable faster assembly. At the production level, several principles and technologies, such as standardised work and material nesting, are proposed to promote material efficiency without disrupting production flow.

9.4 Theoretical Contributions

This research presents several theoretical contributions, extending our understanding of material waste generation in OSC. This can be summarised in the following subsections:

9.4.1 Quantifying Material Waste at Source in OSC

In response to the limited research quantifying material waste at source in OSC, this study employed direct measurement to quantify material waste. Quantifying material waste at such detailed level not only helped proper quantification but also provided a significant opportunity for understanding how and why waste is generated. Different from existing research (Jaillon *et al.*, 2009; W Lu *et al.*, 2021; Loizou *et al.*, 2021; Hao *et al.*, 2021; Qiankun Wang *et al.*, 2020) that focused on quantifying final onsite construction waste associated with OSC products, this research focused on material waste initially generated offsite. In doing so, this study addresses a significant gap in the literature, providing waste quantification across activities, materials, factories, waste categories, and root causes. This level granularity provides a solid empirical

foundation for further theoretical and practical investigation and experimentation in relation to material waste generation in OSC.

9.4.2 Detailed Understanding of Material Waste in OSC

Existing literature (Balasbaneh and Sher, 2021; Andersen *et al.*, 2022; Jayawardana *et al.*, 2023; Hernández *et al.*, 2023) largely relies on assumptions drawn from traditional construction when examining construction waste generation, offering only limited evidence on how and why material waste is generated in OSC. This study addresses this gap by employing a multiple case study approach to generate novel insights into the generation of material waste in OSC. Micro-level waste data collected from four factories were analysed to identify distinct categories of material waste and their root causes. These were then mapped to develop meaningful frameworks of material flow possibilities, linking each waste category to its associated causal practices and the corresponding waste outcomes, whether generation, reduction, or avoidance. This responds to the call of Formoso *et al.* (2020) on the need for further research to define and map different categories of waste into their root causes across different contexts. In doing so, a rich solid basis was built for further research interest to further explore the promising environment of OSC in reducing material waste.

9.4.3 Empirical Analysis of Automation's Impact on Material Waste Outcomes

Existing research (Gbadamosi *et al.*, 2019; Liu *et al.*, 2019; Shafiee *et al.*, 2025) has widely assumed that automation enhances material efficiency, yet it often adopted a positivist perspective with limited case-based validation or real-world experimentation. This study challenges these assumptions by providing empirical evidence from automated technologies observed across four factories, revealing less favourable waste outcomes than commonly expected. Specifically, the findings suggest that automation contributes to material efficiency only when it also supports or at least does not compromise production flow. Although some of the observed technologies had the technical potential to reduce material waste, they were largely underutilised due to their direct impact on production flow. In doing so, this research questions the applicability and effectiveness of existing deductive studies that propose automation-based waste reduction solutions without rigorous validation or testing from multiple operational perspectives.

9.4.4 Empirical Analysis of the Impact of Interacting Priorities on Waste Outcomes

Previous literature (Banihashemi *et al.*, 2018; Malik *et al.*, 2021) has predominantly adopted a positivist perspective, often overlooking the practical complexities surrounding material waste generation in real-world OSC settings. These studies have primarily focused on improving activity-level conversion efficiency to reduce material waste, with limited testing of the wider impacts on production flow and stability. This study advances existing knowledge by providing a detailed analysis of how different scenarios involving interacting operational priorities affect waste outcomes. These scenarios include: 1) when both production flow and material efficiency are prioritised; 2) when production flow is prioritised over material efficiency; 3) when material efficiency is prioritised over production flow; and 4) when both are compromised in favour of a third priority. The results indicate that material efficiency is most likely to be achieved when it either supports, or at least does not hinder, production flow. This aligns with lean theory, which emphasises balancing conversion efficiency (to reduce material waste) with flow efficiency (to maintain continuity), ensuring that waste reduction does not compromise production stability. Accordingly, these findings highlight the importance of understanding the broader operational system in OSC and the decision-making factors that shape practice when developing effective material waste reduction strategies.

9.5 Practical Implications

The findings of this study provide important insights for OSC manufacturers and practitioners seeking to optimise material waste by adopting reduction measures at design, procurement, and production levels. This research showed that material waste is not only a result of poor production practices, but also a result of poorly integrated design and procurement processes. Addressing these inefficiencies necessitates a more collaborative approach across design, procurement and production processes as discussed below:

9.5.1 Design

A key takeaway for OSC practice is the need to adopt a pull-based design approach, where design decisions are informed by the requirements and capabilities of production, procurement, and sales (i.e., customer demand) processes. This approach promotes proactive and integrative collaboration across design, procurement, production, and sales teams to ensure that the final product aligns with customer needs while achieving high production flow and minimal material waste from the early stages. By integrating design with production, procurement, and sales

processes, the likelihood of material inefficiencies can be minimised, reducing the need for reactive mitigation strategies later across the procurement or production processes.

9.5.2 Procurement

This study highlights the crucial role of agile and responsive procurement practices in reducing material waste in OSC. The ability to source a diverse range of standard and custom material sizes enables both designers and manufacturers to minimise material waste. For designers, access to various standard sizes increases the likelihood of aligning customer requirements with available material dimensions. For manufacturers, the ability to source custom-sized materials can eliminate the need for cutting, thereby avoiding offcuts and enabling more streamlined production. Additionally, having access to a variety of standard sizes is likely to allow manufacturers to select material dimensions that generate the least waste. Achieving such agile procurement capabilities necessitates building long-term relationships with suppliers to ensure that custom orders remain cost-effective and procurement lead times are manageable. However, the absence of responsive procurement practices is likely to shift the burden of managing material waste onto the production process itself, as discussed in the following section.

9.5.3 Production

This research also underscores the importance of adopting efficient production capabilities that promote both material efficiency and production flow. These capabilities include 1) automated technologies for material nesting that promote material efficiency without disrupting production flow; and 2) precision tools that minimise material overuse; and 3) adaptive application techniques, such as 3D printing, that enable the production of highly customised components with minimal offcuts. Implementing such advanced manufacturing capabilities can help to some extent mitigate potential upstream inefficiencies in design and procurement. Conversely, the absence of efficient production techniques and technologies is likely to result in significant material waste, which would then require downstream corrective measures to promote reuse and recycling, processes that fall beyond the scope of this research.

9.6 Research Limitations

This research adopted a rigorous research design using multiple case study factories. However, certain limitations that may affect the transferability and interpretation of the findings are acknowledged, along with the strategies adopted to mitigate them. These limitations and mitigation measures are outlined in the following subsections:

9.6.1 Limited Generalisability

A major limitation in the case study research is the limited generalisability of findings beyond the researched cases. Although the selected cases provided a significant empirical depth, they are less likely to represent the full variety of OSC practices worldwide. Yin (2014) stresses that the main purpose of adopting case study research is not statistical inference but analytic generalisation. To promote analytic generalisation, purposive sampling was adopted in this study to reflect a variety of factory sizes, automation levels, product types, and market focus, seeking wider theoretical understandings than statistical generalisation.

9.6.2 Potential for Researcher Bias

One key limitation associated with analysing qualitative data, such as interviews and observations, is potential risk of researcher bias (Creswell, 2013). To mitigate this, this study adopted two key strategies. First, data triangulation was sought by using multiple sources of data, including direct observations, design documents analysis, and semi-structured interviews, to allow different patterns of evidence to be cross validated. Second, the initial analysis of how, how much, and why material waste is generated across the four factories was validated through an additional interview conducted for each factory. This approach helped minimise the risk of researcher bias and thereby enhanced the reliability of the findings.

9.6.3 Scope Limitation

The scope of this study is intentionally limited to the material waste initially generated throughout the production process. Although this may include waste potentially set for reuse, recycle, and disposal, the study does not include assessment of downstream practice efficiency of recycling and reuse effectiveness. The main purpose of adopting this scope is to focus the analysis on OSC's preventive capability to reduce material waste, rather than its corrective capability to promote waste reuse or recycling. While the narrowed scope of the study constrains assessing the full lifecycle of material waste in OSC, it allows for deeper understanding of the root cause practices underpinning waste generation at source.

9.6.4 Lack of Validation of Proposed Interventions

Drawing on the root cause practices identified throughout the research, a range of targeted interventions aimed at reducing material waste was proposed. While these interventions offer valuable and theoretically grounded insights into reducing material waste in OSC, they were not tested in real-world settings. Consequently, their practical effectiveness remains unverified,

as validation lies beyond the scope of this study. Nevertheless, the proposed interventions are firmly grounded in empirical findings, providing a robust contextual foundation for future validation and practical implementation.

9.7 Future Research Directions

This research offers novel insights into the quantification and understanding of material waste in OSC, laying the groundwork for future studies to explore and test broader sustainability metrics. Three key avenues for future research can be identified.

9.7.1 Evaluating Post-Generation Waste Practices

This study focused exclusively on the material waste initially generated during the manufacturing process, in order to centre the analysis on preventive measures. Future research should expand this scope to include the evaluation of post-generation practices such as reuse, recycling, and disposal. Such an extension would contribute to a more holistic understanding of corrective strategies and support the development of closed-loop material flows in OSC.

9.7.2 Comparing Waste with Traditional Construction

This research has specifically focused on material waste initially generated in OSC, addressing a significant gap in the existing literature. Future studies are needed to conduct like-for-like comparisons of construction waste between OSC and traditional construction methods, taking into account both onsite and offsite waste generation. Such research would offer a clearer understanding of whether OSC delivers meaningful reductions in overall material waste.

9.7.3 Validation of Proposed Interventions

While the targeted interventions proposed in this study are grounded in empirical evidence, they remain untested in practice. Future research is needed to pilot, adapt, and validate these interventions in real-world OSC environments. This would provide critical evidence on their practical applicability and effectiveness, ultimately supporting broader industry adoption and informing policy development.

9.7.4 Exploring Automation for Production flow and Material Efficiency

While this research identified and analysed several scenarios in which material efficiency and production flow are either in tension or in synergy, it was beyond the scope of this study to explore specific technological solutions that could help reconcile these priorities. Therefore,

future research is needed to propose and evaluate a range of automated technologies with the potential to promote synergy between production flow and material efficiency in OSC.

9.8 Conclusions

This study provides novel insights into the understanding and quantification of material waste generation at source in OSC, addressing a significant gap in the existing literature. Using a multiple case study approach across four factories, the research employed various data collection methods, including direct observations, design document analysis, and semi-structured interviews, to enhance the study's validity and credibility. This study identified five categories of material waste and mapped them to their root causes. It examined the effects of automation and competing operational priorities on waste outcomes, and modelled waste variability across multiple dimensions, offering a nuanced understanding of material waste dynamics in OSC. This study also proposed a range of targeted interventions to address the identified root causes. These insights form the basis for several key conclusions:

First, a poorly integrated design process is a substantial source of material waste in OSC. Limited integration with procurement often leads to a mismatch between design specifications and available material sizes, while poor coordination with production results in inadequate design detailing (e.g., lack of cut planning around openings). In doing so, material overcutting and ad-hoc cut planning become more likely, resulting in significant waste generation.

Second, rigid procurement practices that can source only a limited range of standard material sizes represent a significant source of material waste in OSC. In particular, the inability of procurement to supply a broader selection of standard and custom sizes constrains the design team's ability to balance customer-specific sizing requirements with material availability. As a result, mismatches between design specifications and available material sizes are likely to generate material waste, unless mitigated by adaptable production capabilities.

Third, inadequate production capabilities, such as inefficient nesting and manual work inaccuracies, are likely to contribute to material waste in OSC. While material nesting can help mitigate upstream design and procurement rigidities by enabling efficient cut integration to minimise waste, its use is often limited due to conflicts with production flow. Additionally, reliance on manual work and the absence of precision tools often lead to material overapplication, particularly in the processing of flexible materials.

Lastly, the substantial quantities of material waste recorded across various materials reveal that OSC factories often rely more on downstream corrective measures of reuse and recycling, than on upstream prevention. This reliance highlights missed opportunities to leverage the controlled environment of OSC to reduce waste at its source.

References

- Abdullah, M., Sommerfeld, R., Seidel, L., Noack, J., Zhang, R., Roumen, T., Baudisch, P. (2021) Roadkill: Nesting Laser-Cut Objects for Fast Assembly. *UIST 2021 - Proceedings of the 34th Annual ACM Symposium on User Interface Software and Technology*, 972–984.
- Abkar, M.M.A., Yunus, R., Harouache, A., Gamil, Y., Al-Shameri, A.S.A.S. (2025) The adoption of automation technology for the mitigation of material waste on construction sites in the Malaysian construction industry. *International Journal of Construction Management*. **25**(5), 530–541.
- Adewuyi, T., Oтали, M. (2013) Evaluation of Causes of Construction Material Waste: Case of River State, Nigeria. *Ethiopian Journal of Environmental Studies and Management*. **6**(6), 746–753.
- Afifi, M., Al-Hussein, M., Abourizk, S., Fotouh, A., Bouferguene, A. (2016) Discrete and continuous simulation approach to optimize the productivity of modular construction element. In *ISARC 2016 - 33rd International Symposium on Automation and Robotics in Construction*. pp. 350–356.
- Afifi, M., Fotouh, A., Al-Hussein, M., Abourizk, S. (2022) Integrated lean concepts and continuous/discrete-event simulation to examine productivity improvement in door assembly-line for residential buildings. *International Journal of Construction Management*. **22**(13), 2423–2434.
- Ahmed, V., Opoku, A., Aziz, Z. (2016) *Research methodology in the built environment: A selection of case studies*. 1st ed. V. Ahmed, A. Opoku, & Z. Aziz, eds. Routledge.
- Ajayi, S.O., Oyedele, L.O. (2018) Critical design factors for minimising waste in construction projects: A structural equation modelling approach. *Resources, Conservation and Recycling*. **137**, 302–313.
- Ajayi, S.O., Oyedele, L.O., Akinade, O.O., Bilal, M., Alaka, H.A., Owolabi, H.A., 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**, 1333–1341.
- Alaloul, W.S., Musarat, M.A., Rabbani, M.B.A., Altaf, M., Alzubi, K.M., Salaheen, M. Al (2022) Assessment of Economic Sustainability in the Construction Sector: Evidence from

Three Developed Countries (the USA, China, and the UK). *Sustainability* 2022, Vol. 14, Page 6326. **14**(10), 6326.

Alarcón, L., Rivas, R., Serpell, A. (1999) Evaluation and improvement of the procurement process in construction projects. In *7th Annual Conference of the International Group for Lean Construction*. pp. 219–230.

Andersen, S.C., Sohn, J., Oldfield, P., Birkved, M. (2022) Evaluating the environmental impacts of conventional and modular buildings in absolute measures: A case study across different geographical contexts. *Building and Environment*. **223**.

Antoniou, F., Marinelli, M. (2020) Proposal for the Promotion of Standardization of Precast Beams in Highway Concrete Bridges. *Frontiers in Built Environment*. **6**.

Arashpour, M., Wakefield, R., Blismas, N., Maqsood, T. (2015) Autonomous production tracking for augmenting output in off-site construction. *Automation in Construction*. **53**, 13–21.

Arbulu, R., Ballard, G. (2004) Lean Supply Systems in Construction. In *Proceedings of the 12th Annual Conference of the International Group for Lean Construction*. pp. 1–13.

Assaad, R., El-adaway, I.H., Hastak, M., LaScola Needy, K. (2023) Opportunities and Challenges of Offsite Construction. In *Lecture Notes in Civil Engineering*. pp. 555–568.

Ayinla, K., Cheung, F., Skitmore, M. (2022) Process Waste Analysis for Offsite Production Methods for House Construction: A Case Study of Factory Wall Panel Production. *Journal of Construction Engineering and Management*. **148**(1), 05021011.1–14.

Ayinla, K., Cheung, F., Towe, B. (2025) Time-driven activity-based costing (TDABC) model for performance optimization of offsite manufacturing methods housebuilding. *Construction Management and Economics*. **43**(8), 637–656.

Bahrami, S., Zeinali, D. (2022) The sustainability challenge of product information quality in the design and construction of facades: lessons from the Grenfell Tower fire. *Smart and Sustainable Built Environment*. **12**(3), 488–506.

Bakchan, A., Faust, K.M., Leite, F. (2019) Seven-dimensional automated construction waste quantification and management framework: Integration with project and site planning. *Resources, Conservation and Recycling*. **146**, 462–474.

- Bakshan, A., Srour, I., Chehab, G., El-Fadel, M. (2015) A field based methodology for estimating waste generation rates at various stages of construction projects. *Resources, Conservation and Recycling*. **100**, 70–80.
- Balasbaneh, A.T., Sher, W. (2021) Life cycle sustainability assessment analysis of different concrete construction techniques for residential building in Malaysia. *The International Journal of Life Cycle Assessment*. **26**(7), 1301–1318.
- Balkhy, W. Al, Sweis, R., Lafhaj, Z. (2021) Barriers to adopting lean construction in the construction industry—the case of Jordan. *Buildings*. **11**(6), 1–17.
- Ballard, G. (1999a) *Can pull techniques be used in design management?*
- Ballard, G. (2020) The Last Planner System. In Patricia Tzortzopoulos, Mike Kagioglou, & Lauri Koskela, eds. *Lean Construction: Core Concepts and New Frontiers*. Routledge, pp. 45–53.
- Ballard, G. (1999b) Work Structuring. *LCI-White Paper*. **5**.
- Ballard, G., Howell, G. (1994) Implementing lean construction: stabilizing work flow. *Lean construction*. **2**, 105–114.
- Ballard, H.G. (2000) *The last planner system of production control*. Birmingham, UK: University of Birmingham.
- Banihashemi, S., Tabadkani, A., Hosseini, M.R. (2018) Integration of parametric design into modular coordination: A construction waste reduction workflow. *Automation in Construction*. **88**(December 2017), 1–12.
- Banihashemi, S., Tabadkani, A., Hosseini, M.R. (2017) Modular Coordination-based Generative Algorithm to Optimize Construction Waste. *Procedia Engineering*. **180**, 631–639.
- Bao, Z., Laovisutthichai, V., Tan, T., Wang, Q., Lu, W. (2022) Design for manufacture and assembly (DfMA) enablers for offsite interior design and construction. *Building Research and Information*. **50**(3), 325–338.
- Barkokebas, B., Khalife, S., Al-Hussein, M., Hamzeh, F. (2021) A BIM-lean framework for digitalisation of premanufacturing phases in offsite construction. *Engineering, Construction and Architectural Management*. **28**(8), 2155–2175.

Barkokebas, B., Martinez, P., Bouferguene, A., Hamzeh, F., Al-Hussein, M. (2023) Digitalization-based process improvement and decision-making in offsite construction. *Automation in Construction*. **155**, 105052.

Barkokebas, B., Ritter, C., Al-Hussein, M., Li, X. (2021) Simulation-based decision support for production improvement using integrated ergonomic and productivity performance indicators. *International Journal of Simulation and Process Modelling*. **16**(2), 161–174.

Bataglin, F., Viana, D., Formoso, C., Bulhões, I. (2020) Model for planning and controlling the delivery and assembly of engineer-to-order prefabricated building systems: Exploring synergies between lean and BIM. *Canadian Journal of Civil Engineering*. **47**(2), 165–177.

Bataglin, F.S., Viana, D.D., Formoso, C.T., Bulhões, I.R. (2017) Application of BIM for supporting decision-making related to logistics in prefabricated building systems. In *IGLC 2017 - Proceedings of the 25th Annual Conference of the International Group for Lean Construction*. pp. 71–78.

Bøe, A.S., Mäger, K.N., Friquin, K.L., Just, A. (2023) Experimental Study of the Charring of I-Joists and Recession of Combustible Insulation in Light Timber Frame Assemblies with Comparison to Eurocode 5. *Fire Technology* 2023 59:6. **59**(6), 3283–3325.

Bølviken, T., Koskela, L. (2016) Why hasn't waste reduction conquered construction? In *IGLC 2016 - 24th Annual Conference of the International Group for Lean Construction*.

Bølviken, T., Rooke, J., Koskela, L. (2014) The Wastes of Production in Construction – a TFFV Based Taxonomy. In B. T. Kalsaas, L. Koskela, & T. A. Saurin, eds. *22nd Annual Conference of the International Group for Lean Construction*. Oslo, Norway, pp. 811–822.

Boothroyd, G., Dewhurst, P., Knight, W.A. (2010) *Product Design for Manufacture and Assembly*. 3rd ed. Routledge.

Bortolini, R., Formoso, C.T., Viana, D.D. (2019) Site logistics planning and control for engineer-to-order prefabricated building systems using BIM 4D modeling. *Automation in Construction*. **98**.

Bortolini, R., Shigaki, J.S.-I., Formoso, C.T. (2015) Site logistics planning and control using 4d modeling: A study in a lean car factory building site. In *Proceedings of IGLC 23 - 23rd Annual Conference of the International Group for Lean Construction: Global Knowledge - Global Solutions*. pp. 361–370.

- Bossink, B.A.G., Brouwers, H.J.H. (1996) Construction Waste: Quantification and Source Evaluation. *Journal of Construction Engineering and Management*. **122**(1).
- Brown, R., Barkokebas, B., Ritter, C., Al-Hussein, M. (2019) Predicting performance indicators using BIM and simulation for a wall assembly line. *27th Annual Conference of the International Group for Lean Construction, IGLC 2019*. (February 2020), 853–862.
- Chen, T.Y., Burnett, J., Chau, C.K. (2001) Analysis of embodied energy use in the residential building of Hong Kong. *Energy*. **26**(4), 323–340.
- Chen, Y., Zhou, Y., Feng, W., Fang, Y., Feng, A. (2022) Factors That Influence the Quantification of the Embodied Carbon Emission of Prefabricated Buildings: A Systematic Review, Meta-Analysis and the Way Forward. *Buildings 2022, Vol. 12*,. **12**(8).
- Cheung, F.K.T., Kurul, E., Oti, A.H. (2016) A case study of hybrid strategies to create value for a contracting business in the education sector in England and Wales. *Construction Management and Economics*. **34**(4–5).
- Choi, J.O., Shrestha, B.K., Kwak, Y.H., Shane, J.S. (2020) Innovative Technologies and Management Approaches for Facility Design Standardization and Modularization of Capital Projects. *Journal of Management in Engineering*. **36**(5), 1–11.
- Creswell, J. (2013) *Research Design - Qualitative, Quantitative and Mixed Methods Approaches*. 4th ed. London: SAGE Publications, Inc.
- Creswell, J.W., Clark, V.L.P. (2018) *Designing and Conducting Mixed Methods Research*.
- Darwish, M., Mohsen, O., Mohamed, Y., Al-Hussein, M. (2020) Integrated simulation and lean approach for production line improvement in a prefabricated panelized homebuilding facility. In *IGLC 28 - 28th Annual Conference of the International Group for Lean Construction 2020*. pp. 649–660.
- DEFRA (2023) *The government's resources and waste reforms for England*.
- Domingo, N., Batty, T. (2021) Construction waste modelling for residential construction projects in New Zealand to enhance design outcomes. *Waste Management*. **120**.
- Domingo, N., Edirisinghe, H.M., Kahandawa, R., Wedawatta, G. (2024) Generalised Linear Modelling for Construction Waste Estimation in Residential Projects: Case Study in New Zealand. *Sustainability 2024, Vol. 16, Page 1941*. **16**(5), 1941.

- Dubois, A., Hulthén, K., Sundquist, V. (2019) Organising logistics and transport activities in construction. *International Journal of Logistics Management*. **30**(2), 620–640.
- Eastman, C.M., Sacks, R. (2008) Relative Productivity in the AEC Industries in the United States for On-Site and Off-Site Activities. *Journal of Construction Engineering and Management*. **134**(7).
- Eghbali, S.R., Azizzadeh Araee, R., Mofrad Boushehri, A. (2019) Construction waste generation in the Iranian building industry. *Civil Engineering Infrastructures Journal*. **52**(1), 1–10.
- Elfving, J.A. (2003) *Exploration of opportunities to reduce lead times for engineered-to-order products*. University of California, Berkeley.
- EU Commission (2025) *SMALL MID-CAPS Helping Europe's growing businesses*.
- Ezzeddine, A., García de Soto, B. (2021) Connecting teams in modular construction projects using game engine technology. *Automation in Construction*. **132**, 103887.
- Flick, U. (2012) *Designing Qualitative Research*.
- Flyvbjerg, B. (2006) Five misunderstandings about case-study research. *Qualitative Inquiry*. **12**(2).
- Formoso, C.T., Bølviken, T., Viana, D.D. (2020) Understanding waste in construction. In *Lean Construction*. Routledge, pp. 129–145.
- Formoso, C.T., Soibelman, L., Cesare, C. De, Isatto, E.L. (2002) Material Waste in Building Industry: Main Causes and Prevention. *Journal of Construction Engineering and Management*. **128**(4), 316–325.
- Formoso, C.T., Sommer, L., Koskela, L., Isatto, E.L. (2011) An Exploratory Study on the Measurement and Analysis of Making-Do in Construction Sites. In J. Rooke & B. Dave, eds. *19th Annual Conference of the International Group for Lean Construction*. Lima, Peru.
- Formoso, C.T., Sommer, L., Koskela, L., Isatto, E.L. (2017) The identification and analysis of making-do waste: insights from two Brazilian construction sites. *Ambiente Construído*. **17**(3), 183–197.
- Gao, S., Jin, R., Lu, W. (2020) Design for manufacture and assembly in construction: a review. *Building Research and Information*. **48**(5), 538–550.

- Gavilan, R.M., Bernold, L.E. (1994) Source Evaluation of Solid Waste in Building Construction. *Journal of Construction Engineering and Management*. **120**(3).
- Gbadamosi, A.-Q., Mahamadu, A.-M., Oyedele, L.O., Akinade, O.O., Manu, P., Mahdjoubi, L., Aigbavboa, C. (2019) Offsite construction: Developing a BIM-Based optimizer for assembly. *Journal of Cleaner Production*. **215**, 1180–1190.
- George, A., Bennett, A. (2005) *Case Study and Theory Development in the Social Science*.
- Ghinato, P. (1998) Quality control methods: Towards modern approaches through well established principles. *Total Quality Management*. **9**(6), 463–477.
- Gibb, A.G. (1999) *Off-site fabrication: prefabrication, pre-assembly and modularisation*. Whittles Publishing.
- Gibb, A.G.F. (2001) Pre-assembly in construction - A review of recent and current industry and research initiatives on pre-assembly in construction. In *Construction In Construction Research & Innovation Strategy Panel CRISP Consultancy Commission 00/19*.
- Goh, M., Goh, Y.M. (2019) Lean production theory-based simulation of modular construction processes. *Automation in Construction*. **101**(February), 227–244.
- Goldberg, L.R. (2019) The Book of Why: The New Science of Cause and Effect. *Notices of the American Mathematical Society*. **66**(07).
- Grünbaum, N.N. (2007) Identification of ambiguity in the case study research typology: What is a unit of analysis? *Qualitative Market Research*. **10**(1).
- Guerra, B.C., Bakchan, A., Leite, F., Faust, K.M. (2019) BIM-based automated construction waste estimation algorithms: The case of concrete and drywall waste streams. *Waste Management*. **87**.
- Guerra, B.C., Koo, H.J., Caldas, C., Leite, F. (2024) Prediction of waste diversion and identification of trends in construction and demolition waste data using data mining. *International Journal of Construction Management*. **24**(4).
- Gulghane, A., Sharma, R.L., Borkar, P. (2024) A formal evaluation of KNN and decision tree algorithms for waste generation prediction in residential projects: a comparative approach. *Asian Journal of Civil Engineering*. **25**(1), 265–280.

- Gulghane, A., Sharma, R.L., Borkar, P. (2023) Performance analysis of machine learning-based prediction models for residential building construction waste. *Asian Journal of Civil Engineering*. **24**(8), 3265–3276.
- Guo, J., Wang, Q., Park, J.H. (2020) Geometric quality inspection of prefabricated MEP modules with 3D laser scanning. *Automation in Construction*. **111**, 103053.
- Gusmao Brissi, S., Wong Chong, O., Debs, L., Zhang, J. (2022) A review on the interactions of robotic systems and lean principles in offsite construction. *Engineering, Construction and Architectural Management*. **29**(1), 383–406.
- Hamzeh, F.R., Ballard, G., Tommelein, I.D. (2009) Is the Last Planner System Applicable to Design? A Case Study. , 165–176.
- Hao, J., Chen, Z., Zhang, Z., Loehlein, G. (2021) Quantifying construction waste reduction through the application of prefabrication: a case study in Anhui, China. *Environmental Science and Pollution Research*. **28**(19), 24499–24510.
- He, D., Li, Z., Wu, C., Ning, X. (2018) An e-commerce platform for industrialized construction procurement based on BIM and linked data. *Sustainability (Switzerland)*. **10**(8).
- He, R., Li, M., Gan, V.J.L., Ma, J. (2021) BIM-enabled computerized design and digital fabrication of industrialized buildings: A case study. *Journal of Cleaner Production*. **278**.
- Heravi, G., Firoozi, M. (2017) Production process improvement of buildings' prefabricated steel frames using value stream mapping. *International Journal of Advanced Manufacturing Technology*. **89**(9–12).
- Heravi, G., Rostami, M., Kebria, M.F. (2020) Energy consumption and carbon emissions assessment of integrated production and erection of buildings' pre-fabricated steel frames using lean techniques. *Journal of Cleaner Production*. **253**, 120045.
- Hernández, H., Ossio, F., Silva, M. (2023) Assessment of Sustainability and Efficiency Metrics in Modern Methods of Construction: A Case Study Using a Life Cycle Assessment Approach. *Sustainability (Switzerland)*. **15**(7).
- Hoang, N.H., Ishigaki, T., Kubota, R., Tong, T.K., Nguyen, T.T., Nguyen, H.G., Yamada, M., Kawamoto, K. (2020) Waste generation, composition, and handling in building-related construction and demolition in Hanoi, Vietnam. *Waste Management*. **117**, 32–41.

- Hong, J., Shen, G.Q., Mao, C., Li, Z., Li, K. (2016) Life-cycle energy analysis of prefabricated building components: An input-output-based hybrid model. *Journal of Cleaner Production*. **112**(2016), 2198–2207.
- Höök, M., Stehn, L. (2008) Lean principles in industrialized housing production: The need for a cultural change. *Lean Construction Journal*. **2008**.
- Howell, G. (1999) What is lean construction. *Concurrent Engineering*. **7**(July).
- Hsu, P.-Y., Aurisicchio, M., Angeloudis, P. (2017) Supply chain design for modular construction projects. In *IGLC 2017 - Proceedings of the 25th Annual Conference of the International Group for Lean Construction*. pp. 797–804.
- Hu, Q., Liu, R., Su, P., Huang, J., Peng, Y. (2023) Construction and demolition waste generation prediction and spatiotemporal analysis: a case study in Sichuan, China. *Environmental Science and Pollution Research*. **30**(14), 41623–41643.
- Hu, R., Chen, K., Chen, W., Wang, Q., Luo, H. (2021) Estimation of construction waste generation based on an improved on-site measurement and SVM-based prediction model: A case of commercial buildings in China. *Waste Management*. **126**.
- Huang, L., Cai, T., Zhu, Ya, Zhu, Yuliang, Wang, W., Sun, K. (2020) Lstm-based forecasting for urban construction waste generation. *Sustainability (Switzerland)*. **12**(20).
- Innella, F., Arashpour, M., Bai, Y. (2019) Lean Methodologies and Techniques for Modular Construction: Chronological and Critical Review. *Journal of Construction Engineering and Management*. **145**(12).
- Jaillon, L., Poon, C. (2010) Design issues of using prefabrication in Hong Kong building construction. *Construction management and economics*. **28**(10), 1025–1042.
- Jaillon, L., Poon, C.S. (2014) Life cycle design and prefabrication in buildings: A review and case studies in Hong Kong. *Automation in Construction*. **39**, 195–202.
- Jaillon, L., Poon, C.S., Chiang, Y.H. (2009) Quantifying the waste reduction potential of using prefabrication in building construction in Hong Kong. *Waste Management*. **29**(1), 309–320.
- Jarkko, E., Lu, W., Lars, S., Thomas, O. (2013) Discrete event simulation enhanced value stream mapping: An industrialized construction case study. *Lean Construction Journal*. **2013**, 47–65.

- Jaskowski, P., Biruk, S., Krzemiński, M. (2024) Synchronizing production of precast elements with on-site erection. *Archives of Civil Engineering*. **70**(3).
- Jayawardana, J., Kulatunga, A.K., Jayasinghe, J.A.S.C., Sandanayake, M., Zhang, G. (2023) Environmental Sustainability of Off-Site Construction in Developed and Developing Regions: A Systematic Review. *Journal of Architectural Engineering*. **29**(2).
- Kaliannan, S., Nagapan, S., Abdullah, A.H., Sohu, S., Jhatial, A.A. (2018) Determining Root Cause of Construction Waste Generation: A Global Context. *Civil Engineering Journal*. **4**(11).
- Kifokeris, D., Xenidis, Y. (2017) Constructability: Outline of Past, Present, and Future Research. *Journal of Construction Engineering and Management*. **143**(8), 04017035.
- Kolo, S.J., Pour Rahimian, F., Goulding, J.S. (2014) Housing Delivery in Nigeria and the Opportunity for Offsite Manufacturing. In *Creative Construction Conference 2014*.
- Kong, L., Li, H., Luo, H., Ding, L., Zhang, X. (2018) Sustainable performance of just-in-time (JIT) management in time-dependent batch delivery scheduling of precast construction. *Journal of Cleaner Production*. **193**, 684–701.
- Koskela, L. (2000) An exploration towards a production theory and its application to construction. *VTT Publications*. (408).
- Koskela, L. (1992) Application of the new production philosophy to construction.
- Koskela, L. (2004) Making-Do — the Eighth Category of Waste. In S. , In Bertelsen & C. T. Formoso, eds. *12th Annual Conference of the International Group for Lean Construction*.
- Koskela, L. (2020) Theory of Lean Construction. *Lean Construction*, 2–13.
- Laika, M., Heravi, G., Rostami, M., Ahmadi, S. (2022) Improving the Performance of Precast Concrete Production Processes by Simultaneous Implementation of Lean Techniques and Root Cause Analysis. *Iranian Journal of Science and Technology - Transactions of Civil Engineering*. **46**(0123456789), 2649–2666.
- Lam, P.T.I., Yu, A.T.W., Wu, Z., Poon, C.S. (2019) Methodology for upstream estimation of construction waste for new building projects. *Journal of Cleaner Production*. **230**.
- Larsson, J., Simonsson, P. (2012) Barriers and drivers for increased use of off-site bridge construction in Sweden. In *Association of Researchers in Construction Management, ARCOM 2012 - Proceedings of the 28th Annual Conference*.

Lawson, R.M., Ogden, R.G., Bergin, R. (2012) Application of modular construction in high-rise buildings. *Journal of architectural engineering*. **18**(2), 148–154.

Lean Construction Institute (2025) An Introduction to Lean Construction. [online]. Available from: <https://leanconstruction.org/lean-topics/lean-construction/> [Accessed December 1, 2025].

Leminen, V., Eskelinen, H., Matthews, S., Varis, J. (2013) Development and utilization of a DFMA-evaluation matrix for comparing the level of modularity and standardization in clamping systems. *Mechanika*. **19**(6), 711–715.

Li, J., Ding, Z., Mi, X., Wang, J. (2013) A model for estimating construction waste generation index for building project in China. *Resources, Conservation and Recycling*. **74**.

Li, Y., Zhang, X., Ding, G., Feng, Z. (2016) Developing a quantitative construction waste estimation model for building construction projects. *Resources, Conservation and Recycling*. **106**.

Li, Z., Shen, G.Q., Xue, X. (2014) Critical review of the research on the management of prefabricated construction. *Habitat International*. **43**, 240–249.

Liker, J. (2020) *The Toyota Way (2nd Edition): 14 Management Principles From the World's Greatest Manufacturer*.

Lim, I., Sawab, J., Wang, J., Fan, S., Mo, Y.L., Li, M. (2021) Characterization of Ultrahigh-Performance Concrete Materials for Application in Modular Construction. *Journal of Materials in Civil Engineering*. **33**(5), 04021087.

Lim, V.A. (2008) Lean construction : knowledge and barriers in implementing into Malaysia construction industry.

Lindhard, S.M., Wyke, S., Mahami, H., Vaezzadeh, S.S., Svidt, K. (2023) Waste Generation Predictions and On-Site Waste Management: A Danish Perspective. *Sustainability 2023, Vol. 15, Page 4207*. **15**(5), 4207.

Liu, H., Holmwood, B., Sydora, C., Singh, G., Al-Hussein, M. (2017) OPTIMIZING MULTI-WALL PANEL CONFIGURATION FOR PANELIZED CONSTRUCTION USING BIM. In *ISEC 2017 - 9th International Structural Engineering and Construction Conference: Resilient Structures and Sustainable Construction*.

- Liu, H., Singh, G., Lu, M., Bouferguene, A., Al-Hussein, M. (2018) BIM-based automated design and planning for boarding of light-frame residential buildings. *Automation in Construction*. **89**, 235–249.
- Liu, H., Sydora, C., Altaf, M.S., Han, S., Al-Hussein, M. (2019) Towards sustainable construction: BIM-enabled design and planning of roof sheathing installation for prefabricated buildings. *Journal of Cleaner Production*. **235**, 1189–1201.
- Liu, J., Lu, M. (2017) Optimization on supply-constrained module assembly process. In *IGLC 2017 - Proceedings of the 25th Annual Conference of the International Group for Lean Construction*. pp. 813–820.
- Liu, S, Liu, Q., Zhang, M. (2022) Research on Modularization of Prefabricated Affordable Housing in Zhengzhou Based on the Concept of Sustainable Development. In *Advances in Transdisciplinary Engineering*. pp. 1012–1023.
- Liu, Yan, Yao, F., Ji, Y., Tong, W., Liu, G., Li, H.X., Hu, X. (2022) Quality Control for Offsite Construction: Review and Future Directions. *Journal of Construction Engineering and Management*. **148**(8), 1–14.
- Loizou, L., Barati, K., Shen, X., Li, B. (2021) Quantifying advantages of modular construction: Waste generation. *Buildings*. **11**(12).
- Lu, W, Lee, W.M.W., Xue, F., Xu, J. (2021) Revisiting the effects of prefabrication on construction waste minimization: A quantitative study using bigger data. *Resources, Conservation and Recycling*. **170**.
- Lu, Weisheng, Lou, J., Webster, C., Xue, F., Bao, Z., Chi, B. (2021) Estimating construction waste generation in the Greater Bay Area, China using machine learning. *Waste Management*. **134**, 78–88.
- Lu, W., Peng, Y., Chen, X., Skitmore, M., Zhang, X. (2016) The S-curve for forecasting waste generation in construction projects. *Waste Management*. **56**.
- Lu, W., Webster, C., Peng, Y., Chen, X., Zhang, X. (2017) Estimating and calibrating the amount of building-related construction and demolition waste in urban China. *International Journal of Construction Management*. **17**(1).

- Luangcharoenrat, C., Intrachooto, S., Peansupap, V., Sutthinarakorn, W. (2019) Factors Influencing Construction Waste Generation in Building Construction: Thailand's Perspective. *Sustainability* 2019, Vol. 11, Page 3638. **11**(13), 3638.
- Luo, L.Z., Mao, C., Shen, L.Y., Li, Z.D. (2015) Risk factors affecting practitioners' attitudes toward the implementation of an industrialized building system a case study from China. *Engineering, Construction and Architectural Management*. **22**(6).
- Ma, Y., Qiao, E. (2021) Visualized Management System of Prefabricated Construction and Installation Engineering Based on BIM and Machine Learning. In *2021 IEEE International Conference on Industrial Application of Artificial Intelligence, IAAI 2021*. pp. 138–143.
- Mah, C.M., Fujiwara, T., Ho, C.S. (2016) Construction and demolition waste generation rates for high-rise buildings in Malaysia. *Waste Management and Research*. **34**(12), 1224–1230.
- Mahamid, I., Elbadawi, I.A.Q. (2014) Construction material waste: Recognition and analysis. *Research Journal of Applied Sciences, Engineering and Technology*. **8**(11), 1312–1318.
- Malik, N., Ahmad, R., Chen, Y., Altaf, M.S., Al-Hussein, M. (2021) Minimizing joist cutting waste through dynamic waste allocation in panelized floor manufacturing. *International Journal of Construction Management*. **21**(10).
- Mao, C., Shen, Q., Shen, L., Tang, L. (2013) Comparative study of greenhouse gas emissions between off-site prefabrication and conventional construction methods: Two case studies of residential projects. *Energy and Buildings*.
- Maués, L.M.F., Nascimento, B. do M.O. do, Lu, W., Xue, F. (2020) Estimating construction waste generation in residential buildings: A fuzzy set theory approach in the Brazilian Amazon. *Journal of Cleaner Production*. **265**.
- McHugh, K., Dave, B., Craig, R. (2019) Integrated lean and BIM processes for modularised construction - A case study. In *27th Annual Conference of the International Group for Lean Construction, IGLC 2019*. pp. 227–238.
- Meng, R., Wang, J., Xiang, C., Du, X., Zeng, W., Jiang, C., Wu, Z., Guan, F. (2025) Collaborative optimization of layout and cutting scheduling for large-scale customized metal structural parts. *Scientific Reports* 2025 15:1. **15**(1), 36648-.
- MHCL (2019) Modern methods of construction, Introducing the MMC Definition Framework. *Ministry of Housing, Communities & Local Government*.

Mignacca, B., Locatelli, G. (2021) Modular Circular Economy in Energy Infrastructure Projects: Enabling Factors and Barriers. *Journal of Management in Engineering*. **37**(5).

Miles, J., Whitehouse., N. (2013) *Offsite housing review*. London: Construction Industry Council.

Miles, M.B.A.M.H. (1994) Qualitative Data Analysis A Methods Sourcebook. *Experiencing Citizenship: Concepts and Models for Service-Learning in Political Science*.

Mirshekarlou, B.R., Budayan, C., Dikmen, I., Birgonul, M.T. (2021) Development of a knowledge-based tool for waste management of prefabricated steel structure projects. *Journal of Cleaner Production*. **323**, 129140.

Moghadam, M., Al-Hussein, M. (2013) Resource optimization for modular construction through value stream map improvement. In *21st Annual Conference of the International Group for Lean Construction 2013, IGLC 2013*. pp. 706–715.

Moghadam, M., Barkokebas, B., Al-Hussein, M. (2014) Post-simulation visualization application for production improvement of modular construction manufacturing. In *31st International Symposium on Automation and Robotics in Construction and Mining, ISARC 2014 - Proceedings*. pp. 270–277.

Mohamad, A., Gehbauer, F., Haghsheno, S. (2014) Improving the implementation of modularization and standardization of mep systems in design. In *22nd Annual Conference of the International Group for Lean Construction: Understanding and Improving Project Based Production, IGLC 2014*. pp. 509–518.

Mohamad, A., Hickethier, G., Hovestadt, V., Gehbauer, F. (2013) Use of modularization in design as a strategy to reduce component variety in one-off projects. In *21st Annual Conference of the International Group for Lean Construction 2013, IGLC 2013*. pp. 285–294.

Molavi, J., Barral, D.L. (2016) A Construction Procurement Method to Achieve Sustainability in Modular Construction. In *Procedia Engineering*.

Morgan, D.L. (2014) Pragmatism as a Paradigm for Social Research. *Qualitative Inquiry*. **20**(8).

Mostafa, S., Chileshe, N., Zuo, J. (2014) A synergistic supply chain enhancing offsite manufacturing uptake in australian house building. In *Proceedings 30th Annual Association of Researchers in Construction Management Conference, ARCOM 2014*. pp. 1143–1152.

- Nagalli, A. (2021) Estimation of construction waste generation using machine learning. *Proceedings of Institution of Civil Engineers: Waste and Resource Management*. **174**(1).
- Nahmens, I., Ikuma, L.H. (2012) Effects of Lean Construction on Sustainability of Modular Homebuilding. *Journal of Architectural Engineering*. **18**(2), 155–163.
- Nahmens, I., Mullens, M.A. (2011) Lean Homebuilding: Lessons Learned from a Precast Concrete Panelizer. *Journal of Architectural Engineering*. **17**(4), 155–161.
- Nascimento, D.L. de M., Sotelino, E.D., Lara, T.P.S., Caiado, R.G.G., Ivson, P. (2017) Constructability in industrial plants construction: a BIM-Lean approach using the Digital Obeya Room framework. *Journal of Civil Engineering and Management*. **23**(8), 1100–1108.
- Nazir, F.A., Edwards, D.J., Shelbourn, M., Martek, I., Thwala, W.D.D., El-Gohary, H. (2021) Comparison of modular and traditional UK housing construction: a bibliometric analysis. *Journal of Engineering, Design and Technology*.
- Ng, M.S., Hall, D.M. (2019) Toward Lean Management for Digital Fabrication: a Review of the Shared Practices of Lean, DfMA and dfab. *27th Annual Conference of the International Group for Lean Construction, IGLC 2019*, 725–736.
- Nicholls, D. (2017) Qualitative research. Part 2: Methodologies. *International Journal of Therapy and Rehabilitation*. **24**(2).
- Nikakhtar, A., Hosseini, A.A., Wong, K.Y., Zavichi, A. (2015) Application of lean construction principles to reduce construction process waste using computer simulation: A case study. *International Journal of Services and Operations Management*. **20**(4).
- Noueihed, K., Hamzeh, F. (2024) Production system state analysis and improvement using VSM, simulation, and fuzzy logic. *Smart and Sustainable Built Environment*. **ahead-of-print**(ahead-of-print).
- O'Connor, J.T., O'Brien, W.J., Choi, J.O.J.O., O'Connor, J.T., O'Brien, W.J., Choi, J.O.J.O. (2015) Standardization Strategy for Modular Industrial Plants. *Journal of Construction Engineering and Management*. **141**(9), 1–10.
- OEP (2024) *Assessment of resources and waste policy in England*.
- Ohno, T. (1988) *Toyota production system: Beyond large-scale production*. 1st ed. New York: Productivity Press.

- Økland, A., Johansen, A., Beste, T., Gjesteb, E. (2017) Standardization and Modularization of Prisons. *Procedia Computer Science*. **121**, 990–997.
- Økland, A., Johansen, A., Olsson, N.O.E. (2018) Shortening lead-time from project initiation to delivery: A study of quick school and prison capacity provision. *International Journal of Managing Projects in Business*. **11**(3), 625–649.
- Oluleye, B.I., Chan, D.W.M., Saka, A.B., Olawumi, T.O. (2022) Circular economy research on building construction and demolition waste: A global review of current trends and future research directions. *Journal of Cleaner Production*, 131927.
- Orlowski, K. (2020) Automated manufacturing for timber-based panelised wall systems. *Automation in Construction*. **109**, 102988.
- Osmani, M., Glass, J., Price, A.D.F. (2008) Architects' perspectives on construction waste reduction by design. *Waste Management*. **28**(7), 1147–1158.
- Othman, A.A.E., El-Saeidy, Y.A. (2024) Early supplier involvement framework for reducing construction waste during the design process. *Journal of Engineering, Design and Technology*. **22**(2), 578–597.
- Ozaki, R. (2003) Customer-focused approaches to innovation in housebuilding. *Construction Management and Economics*. **21**(6).
- Pan, W., Sidwell, R. (2011) Demystifying the cost barriers to offsite construction in the UK. *Construction Management and Economics*. **29**(11).
- Parisi Kern, A., Ferreira Dias, M., Piva Kulakowski, M., Paulo Gomes, L. (2015) Waste generated in high-rise buildings construction: A quantification model based on statistical multiple regression. *Waste Management*. **39**.
- Parrish, K. (2012) Lean and green construction: Lessons learned from design and construction of a modular leed® gold building. In *IGLC 2012 - 20th Conference of the International Group for Lean Construction*.
- Pasquire, C.L., Connolly, G.E. (2002) Leaner construction through off-site manufacturing. In *Proceedings 10th of the International Group of Lean Construction Conference, Gramado, Brazil*.

- Peiris, A., Hui, F.K.P., Duffield, C., Wang, J., Gil Garcia, M., Chen, Y., Ngo, T. (2023) Digitalising modular construction: Enhancement of off-site manufacturing productivity via a manufacturing execution & control (MEC) system. *Computers & Industrial Engineering*. **178**, 109117.
- Poon, C.S. (Chi-sun), Yu, T.W., Ng, L.H. (2001) *A guide for managing and minimizing building and demolition waste*. Dept. of Civil & Structural Engineering, Hong Kong Polytechnic University.
- Quale, J., Eckelman, M.J., Williams, K.W., Sloditskie, G., Zimmerman, J.B. (2012) Construction Matters: Comparing Environmental Impacts of Building Modular and Conventional Homes in the United States. *Journal of Industrial Ecology*. **16**(2), 243–253.
- Ragin, C.C. y H.S.B. (1992) Introduction: Cases of ‘What is a case?’ *What is a case? Exploring the Foundations of Social Inquiry*.
- Sahir, M., Shatiry, A., Ros, I.M., Matlan, M.N., Shafiqah, F., Chelliah, N., Rahim, Z.A. (2024) Artificial Intelligence HSE Monitoring & Digital Value Stream Mapping for Prefabrication Yard. *International Journal of Integrated Engineering*. **16**(8), 134–142.
- El Sakka, F., Eid, K., Narciss, T., Hamzeh, F. (2016) Integrating lean into modular construction: A detailed case study of company X. *IGLC 2016 - 24th Annual Conference of the International Group for Lean Construction*, 23–32.
- Salama, T., Salah, A., Moselhi, O. (2021) Integrating critical chain project management with last planner system for linear scheduling of modular construction. *Construction Innovation*. **21**(4), 525–554.
- Sarhan, S. (2015) The Concept of Waste as Understood in Lean Construction. [online]. Available from: <https://leanconstructionblog.com/The-Concept-of-Waste-as-Understood-in-Lean-Construction.html> [Accessed May 7, 2025].
- Saunders, M., Lewis, P., Thornhill, A. (2016) *Research Methods for Business Students*. 7th ed. 978-1-292-01662-7: Pearson Education Limited.
- Shafiee, S., Piroozfar, P., Forberg, L.F., Hansen, H.N., Farr, E. (2025) Enhancing efficiency and sustainability in construction: a product configurator for customizable off-site building solutions. *Architectural Engineering and Design Management*.

Shahid, M.U., Thaheem, M.J., Arshad, H. (2023) Quantification and benchmarking of construction waste and its impact on cost – a case of Pakistan. *Engineering, Construction and Architectural Management*. **30**(6), 2304–2333.

Shigeo, S. (1988) Non-stock Production, Productivity Press, Cambridge.

Sierra, L., Zamora, J.L. (2013) Balconies, analysis of constructive technology current state and foresight of new industrial development. *Structures and Architecture: Concepts, Applications and Challenges - Proceedings of the 2nd International Conference on Structures and Architecture, ICSA 2013*, 636–643.

Solís-Guzmán, J., Marrero, M., Montes-Delgado, M.V., Ramírez-de-Arellano, A. (2009) A Spanish model for quantification and management of construction waste. *Waste Management*. **29**(9).

Spens, K.M., Kovács, G. (2006) A content analysis of research approaches in logistics research. *International Journal of Physical Distribution and Logistics Management*. **36**(5).

Steinhardt, D.A., Manley, K., Miller, W. (2014) Predicting Australian builders' intentions to use prefabrication.

Tam, V.W.Y., Fung, I.W.H., Sing, M.C.P., Ogunlana, S.O. (2015) Best practice of prefabrication implementation in the Hong Kong public and private sectors. *Journal of Cleaner Production*. **109**.

Tam, V.W.Y., Hao, J.J.L. (2014) Prefabrication as a mean of minimizing construction waste on site. *International Journal of Construction Management*. **14**(2).

Tavares, V., Soares, N., Raposo, N., Marques, P., Freire, F. (2021) Prefabricated versus conventional construction: Comparing life-cycle impacts of alternative structural materials. *Journal of Building Engineering*. **41**.

Thomas, G. (2021) *How to do your case study*.

Tommelein, I.D. (2008) 'Poka Yoke' or Quality by Mistake Proofing Design and Construction Systems. In 16th Annual Conference of the International Group for Lean Construction - Manchester, UK - 2008, pp. 195–205.

Tong, N., Domingo, N., Le, A.T.H. (2023) Construction waste estimation methods: A systematic literature review. , 420–431.

Tsao, C.C.Y., Lidelöw, H. (2017) Development of a materials management strategy to enable continuous work flow on-site. In *IGLC 2017 - Proceedings of the 25th Annual Conference of the International Group for Lean Construction*.

Viana, D., Formoso, C., Wesz, J., Tzortzopoulos, P. (2014) The role of visual management in collaborative integrated planning and control for engineer-to-order building systems. In *22nd Annual Conference of the International Group for Lean Construction: Understanding and Improving Project Based Production, IGLC 2014*. pp. 775–786.

Viana, D.D., Formoso, C.T., Kalsaas, B.T. (2012) Waste in Construction: a Systematic Literature Review on Empirical Studies. In I. D. Tommelein & C. L. Pasquire, eds. *20th Annual Conference of the International Group for Lean Construction*. San Diego, California, USA.

Viana, D.D.D.D., Bulhões, I.R.I.R., Formoso, C.T.C.T. (2013) Guidelines for integrated planning and control of engineer-to-order prefabrication systems. *21st Annual Conference of the International Group for Lean Construction 2013, IGLC 2013*, 486–495.

Vilventhan, A., Ram, V.G., Sugumaran, S. (2019) Value stream mapping for identification and assessment of material waste in construction: A case study. *Waste Management and Research*. **37**(8), 815–825.

Viswalekshmi, B.R., Bendi, D. (2024) A comprehensive model for quantifying construction waste in high-rise buildings in India. *Waste Management and Research*. **42**(2).

Wang, H., Liao, L., Yi, W., Zhen, L. (2024) Transportation scheduling for modules used in modular integrated construction. *International Journal of Production Research*. **62**(11), 3918–3931.

Wang, Meng, Altaf, M.S.M.S., Al-Hussein, M., Ma, Y. (2020) Framework for an IoT-based shop floor material management system for panelized homebuilding. *International Journal of Construction Management*. **20**(2), 130–145.

Wang, Qiankun, Chen, L., Hu, R., Ren, Z., He, Y., Liu, D., Zhou, Z. (2020) An empirical study on waste generation rates at different stages of construction projects in China. <https://doi.org/10.1177/0734242X19886635>. **38**(4), 433–443.

Ward, A.C., Liker, J.K., Sobek, D.K., Cristiano, J.J. (2021) Set-Based Concurrent Engineering and Toyota. *Proceedings of the ASME Design Engineering Technical Conference*. **Part F167892-1**, 79–90.

- Wesz, J.G.B., Formoso, C.T., Tzortzopoulos, P. (2018) Planning and controlling design in engineered-to-order prefabricated building systems. *Engineering, Construction and Architectural Management*. **25**(2), 134–152.
- Wesz, J.G.B., Formoso, C.T., Tzotzopoulos, P. (2013) Design process planning and control: Last planner system adaptation. *21st Annual Conference of the International Group for Lean Construction 2013, IGLC 2013*. (July), 365–374.
- Wieviorka, M. (1992) Case studies: History or sociology? In *What is a case?: Exploring the foundations of social inquiry*.
- Womack, J., Jones, D. (2003) Lean Thinking Intro and Chapter 1. In *Lean Thinking*.
- Womack, J.P., Jones, D.T., Roos., D. (1990) The machine that changed the world. Macmillan Publishing Company. , 323.
- Wu, Z., Yu, A.T.W., Shen, L., Liu, G. (2014) Quantifying construction and demolition waste: An analytical review. *Waste Management*. **34**(9).
- Xie, H., Chowdhury, M.M., Issa, R.R.A., Shi, W. (2018) Simulation of Dynamic Energy Consumption in Modular Construction Manufacturing Processes. *Journal of Architectural Engineering*. **24**(1).
- Xiong, W., Yang, J., Wang, Z., Hu, H., Xu, F., Zhang, J. (2018) Improving supply chain communications for off-site construction using process specification language. In *ISARC 2018 - 35th International Symposium on Automation and Robotics in Construction and International AEC/FM Hackathon: The Future of Building Things*.
- Xu, G., Li, M., Chen, C.H.C.-H.C.H., Wei, Y. (2018) Cloud asset-enabled integrated IoT platform for lean prefabricated construction. *Automation in Construction*. **93**(September 2017), 123–134.
- Yang, Y., Pan, M., Pan, W., Zhang, Z. (2021) Sources of Uncertainties in Offsite Logistics of Modular Construction for High-Rise Building Projects. *Journal of Management in Engineering*. **37**(3), 04021011.
- Yang, Z., Wei, P., Yue, T., Siwei, C. (2024) Construction Waste Reduction in Buildings through Modular and Offsite Construction. *Journal of Management in Engineering*. **40**(4), 04024026.
- Yin, R.K. (2014) *Case Study Research: Design and Methods*. 5th ed. SAGE Publications.

- Yu, H., Al-Hussein, M., Al-Jibouri, S., Telyas, A. (2013) Lean Transformation in a Modular Building Company: A Case for Implementation. *Journal of Management in Engineering*. **29**(1), 103–111.
- Yu, S., Liu, Y., Wang, D., Bahaj, A.B.S., Wu, Y., Liu, J. (2021) Review of thermal and environmental performance of prefabricated buildings: Implications to emission reductions in China. *Renewable and Sustainable Energy Reviews*. **137**, 110472.
- Zakaria, S.G.T., Skitmore, M., Brewer, G. (2018) Key factors influencing the decision to adopt industrialised building systems technology in the Malaysian construction industry: an inter-project perspective. *Architectural Engineering and Design Management*. **14**(1–2), 27–45.
- Zhang, H., Yu, L. (2020) Dynamic transportation planning for prefabricated component supply chain. *Engineering, Construction and Architectural Management*. **27**(9), 2553–2576.
- Zhang, J., Cai, J., Su, Y., He, Q., Lin, X. (2022) *Research and Development and Pilot Application of Innovative Technology of Prefabricated Concrete*.
- Zhang, N., Tian, Y., Wang, J., Al-Hussein, M. (2020) BIM-Based Automated Drainage System Design in Prefabrication Construction. In *Construction Research Congress 2020: Computer Applications - Selected Papers from the Construction Research Congress 2020*. pp. 1146–1155.
- Zhang, Skitmore, M. (2012) Industrialized housing in China: A coin with two sides. *International Journal of Strategic Property Management*. **16**(2).
- Zhang, Skitmore, M., Peng, Y. (2014) Exploring the challenges to industrialized residential building in China. *Habitat International*. **41**.
- Zhang, Xuan, Zhang, Xueqing (2024) Automated component delivery management under uncertainty for prefabricated buildings to minimize cost and harmful emissions. *Automation in Construction*. **162**, 105388.
- Zhang, Y., Pan, W., Teng, Y., Chen, S. (2024) Construction Waste Reduction in Buildings through Modular and Offsite Construction. *Journal of Management in Engineering*. **40**(4), 04024026.
- Zhao, L., Liu, Y., Tian, J. (2022) Spatiotemporal evolution law and output prediction of construction waste in the People's Republic of China. *Waste Management and Research*. **40**(2).

Zheng, R., Li, Z., Li, L., Dou, Y., Yuan, M., Yin, X. (2024) Proposing a Lean-Optimized Scheduling Model of Mixed-Flow Prefabricated Component Production in Off-Site Construction. *Journal of Construction Engineering and Management*. **150**(8), 04024088.

Zhong, R.Y., Peng, Y., Fang, J., Xu, G., Xue, F., Zou, W., Huang, G.Q. (2015) Towards Physical Internet-enabled prefabricated housing construction in Hong Kong. In *IFAC-PapersOnLine*.

Zikmund, W.G., Babin, B.J., Editorial, V.P., Calhoun, J.W., Thomas, J., Assistant, E., Shelton, S., Kanakes, K., Fuller-jacobsen, B. (2010) *Exploring Marketing Research*.

Appendices

Appendix A: Construction Waste Quantification – Factory A

Appendix Table 1: Wall and Ceiling Plasterboard Construction Waste Quantification – Factory A

Ceiling										
Module type	Qty	Net Length	Net Width	Used Plasterboards	Qty	Closing Strip*	Required width	Length/width side offcuts	Openings Offcuts	total plasterboards used m ²
External	2	6000	2863	3000x1200 mm	5	0	2863	1.644	0	36
Internal	2	6000	3000	3000x1200 mm	5	0	3000	0	0	36
Total Used m ²		72		Total Required m ²		70.356	Total Offcuts m ²		1.644	1%
Walls										
Module type	Qty	Net Length	Net Width	Used Plasterboards	Qty	Closing Strip*	Required width	Length/width side offcuts	Openings Offcuts	total plasterboards used m ²
External	2	6000	2863	2700x1200	9	300	2563	0	11.6	58.32
Internal	2	6000	3000	2700x1200	4	300	2400	0	6.47	25.92
Total Used m ²		84.24		Total Required m ²		66.17	Total Offcuts m ²		18.067	12%
Overall										
Used Area m ²		156.24		Required Area m ²		136.53	Offcuts m ²		19.71	13%

* The closing strip is a gap left for on-site between-module plasterboard integration

Appendix B: Construction Waste Quantification – Factory B

Appendix Table 2: Timber Framing Offcuts and Related Cuts - Factory B

Offcut length	Times	Total length	Percentage	Related Cuts		
435	89	38715	32.1%	studs		
2290	13	29770	24.7%	studs		
50	163	8150	6.8%	Trim cut		
1460	4	5840	4.8%	top/bottom rails		
1690	3	5070	4.2%	top/bottom rails		
690	6	4140	3.4%	top/bottom rails		
1625	2	3250	2.7%	top/bottom rails		
1470	2	2940	2.4%	top/bottom rails		
1445	2	2890	2.4%	top/bottom rails		
2650	1	2650	2.2%	Others (sill/lintel)		
1940	1	1940	1.6%	top/bottom rails		
590	3	1770	1.5%	Others (sill/lintel)		
865	2	1730	1.4%	Others (sill/lintel)		
1620	1	1620	1.3%	Others (sill/lintel)		
1555	1	1555	1.3%	Others (sill/lintel)		
640	2	1280	1.1%	Others (sill/lintel)		
1250	1	1250	1.0%	Others (sill/lintel)		
1240	1	1240	1.0%	Others (sill/lintel)		
940	1	940	0.8%	Others (sill/lintel)		
230	4	920	0.8%	Others (sill/lintel)		
780	1	780	0.6%	Others (sill/lintel)		
730	1	730	0.6%	Others (sill/lintel)		
300	2	600	0.5%	Others (sill/lintel)		
340	1	340	0.3%	Others (sill/lintel)		
270	1	270	0.2%	Others (sill/lintel)		
190	1	190	0.2%	Others (sill/lintel)		
102	1	102	0.1%	Others (sill/lintel)		
Required Length	825.207m	Used Length	945.879 m	Offcuts	120.672 m	13%

Appendix Table 3: Required Timber Framing Cuts Across the Observed Wall Panels – Factory B

Panel	Cut	Qty	Total _{mm}
1	43	3	129
	1230	6	7380
	2258	4	9032
	2453	25	61325
	2076	1	2076
	3009	1	3009
	3882	1	3882
	1809	1	1809
	3276	1	3276
	3882	1	3882
	1070	2	2140
	3129	1	3129
	4129	1	4129
2	43	6	258
	2258	8	18064
	2453	22	53966
	4052	1	4052
	4446	1	4446
	4052	1	4052
	4446	1	4446
	1070	4	4280
	3504	1	3504
	3693	1	3693
3	43	3	129
	2258	4	9032
	2453	24	58872
	1987	1	1987
	3278	1	3278
	4047	1	4047
	2074	1	2074
	3191	1	3191
	4047	1	4047
	1070	2	2140
	1019	1	1019
	3494	1	3494
	4101	1	4101

Panel	Cut	Qty	Total _{mm}
4	43	3	129
	2258	4	9032
	2453	31	76043
	3291	1	3291
	4053	1	4053
	4517	1	4517
	3291	1	3291
	4053	1	4053
	4517	1	4517
	1070	2	2140
	2800	1	2800
	3300	1	3300
	3964	1	3964
5	43	3	129
	2258	4	9032
	2453	29	71137
	3052	1	3052
	4160	1	4160
	4253	1	4253
	3052	1	3052
	4160	1	4160
	4253	1	4253
	1070	2	2140
	2299	1	2299
	3300	1	3300
	4015	1	4015
6	88	3	264
	117	4	468
	2258	6	13548
	2453	28	68684
	2924	1	2924
	3255	1	3255
	3719	1	3719
	2924	1	2924
	3255	1	3255
	3719	1	3719
	963	2	1926
	1070	1	1070
	35	1	35
	48	1	48
	136	1	136
	238	1	238
	287	1	287
	292	1	292

Panel	Cut	Qty	Total _{mm}
7	117	4	468
	2258	4	9032
	2453	22	53966
	3055	1	3055
	3890	1	3890
	3055	1	3055
	3890	1	3890
	963	2	1926
	48	1	48
	138	1	138
	238	1	238
	287	1	287
	312	1	312
	344	1	344
8	355	9	3195
	2500	1	2500
	3130	1	3130
	117	4	468
	2258	4	9032
	2453	22	53966
	3054	1	3054
	3887	1	3887
	3054	1	3054
	3887	1	3887
	963	2	1926
	44	1	44
	136	1	136
	238	1	238
	287	1	287
	312	1	312
	344	1	344
	355	9	3195
	2499	1	2499
	3130	1	3130
Total required length = 825.207 m No of Panels = eight Panels			

Appendix Table 4: Required and Used OSB Sizes and Quantities - Factory B

Panel	Cut	Type	Height	Width	Qty	Required m2	Used m2	Source	boards
1	A	OSB2700	2585	1197	4	12.37698	12.96	new	4
	B	OSB2700	415	1067	1	0.442805	2.0572	reuse	0
	C	OSB2700	2585	854	1	2.20759	3.24	new	1
	D	OSB2700	2585	836	1	2.16106	3.24	new	1
	E	OSB2700	2585	595	1	1.538075	3.24	new	1
	F	OSB2700	2585	470	1	1.21495	1.563925	reuse	0
	G	OSB2700	2585	229	1	0.591965	0.89441	reuse	0
2	A	OSB2700	2585	1197	2	6.18849	6.48	new	2
	B	OSB2700	2585	1093	1	2.825405	3.24	new	1
	C	OSB2700	2585	1084	1	2.80214	3.24	new	1
	D	OSB2700	415	1067	2	0.88561	1.4548	reuse	0
	E	OSB2700	2585	646	2	3.33982	6.48	new	2
	F	OSB2700	2585	274	1	0.70829	1.5	reuse	0
3	A	OSB2700	2585	1197	4	12.37698	12.96	new	4
	B	OSB2700	2585	1091	1	2.820235	3.24	new	1
	C	OSB2400	415	1067	1	0.442805	2.88	new	1
	D	OSB2700	2585	1010	1	2.61085	3.24	new	1
	E	OSB2700	2585	914	1	2.36269	3.24	new	1
	F	OSB2700	2585	416	1	1.07536	1.385	reuse	0
4	A	OSB2700	2585	1197	5	15.471225	16.2	new	5
	B	OSB2700	2585	1170	1	3.02445	3.24	new	1
	C	OSB2700	415	1067	1	0.442805	2.117	reuse	0
	D	OSB2700	2585	961	1	2.484185	3.24	new	1
	E	OSB2700	2585	796	1	2.05766	3.24	new	1
	F	OSB2700	2585	754	1	1.94909	3.24	new	1
	G	OSB2700	2585	597	1	1.543245	3.24	new	1
	H	OSB2700	2585	400	1	1.034	1.04434	reuse	0
5	A	OSB2700	2585	1197	6	18.56547	19.44	new	6
	B	OSB2700	415	1067	1	0.442805	1.675	reuse	0
	C	OSB2700	2585	925	1	2.391125	3.24	new	1
	D	OSB2700	2585	913	1	2.360105	3.24	new	1
	E	OSB2700	2585	597	1	1.543245	3.24	new	1
	F	OSB2700	2585	595	1	1.538075	1.558755	reuse	0
6	A	OSB2700	2585	1187	1	3.068395	3.24	new	1
	B	OSB2700	2585	1117	1	2.887445	3.24	new	1
	C	OSB2700	2585	1006	1	2.60051	3.24	new	1
	D	OSB2700	2585	989	1	2.556565	3.24	new	1
	E	OSB2700	2585	897	1	2.318745	3.24	new	1
	F	OSB2700	2585	877	1	2.267045	3.24	new	1
	G	OSB2700	2585	758	1	1.95943	3.24	new	1
	H	OSB2400	457	692	2	0.632488	2.88	new	1
	I	OSB2700	2585	474	1	1.22529	1.538	reuse	0
7	A	OSB2700	2585	1197	3	9.282735	9.72	new	3
	B	OSB2700	2585	998	1	2.57983	3.24	new	1
	C	OSB2700	2585	877	1	2.267045	3.24	new	1
	D	OSB2700	2585	854	1	2.20759	3.24	new	1
	E	OSB2400	457	692	2	0.632488	2.88	new	1
	F	OSB2700	2585	516	1	1.33386	3.24	new	1
	G	OSB2700	2585	470	1	1.21495	1.76814	reuse	0
8	A	OSB2400	457	1817	1	0.830369	2.88	new	1
	B	OSB2700	2585	1187	1	3.068395	3.24	new	1
	C	OSB2700	2585	1035	1	2.675475	3.24	new	1

	D	OSB2700	2585	933	1	2.411805	3.24	new	1
	E	OSB2700	457	917	1	0.419069	0.419069	reuse	0
	F	OSB2700	2585	831	1	2.148135	3.24	new	1
	G	OSB2700	457	692	1	0.316244	0.316244	reuse	0
	H	OSB2700	2585	616	1	1.59236	3.24	new	1
	I	OSB2700	2585	556	1	1.43726	1.50964	reuse	0
	J	OSB2700	2585	427	1	1.103795	1.381	reuse	0
9	A	OSB2700	457	1817	1	0.830369	1.35	reuse	0
	B	OSB2700	2585	1035	1	2.675475	3.24	new	1
	C	OSB2700	2585	1026	1	2.65221	3.24	new	1
	D	OSB2700	457	917	1	0.419069	1.028	reuse	0
	E	OSB2700	2585	831	1	2.148135	3.24	new	1
	F	OSB2700	457	692	2	0.632488	1.219	reuse	0
	G	OSB2700	2585	617	1	1.594945	3.24	new	1
	H	OSB2700	2585	582	1	1.50447	3.24	new	1
	I	OSB2700	2585	527	1	1.362295	3.24	new	1
	J	OSB2700	2585	522	1	1.34937	1.59753	reuse	0
	K	OSB2700	2585	427	1	1.103795	1.507055	reuse	0
10	A	OSB2700	2585	1197	2	6.18849	6.48	new	1
	B	OSB2700	2585	1129	1	2.918465	3.24	new	1
	C	OSB2700	2585	1001	1	2.587585	3.24	new	1
	D	OSB2700	2585	988	1	2.55398	3.24	new	1
	E	OSB2700	457	917	1	0.419069	0.419069	reuse	0
	F	OSB2700	2585	760	1	1.9646	3.24	new	1
	G	OSB2700	2585	711	1	1.837935	3.24	new	1
	H	OSB2700	457	692	1	0.316244	0.365	reuse	0
	I	OSB2700	2585	473	1	1.222705	1.264065	reuse	0
	J	OSB2700	2585	365	1	0.943525	1.1374	reuse	0
11	A	OSB2400	457	1817	1	0.830369	2.88	new	1
	B	OSB2700	2585	1035	1	2.675475	3.24	new	1
	C	OSB2700	2585	933	1	2.411805	3.24	new	1
	D	OSB2700	457	917	1	0.419069	1.417143	reuse	0
	E	OSB2700	2585	831	1	2.148135	3.24	new	1
	F	OSB2700	457	692	2	0.632488	2.722	reuse	0
	G	OSB2700	2585	647	1	1.672495	3.24	new	1
	H	OSB2700	2585	616	1	1.59236	3.24	new	1
	I	OSB2700	2585	582	1	1.50447	1.77	reuse	0
	J	OSB2700	2585	552	1	1.42692	1.50964	reuse	0
	K	OSB2700	2585	427	1	1.103795	1.429505	reuse	0
12	A	OSB2700	2585	1197	3	9.282735	9.72	new	3
	B	OSB2700	2585	877	1	2.267045	3.24	new	1
	C	OSB2700	2585	776	1	2.00596	3.24	new	1
	D	OSB2700	2585	772	1	1.99562	3.24	new	1
	E	OSB2400	457	692	2	0.632488	2.88	new	1
	F	OSB2700	2585	594	1	1.53549	3.24	new	1
	G	OSB2700	2585	548	1	1.41658	1.56651	reuse	0
Required Area m ²			241.635		Used Area m ²	286.2	Offcuts m ²	44.56	15.6 %

Appendix Table 5: Required, Used, and Wasted Areas of Polyethene Vapour Barrier – Factory B

Panel	Panel Length mm	Used Length mm	Panel Width mm	Used Width mm	Used Qty m²	Opening m²	Required Qty m²	Width-side Offcuts m²	Length-side Offcuts m²	
1	9192	9472	2,543	3000	28.416	7.79	15.59	4.20	0.84	
2	8870	9150	2,543	3000	27.45	2.97	19.59	4.05	0.84	
3	8920	9200	2,543	3000	27.6	2.97	19.71	4.08	0.84	
4	9872	10152	2,543	3000	30.456	8.79	16.31	4.51	0.84	
5	9914	10194	2,543	3000	30.582	3.44	21.77	4.53	0.84	
6	9978	10258	2,543	3000	30.774	8.79	16.58	4.56	0.84	
7	8722	9002	2,543	3000	27.006	2.96	19.22	3.99	0.84	
8	6941	7221	2,543	3000	21.663	1.99	15.66	3.17	0.84	
Used Area m²		223.95		Required Area m²		144.44		Offcuts m²	79.51	36%

Appendix Table 6: Brick Slips Required, Used, and Generated Offcuts – Factory B

Required Shape	Required Area	Qty	Total Required	Offcuts	Total Used	%
Full Surface Piece	0.33705	12	4.0446	0	4.0446	0%
Corner Piece	0.20223	4.75	0.9605925	0.050558	1.01115	0.3%
Openings Corner	0.13482	21	2.83122	0.707805	3.539025	3.8%
Vertical Single Strip	0.13482	7	0.94374	0.40446	1.3482	2.2%
Height End	0.26964	11	2.96604	0.74151	3.70755	3.9%
Vertical double Strip	0.26964	4	1.07856	0.26964	1.3482	1.4%
Half Shape Piece	0.168525	4.75	0.80049375	0.842625	1.6431188	4.5%
Horizontal triple lines	0.12639375	7	0.88475625	0.800494	1.68525	4.3%
Single Brick	0.0168525	52	0.87633	0	0.87633	0.0%
Total Required	15.39 m ²	Total Used	19.20 m ²	Total Offcuts	3.82 m ²	20.3%

Appendix Table 7: Timber Batten Sections: Requirements, Usage, Offcuts, and Sources – Factory B

Length	Qty	Total Required	Source	New Section	Used Length	total Length	Offcut	No of offcuts	total offcuts	Sent to
2822	105	296310	New	105	3000	315000	178	105	18690	recycle
2183	12	26196	New	12	3000	36000	817	12	9804	reuse
2123	38	80674	New	38	3000	114000	877	38	33326	reuse
1986	3	5958	new	3	3000	9000	1014	3	3042	reuse
1866	3	5598	new	3	3000	9000	1134	3	3402	reuse
1086	4	4344	New	2	3000	6000	828	2	1656	reuse
589	10	5890	New	2	3000	6000	55	2	110	recycle
529	60	31740	New	12	3000	36000	355	13	4615	recycle
529	3	1587	New	1	3000	3000	1413	1	1413	reuse
966	3	2898	reuse	0	1134	3402	168	3	504	recycle
966	1	966	reuse	0	1014	1014	48	1	48	recycle
861	12	10332	reuse	0	877	10524	16	12	192	recycle
741	12	8892	reuse	0	817	9804	76	12	912	recycle
589	26	15314	reuse	0	877	22802	288	26	7488	recycle
589	2	1178	Reuse	0	1413	1413	235	1	235	recycle
200	3	600	reuse	0	828	828	228	1	228	recycle
Total required	498.5 m			Total Used	534 m		Offcuts	35.5 m		7%

Appendix Table 8: Required, Used, and Wasted Cladding Board Areas – Factory B

Panel	Tag	Height	Width	Qty	Required m ²	Used m ²	Source	Boards	Sent to skip	Kept for reuse	reused
1	A	1197	1802	2	4.313988	5.76	new	2	0	1.446	not reused
	B	440	1802	1	0.79288	2.88	new	1	0	2.087	not reused
2	A	440	2251	1	0.99044	1.824	reuse	-	-	-	-
	B	440	2201	1	0.96844	2.88	new	1	0	1.911	reused in this job
	C	272	1863	1	0.506736	0.768	reuse	-	0.089	0.172	not reused
	D	440	1539	1	0.67716	1.91	reuse	-	0.1152	1.119	not reused
	E	1197	1506	2	3.605364	5.76	new	2	0	2.155	reused in this job
	F	440	1388	1	0.61072	2.88	new	1	0	2.269	not reused
	G	1197	1056	2	2.528064	5.76	new	2	0	3.232	reused in this job
	H	272	963	1	0.261936	0.677	reuse	-	0	-	-
	I	1197	863	2	2.066022	2.155	reuse	-	0.089	0	-
	J	272	738	1	0.200736	0.415	reuse	-	-	0.214	not reused
	K	1197	381	2	0.912114	3.232	reuse	-	0	2.32	not reused
3	A	440	1765	1	0.7766	2.88	new	1	0	2.10	reused in this job
	B	440	1629	1	0.71676	2.103	reuse	-	-	1.387	reused in this job
	C	1197	1628	2	3.897432	5.76	new	2	0	1.86	not reused
	D	440	1628	1	0.71632	2.88	new	1	0	2.16	reused in this job
	E	440	1572	1	0.69168	2.164	reuse	-	-	1.47	not reused
	F	1197	1394	2	3.337236	5.76	new	2	0	2.423	reused in this job
	G	1197	1259	2	3.014046	5.76	new	2	0	2.74	not reused
	H	1197	831	2	1.989414	2.423	reuse	-	-	0.43	not reused
	I	272	738	2	0.401472	1.387	reuse	-	-	0.985	not reused
4	A	1197	1920	2	4.59648	5.76	New	2	0	1.16	not reused
	B	440	1920	1	0.8448	0.845	Reuse	-	0	0	-
	C	440	1766	1	0.77704	1.056	Reuse	-	0	-	-
	D	440	1572	1	0.69168	1.056	Reuse	-	0	-	-
	E	1197	1396	2	3.342024	5.76	New	2	0	2.418	reused in this job
	F	440	1336	1	0.58784	1.056	Reuse	-	0	-	-
	G	1197	966	2	2.312604	2.418	Reuse	-	0	0.1054	not reused
	H	272	738	2	0.401472	0.7	Reuse	-	-	-	-
	I	1197	527	2	1.261638	2.88	New	1	0	1.618	not reused
	J	1197	302	2	0.722988	1.163	Reuse	-	0	0.44	not reused
Total Required			49.51 m ²		Total Used		63.36 m ²		Offcuts		20.45 m ² 33%
Length-side Offcuts			19.3%		Width-side Offcuts		11.1%		Filler Offcuts		2.3%

Appendix Table 9: Required, Used, and Wasted Breather Membrane – Factory B

Length	Required length	Height	Required/Used Height	Required area	Used length	Used area	No of Openings	Opening width	Opening height	Openings area m ²	Openings strip membrane	Total required	Total used
1790	1940	2850	3000	5.82	2490	7.47	1.65	0	0	2100	0	0	5.82
7415	7565	2850	3000	22.695	8115	24.345	1.65	3	3405	2100	7.1505	4.8015	20.346
6627	6777	2850	3000	20.331	7327	21.981	1.65	2	1370	2100	2.877	2.931	20.385
6627	6777	2850	3000	20.331	7327	21.981	1.65	2	1370	2100	2.877	2.931	20.385
7415	7565	2850	3000	22.695	8115	24.345	1.65	3	3405	2100	7.1505	4.8015	20.346
2240	2390	2850	3000	7.17	2940	8.82	1.65	0	0	2100	0	0	7.17
2427	2577	2850	3000	7.731	3127	9.381	1.65	1	685	2100	1.4385	1.4655	7.758
3233	3383	2850	3000	10.149	3933	11.799	1.65	1	910	2100	1.911	1.533	9.771
4940	5090	2850	3000	15.27	5640	16.92	1.65	1	685	2100	1.4385	1.4655	15.297
1150	1300	2850	3000	3.9	1850	5.55	1.65	0	0	2100	0	0	3.9
2559	2709	2850	3000	8.127	3259	9.777	1.65	1	685	2100	1.4385	1.4655	8.154
2240	2390	2850	3000	7.17	2940	8.82	1.65	0	0	2100	0	0	7.17
7415	7565	2850	3000	22.695	8115	24.345	1.65	3	3405	2100	7.1505	4.8015	20.346
6740	6890	2850	3000	20.67	7440	22.32	1.65	2	1370	2100	2.877	2.931	20.724
2015	2165	2850	3000	6.495	2715	8.145	1.65	0	0	2100	0	0	6.495
Total Required			194.067 m²		Total Used		255.13 m²		Waste		61.06 m²		24%

Appendix C: Construction Waste Quantification – Factory C

Appendix Table 10: Timber Lengths Required, Used, and Wasted - Factory C

Panel	Description	Length	Qty	Total Length	Used Timber	Source	offcuts	Qty	Reuse/Recycle	Total waste	Final Status	
All	Vertical stud	2180	106	231080	4800	New	440	53	Sent for recycle	23320	Recycled	
EX1	Bottom Rail	5340	1	5340	5400	New	60	1	Sent for recycle	60	Recycled	
EX1	Top Rail	5340	1	5340	5400	New	60	1	Sent for recycle	60	Recycled	
EX2	Door Header	1540	1	1540	4800	New	3260	1	Sent for reuse	3260	Reused	
EX2	Bottom Rail	3563	1	3563	4800	New	1237	1	Sent for reuse	1237	Reused	
EX2	Top Rail	3563	1	3563	4800	New	1237	1	Sent for reuse	1237	Reused	
EX2	Vertical stud A	108	4	432	440	Reuse	8	1	Sent for recycle	8	Recycled	
EX3	Door Header	1540	1	1540	3260	Reuse	1720	1	Sent for reuse	1720	Reused	
EX3	Bottom Rail	2990	1	2990	4800	New	1810	1	Sent for reuse	1810	Reused	
EX3	Top Rail	2990	1	2990	4800	New	1810	1	Sent for reuse	1810	Reused	
EX3	Vertical stud	108	5	540	600	Reuse	60	1	Sent for recycle	60	Recycled	
EX4	window header	955	1	955	1237	Reuse	282	1	Sent for recycle	282	Recycled	
EX4	Window sill plate	955	1	955	1237	Reuse	282	1	Sent for recycle	282	Recycled	
EX4	Bottom Rail	4815	1	4815	5400	New	585	1	Sent for recycle	585	Recycled	
EX4	Top Rail	4815	1	4815	5400	New	585	1	Sent for recycle	585	Recycled	
EX4	Vertical stud A	108	3	324	440	Reuse	116	1	Sent for recycle	116	Recycled	
EX4	Vertical stud A	796	3	2388	3530	reuse	1142	1	Sent for reuse	1142	Reused	
EX5	Window sill plate	955	1	955	1142	reuse	187	1	Sent for recycle	187	Recycled	
EX5	Bottom Rail	2998	1	2998	4800	New	1802	1	Sent for reuse	1802	Reused	
EX5	Top Rail	2998	1	2998	4800	New	1802	1	Sent for reuse	1802	Reused	
EX5	Window header	955	1	955	1810	Reuse	855	1	Sent for reuse	855	Reused	
EX5	Lintel	1031	3	3093	4800	New	1707	1	Sent for reuse	1707	Reused	
EX5	Vertical stud A	1096	3	3288	4800	New	1512	1	Sent for reuse	1512	Reused	
EX5	Vertical stud A	2058	2	4116	4800	New	684	1	Sent for reuse	684	Reused	
EX6	Bottom Rail	3390	1	3390	4800	New	1410	1	Sent for reuse	1410	Reused	
EX6	Top Rail	3390	1	3390	4800	New	1410	1	Sent for reuse	1410	Reused	
EX6	window header	955	1	955	1410	Reuse	455	1	Sent for recycle	455	Recycled	
EX6	Lintel	1031	3	3093	4800	New	1707	1	Sent for reuse	1707	Reused	
EX6	vertical stud A	758	4	3032	3604	Reuse	572	1	Sent for recycle	572	Recycled	
EX6	Window sill plate	955	2	1910	3219	Reuse	590	2	Sent for recycle	1180	Recycled	
EX6	vertical stud A	2058	2	4116	4800	New	684	1	Sent for reuse	684	Reused	
EX7	Door Header	983	1	983	1410	Reuse	427	1	Sent for recycle	427	Recycled	
EX7	window header	955	1	955	4800	New	3845	1	Sent for reuse	3845	Reused	
EX7	Window sill plate	955	1	955	2890	Reuse	1935	1	Sent for reuse	1935	Reused	
EX7	Bottom Rail	4800	1	4800	4800	New	0	1	-	0	-	
EX7	Top Rail	4800	1	4800	4800	New	0	1	-	0	-	
EX7	Vertical Stud A	108	7	756	855	Reuse	99	1	Sent for recycle	99	Recycled	
EX7	Vertical Stud A	646	3	1938	2391	Reuse	453	1	Sent for recycle	453	Recycled	
EX8	window header	955	1	955	1935	Reuse	980	1	Sent for reuse	980	Reused	
EX8	Window sill plate	955	1	955	980	Reuse	25	1	Sent for recycle	25	Recycled	
EX8	Bottom Rail	3727	1	3727	4800	New	1073	1	Sent for reuse	1073	Waiting reuse	
EX8	Top Rail	3727	1	3727	4800	New	1073	1	Sent for reuse	1073	Waiting reuse	
EX8	Vertical Stud A	108	4	432	440	Reuse	8	1	Sent for recycle	8	Recycled	
EX8	Vertical Stud A	646	4	2584	4800	New	2216	1	Sent for reuse	2216	Waiting reuse	
Required Length		339.026 m		Used Length		372 m		Offcuts		32.974 m		9%

Appendix Table 11: Total OSB Area Used, Required, and Wasted - Factory C

Panel	Thickness	Height	Width	Qty	Used OSB Area	Length-side Offcuts mm	Length-side Offcuts m2	Width-side Offcuts mm	Width-side Offcuts m2	Opening offcuts
EX1	9 mm	2397	1197	4	11.476836	141	0.675108	0	0	0
EX1	9 mm	2397	597	1	1.431009	141	0.084177	60	0.13536	
EX2	9 mm	2397	1197	2	5.738418	141	0.337554	0	0	3.3572
EX2	9 mm	2397	597	1	1.431009	141	0.084177	0	0	
EX2	9 mm	2397	597	1	1.431009	141	0.084177	37	0.083472	
EX3	9 mm	2397	1197	2	5.738418	141	0.337554	0	0	3.3572
EX3	9 mm	2397	597	1	1.431009	141	0.084177	10	0.02256	
EX4	9 mm	2397	1197	3	8.607627	141	0.506331	0	0	1.146
EX4	9 mm	2397	597	1	1.431009	141	0.084177	0	0	
EX4	9 mm	2397	797	1	1.910409	141	0.112377	185	0.41736	
EX5	9 mm	2397	1197	1	2.869209	141	0.168777	0	0	0.8595
EX5	9 mm	2397	1197	1	2.869209	141	0.168777	2	0.004512	
EX5	9 mm	2397	597	1	1.431009	141	0.084177	0	0	
EX6	9 mm	2397	1197	2	5.738418	141	0.337554	0	0	1.146
EX6	9 mm	2397	1197	1	2.869209	141	0.168777	210	0.47376	
EX7	9 mm	2397	1197	4	11.476836	141	0.675108	0	0	3.43219
EX8	9 mm	2397	1197	2	5.738418	141	0.337554	0	0	1.28925
EX8	9 mm	2397	597	1	1.431009	141	0.084177	73	0.164688	
EX8	9 mm	2397	797	1	1.910409	141	0.112377	0	0	
Used Area m ²				76.96	Required Area m ²	56.54	Total Offcuts m ²	20.42	26.5%	

Appendix Table 12: : Total Area of Rigid Insulation Required, Used, and Wasted - Factory C

Panel	Section	Height	Width	Qty	Req Area	Used Area	Source	No Boards	Length-side Offcuts	Area	Status	Width-side Offcuts	Area	Status
EX1	A	2178	560	4	4.879	5.760	New	2	222	0.532		80	0.348	
EX1	A	2178	560	1	1.220	2.880	New	1	222	0.266	Reused	640	1.394	Reused
EX1	B	2178	503	1	1.096	1.394	Reuse	0	0	0		137	0.298	Reused
EX1	C	2178	443	1	0.965	2.880	New	1	222	0.266	Reused	757	1.649	Reused
EX1	D	2178	423	1	0.921	1.649	Reuse	0	0	0		334	0.727	Reused
EX1	D	2178	423	1	0.921	2.880	New	1	222	0.266		777	1.692	Reused
EX1	E	2178	97	2	0.423	0.727	Reuse	0	0	0		140	0.305	
EX2	A	2178	434	1	0.945	1.692	Reuse	0	0	0		343	0.747	Reused
EX2	B	2178	324	1	0.706	0.747	Reuse	0	0	0		19	0.041	
EX2	C	2178	310	1	0.675	2.880	New	1	222	0.266		890	1.938	Reused
EX2	D	2178	220	1	0.479	1.938	Reuse	0	0	0		670	1.459	Reused
EX2	E	2178	165	1	0.359	1.459	Reuse	0	0	0		669	1.457	Reused
EX2	F	2178	102	1	0.222	0.298	Reuse	0	0	0		35	0.076	
EX2	G	106	560	1	0.059	0.266	Reuse	0	116	0.139	Reused	640	0.068	Reused
EX2	H	106	474	1	0.050	0.068	Reuse	0	0	0		166	0.018	
EX2	I	106	348	1	0.037	0.139	Reuse	0	10	0.012		852	0.090	
EX3	A	2178	541	1	1.178	1.457	Reuse	0	0	0		129	0.281	
EX3	B	2178	329	1	0.717	2.880	New	1	222	0.266		871	1.897	Reused
EX3	C	2178	270	1	0.588	1.897	Reuse	0	0	0		601	1.309	Reused
EX3	D	106	560	2	0.119	0.266	Reuse	0	116	0.139	Reused	80	0.008	
EX3	E	106	174	1	0.018	0.139	Reuse	0	10	0.012		1026	0.109	Reused
EX3	F	106	48	1	0.005	0.109	Reuse	0	0	0		978	0.104	Reused
EX4	A	2178	560	2	2.439	2.880	New	1	222	0.266		80	0.174	
EX4	A	2178	560	1	1.220	1.309	Reuse	0	0	0		41	0.089	
EX4	B	2178	527	1	1.148	2.880	New	1	222	0.266		673	1.466	Reused
EX4	C	2178	518	1	1.128	1.466	Reuse	0	0	0		155	0.338	
EX4	D	2178	360	1	0.784	2.880	New	1	222	0.266		840	1.830	Reused
EX4	E	2178	267	1	0.582	1.830	Reuse	0	0	0		573	1.248	Reused
EX4	F	794	460	1	0.365	2.880	New	1	1606	1.927	Reused	740	0.588	Reused
EX4	G	794	377	1	0.299	0.588	Reuse	0	0	0		363	0.288	
EX4	H	106	460	1	0.049	0.104	Reuse	0	0	0		518	0.055	Reused
EX4	I	106	377	1	0.040	0.055	Reuse	0	0	0		141	0.015	
EX5	A	2178	560	1	1.220	1.248	Reuse	0	0	0		13	0.028	
EX5	B	2178	533	1	1.161	2.880	New	1	222	0.266		667	1.453	Reused
EX5	C	2178	503	1	1.096	1.453	Reuse	0	0	0		164	0.357	Reused
EX5	D	2178	59	1	0.129	0.357	Reuse	0	0	0		105	0.229	
EX5	E	1094	452	1	0.494	1.927	Reuse	0	512	0.614		748	0.818	Reused
EX5	F	1094	385	1	0.421	0.818	Reuse	0	0	0		363	0.397	
EX6	A	2178	527	1	1.148	2.880	New	1	222	0.266		673	1.466	Reused
EX6	B	2178	326	1	0.710	1.466	Reuse	0	0	0		347	0.756	Reused
EX6	C	2178	291	1	0.634	0.756	Reuse	0	0	0		56	0.122	

EX6	D	2178	286	1	0.623	2.880	New	1	222	0.266		914	1.991	Reused
EX6	E	2178	241	1	0.525	1.991	Reuse	0	0	0		673	1.466	Reused
EX6	F	2178	182	1	0.396	1.466	Reuse	0	0	0		491	1.069	Reused
EX6	G	2178	74	1	0.161	1.069	Reuse	0	0	0		417	0.908	
EX6	H	756	560	1	0.423	2.880	New	1	1644	1.973	Reused	640	0.484	Reused
EX6	I	756	148	1	0.112	0.484	Reuse	0	0	0		492	0.372	Reused
EX6	J	756	89	1	0.067	0.372	Reuse	0	0	0		403	0.305	
EX7	A	2178	560	1	1.220	2.880	New	1	222	0.266		640	1.394	Reused
EX7	B	2178	407	1	0.886	1.394	Reuse	0	0	0		233	0.507	
EX7	C	2178	288	1	0.627	2.880	New	1	222	0.266	Reused	912	1.986	Reused
EX7	D	2178	284	1	0.619	1.986	Reuse	0	0	0		628	1.368	Reused
EX7	E	2178	281	1	0.612	1.368	Reuse	0	0	0		347	0.756	Reused
EX7	F	2178	203	1	0.442	0.756	Reuse	0	0	0		144	0.314	Reused
EX7	G	2178	72	1	0.157	0.314	Reuse	0	0	0		72	0.157	Reused
EX7	H	2178	67	1	0.146	0.157	Reuse	0	0	0		5	0.011	
EX7	I	644	460	1	0.296	1.973	Reuse	0	1000	1.2	Reused	740	0.477	Reused
EX7	J	644	377	1	0.243	0.477	Reuse	0	0	0		363	0.234	
EX7	K	106	560	1	0.059	0.266	Reuse	0	116	0.139	Reused	640	0.068	Reused
EX7	L	106	460	1	0.049	0.068	Reuse	0	0	0		180	0.019	
EX7	M	106	377	1	0.040	0.139	Reuse	0	10	0.012		823	0.087	Reused
EX7	N	106	144	1	0.015	0.087	Reuse	0	0	0		679	0.072	Reused
EX7	O	106	121	1	0.013	0.072	Reuse	0	0	0		558	0.059	
EX8	A	2178	527	1	1.148	2.880	New	1	222	0.266		673	1.466	Reused
EX8	B	2178	430	1	0.937	1.466	Reuse	0	0	0		243	0.529	Reused
EX8	C	2178	430	1	0.937	2.880	New	1	222	0.266	Reused	770	1.677	Reused
EX8	D	2178	288	1	0.627	1.677	Reuse	0	0	0		482	1.050	Reused
EX8	E	2178	223	1	0.486	1.050	Reuse	0	0	0		259	0.564	Reused
EX8	F	2178	170	1	0.370	0.564	Reuse	0	0	0		89	0.194	
EX8	G	2178	158	1	0.344	0.529	Reuse	0	0	0		85	0.185	
EX8	H	644	360	1	0.232	1.200	Reuse	0	356	0.427		840	0.541	Reused
EX8	I	644	223	1	0.144	0.541	Reuse	0	0	0		617	0.397	Reused
EX8	J	644	214	1	0.138	0.397	Reuse	0	0	0		403	0.260	
EX8	K	106	360	1	0.038	0.266	Reuse	0	116	0.139		840	0.089	Reused
EX8	L	106	223	1	0.024	0.089	Reuse	0	0	0		617	0.065	Reused
EX8	M	106	214	1	0.023	0.065	Reuse	0	0	0		403	0.043	
Required Area m ²		44.83		Used Area m ²		54.72		Total Offcuts m ²		9.89		18%		

Appendix Table 13: Total Area of Breather Membrane Required, Used, and Overused - Factory C

Panel	Height	Req Height	Used Height	Length	Req Length	Used Length	Openings	Total Req	Used Area	Width-side Overuse	Length-side Overuse	Opening Offcuts
EX1	2256	2406	2700	5340	5490	5640	0	13.21	15.23	1.658	0.3384	3.36
EX2	2256	2406	2700	3563	3713	3863	3.36	5.57	10.43	1.136	0.3384	3.36
EX3	2256	2406	2700	2990	3140	3290	3.36	4.20	8.88	0.967	0.3384	1.146
EX4	2256	2406	2700	4815	4965	5115	1.146	10.80	13.81	1.504	0.3384	0.86
EX5	2256	2406	2700	2998	3148	3298	0.86	6.71	8.90	0.97	0.3384	1.146
EX6	2256	2406	2700	3390	3540	3690	1.146	7.37	9.96	1.085	0.3384	3.43
EX7	2256	2406	2700	4800	4950	5100	3.43	8.48	13.77	1.5	0.3384	1.29
EX8	2256	2406	2700	3727	3877	4027	1.29	8.04	10.87	1.184	0.3384	3.36
Required Area m ²		64.385		Used Area m ²		91.86		Wasted Area m ²		27.3		30%

Appendix D: Construction Waste Quantification – Factory D

Appendix Table 14: Timber Lengths Required, Used, and Wasted - Factory D

Panel	Description	Qty	Width	Depth	Length	Required	Used	Offcuts	Qty	Total Offcuts	Status
EX1	Noggin	2	38	140	543	1086	651	108	2	216	Sent to recycling
	Noggin	2	38	140	543	1086	1200	114	1	114	Sent to recycling
	T/B plate	2	38	140	1200	2400	3600	1200	1	1200	Directly Reused
	Stud	3	38	140	2949	8847	3600	651	3	1953	Directly Reused
EX2	Noggin	2	38	140	543	1086	651	108	2	216	Sent to recycling
	Noggin	2	38	140	543	1086	1200	114	1	114	Sent to recycling
	T/B plate	2	38	140	1200	2400	3600	1200	1	1200	Directly Reused
	Stud	3	38	140	2949	8847	3600	651	3	1953	Directly Reused
EX3	Noggin	2	38	140	188	376	450	74	1	74	Sent to recycling
	Noggin	2	38	140	196	392	842	450	1	450	Directly Reused
	Noggin	2	38	140	422	844	1686	842	1	842	Directly Reused
	T/B plate	2	38	140	957	1914	3600	1686	1	1686	Directly Reused
	Stud	5	38	140	2949	14745	3600	651	5	3255	Kept for reuse
EX4	Cripple	1	38	140	900	900	1216	316	1	316	Sent to recycling
	Cripple	1	38	140	900	900	1368	468	1	468	Kept for reuse
	Stud	3	38	140	924	2772	3600	828	1	828	Kept for reuse
	Stud	3	38	140	1049	3147	3600	453	1	453	Kept for reuse
	Sill	2	38	140	1116	2232	3600	1368	1	1368	Directly Reused
	T/B plate	2	38	140	1192	2384	3600	1216	1	1216	Directly Reused
	Stud	2	38	140	2949	5898	3600	651	2	1302	Directly Reused
EX5	Noggin	2	38	140	460	920	651	191	2	382	Sent to recycling
	T/B plate	2	38	140	536	1072	651	115	2	230	Sent to recycling
	Stud	2	38	140	2949	5898	3600	651	2	1302	Directly Reused
EX6	Noggin	4	38	140	356	1424	1948	524	1	524	Kept for reuse
	T/B plate	2	38	140	826	1652	3600	1948	1	1948	Directly Reused
	Stud	3	38	140	2949	8847	3600	651	3	1953	Kept for reuse
EX7	Cripple	1	38	140	900	900	1368	468	1	468	Kept for reuse
	Cripple	1	38	140	900	900	1216	316	1	316	Directly Reused
	Stud	3	38	140	924	2772	3600	828	1	828	Directly Reused
	Stud	3	38	140	1049	3147	3600	453	1	453	Kept for reuse
	Sill	2	38	140	1116	2232	3600	1368	1	1368	Directly Reused
	T/B plate	2	38	140	1192	2384	3600	1216	1	1216	Directly Reused
	Stud	2	38	140	2949	5898	3600	651	2	1302	Kept for reuse
EX8	Noggin	1	38	140	140	140	316	176	1	176	Sent to recycling
	Noggin	2	38	140	357	714	828	114	1	114	Sent to recycling
	Noggin	2	38	140	551	1102	1200	98	1	98	Sent to recycling
	T/B plate	2	38	140	1200	2400	3600	1200	1	1200	Directly Reused
	Stud	1	38	140	1436	1436	3600	2164	1	2164	Directly Reused
	Stud	5	38	140	2949	14745	3600	651	5	3255	Kept for reuse
EX9	Noggin	2	38	140	82	164	216	134	2	268	Sent to recycling
	Noggin	2	38	140	423	846	651	228	2	456	Sent to recycling
	Noggin	2	38	140	543	1086	1200	114	1	114	Sent to recycling
	T/B plate	2	38	140	1200	2400	3600	1200	1	1200	Directly Reused
	Stud	1	38	140	1436	1436	2164	728	1	728	Kept for reuse
	Stud	5	38	140	2949	14745	3600	651	5	3255	Kept for reuse
EX10	Noggin	2	38	140	543	1086	651	108	2	216	Sent to recycling
	Noggin	2	38	140	543	1086	1200	114	1	114	Directly Reused
	T/B plate	2	38	140	1200	2400	3600	1200	1	1200	Directly Reused
	Stud	3	38	140	2949	8847	3600	651	3	1953	Directly Reused
Required Length		156.021 m		Used Length		176.4 m		Offcuts		20.379 m	11.6%

Appendix Table 15: Total OSB Area Used, Required, and Wasted - Factory D

Panel	Lbl	Qty	Width	Height	Req	Used Dim	New Board	Length-side Offcuts	Status	Width-side Offcuts	Status
EX1	D	1	1200	625	0.75	1200 x 2400	1	1200 x 1775	Integrated	-	-
	E	1	1200	2400	2.88	1200 x 2400	1	-		-	-
EX2	D	1	1200	625	0.75	1200 x 1775	0	1200 x 1150	Integrated	-	-
	E	1	1200	2400	2.88	1200 x 2400	1	-		-	-
EX3	F	1	957	625	0.6	1200 x 2400	1	1200 x 1775	Integrated	243 x 625	-
	G	1	957	2400	2.297	1200 x 2400	1	-		243 x 2400	-
EX4	I	1	1040	1000	1.04	1200 x 2400	1	1200 x 1400	Integrated	160 x 1000	-
	J	1	1040	1125	1.17	1200 x 1400	0	1040 x 75		160 x 1400	-
EX5	D	1	536	625	0.335	1200 x 1150	0	1200 x 525		664 x 625	-
	E	1	536	2400	1.286	1200 x 2400	1	-		664 x 2400	-
EX6	D	1	826	625	0.516	1200 x 1175	0	1200 x 1150	Integrated	374 x 625	-
	E	1	826	2400	1.982	1200 x 2400	1	-		374 x 1200	-
EX7	I	1	1040	1000	1.04	1200 x 2400	1	1200 x 1400	Integrated	160 x 1000	-
	J	1	1040	1125	1.17	1200 x 1400	0	1040 x 75		160 x 1400	-
EX8	G	1	1200	625	0.75	1200 x 1150	0	1200 x 525		-	-
	H	1	1200	2400	2.88	1200 x 2400	1	-		-	-
EX9	G	1	1200	625	0.75	1200 x 2400	1	1200 x 1775	Integrated	-	-
	H	1	1200	2400	2.88	1200 x 2400	1	-		-	-
EX10	D	1	1200	625	0.75	1200 x 1775	0	1200 x 1150		-	-
	E	1	1200	2400	2.88	1200 x 2400	1	-		-	-
Used Area m ²		37.44	Required Area m ²		29.58	Total Offcuts m ²		7.86	21%		

Appendix E: Summary of Activity-level Analysis

Appendix Table 16: Summary of Activity-Level Analysis: How, How Much, and Why Material waste is Generated

Factory	Component	Waste Outcome	Observed at	How?	How much?	Why?
A	Structural Frame	Avoidance	Whole	By using pre-finished frame components	0.0%	Waste transfer by outsourcing
A	Plasterboard	Reduction	Ceiling	By using plasterboard sizes closely match ceiling dimensions	1.0%	Standard Size Alignment
A	Plasterboard	Avoidance	Wall	By using plasterboard sizes that match the required wall dimensions	0.0%	Standard Size Alignment
A	Plasterboard	Generation	Openings	By cutting out the plasterboard layer fitted over the openings	12.0%	Lack of Cut Planning
A	Rigid Insulation Board	Reduction	Width-side	By consistently integrating offcuts from one module into the next	2.0%	Effective Manual Nesting
A	Rigid Insulation Board	Avoidance	Length-side	By using rigid insulation panel sizes that match module dimensions	0.0%	Standard Size Alignment
A	Plywood Decking	Reduction	Length-side	By consistently integrating offcuts from one module into the next	3.0%	Effective Manual Nesting
A	Plywood Decking	Avoidance	Width-side	By consistently integrating offcuts from one module into the next	0.0%	Effective Manual Nesting
A	Wall Framing Components	Avoidance	Whole	By using pre-finished frame components	0.0%	Waste transfer by outsourcing
A	Rockwool Insulation	Generation	Whole	By slightly overfilling the cavities with more insulation than required	7.0%	Manual Work Inaccuracies
A	Roof Sheets	Avoidance	Length-side	By using panel lengths that precisely match module dimensions	0.0%	Custom-Size Ordering
A	Roof Sheets	Avoidance	Width-side	By using panel width that matches module dimensions	0.0%	Standard Size Alignment
A	Cladding Panels	Generation	Width-side	By using a full-width cladding panel to cover the final section	11.0%	Lack of custom-size ordering
A	Cladding Panels	Avoidance	Length-side	By using cladding panel width that matches module dimensions	0.0%	Custom-Size Ordering
A	Cladding Panels	Generation	Openings	By cutting out the cladding layer fitted over the openings	15.0%	Lack of Cut Planning
B	Timber Framing	Generation	435 mm	By using a timber section that spans more than two stud spaces	4.1%	Lack of custom-size ordering
B	Timber Framing	Generation	2290 mm	By using a timber section that spans more than one stud space	3.1%	Poor choice of material size
B	Timber Framing	Generation	50 mm	By conducting a trim cut to the new timber sections	0.9%	Inconsistent Material Quality
B	Timber Framing	Generation	Others	By cutting different lengths of different timber sections	4.8%	Lack of Effective Nesting
B	OSB Sheathing	Generation	Length-side	By using OSB boards larger than the required panel height	5.6%	Limited Standard Size Alignment
B	OSB Sheathing	Generation	Width-side	By cutting OSB sheets into irregular sizes for non-uniform stud spacing	6.6%	Limited Standard Size Alignment
B	OSB Sheathing	Generation	Infill	By cutting the opening infill pieces (i.e., door/window headers)	3.3%	Lack of Effective Nesting
B	OSB Sheathing	Avoidance	Openings	By cutting and fitting the required OSB cuts around the openings	0.0%	Cut Planning Adoption

B	Vapour Barrier	Generation	Width-side	By using standard polyethene sheet width bigger than required	15.0%	Lack of custom-size ordering
B	Vapour Barrier	Generation	Length-side	By using polyethene sheet length bigger than required	3.0%	Manual Work Inaccuracies
B	Vapour Barrier	Generation	Openings	By cutting out the polyethene layer fitted over the openings	18.0%	Lack of precision-adaptive application
B	Rockwool Insulation	Generation	Whole	By slightly overfilling the cavities with more insulation than required	8.8%	Manual Work Inaccuracies
B	Brick Slip Panel	Generation	Half Brick	By using oversized corner brick slips at openings	3.8%	Lack of custom-size ordering
B	Brick Slip Panel	Generation	Others	By cutting different sizes out of the standard brick slip shape	16.5%	Lack of Effective Nesting
B	Timber Battens	Generation	178 mm	By using timber sections (3000 mm) larger than required (2822 mm)	3.5%	Limited Standard Size Alignment
B	Timber Battens	Reduction	Others	By consistently integrating offcuts from one section into the next	3.5%	Effective Manual Nesting
B	Cladding Boards	Generation	Length-side	By cutting the panel length into random sizes to fit varying inter-stud spaces	19.3%	Limited Standard Size Alignment
B	Cladding Boards	Generation	Width-side	By using standard boards with a width multiple slightly smaller than the required	11.1%	Limited Standard Size Alignment
B	Cladding Boards	Generation	Infill	By cutting the opening infill pieces (i.e., door/window headers)	2.3%	Lack of Effective Nesting
B	Cladding Boards	Avoidance	Openings	By cutting and fitting the required cladding board cuts around the openings	0.0%	Cut Planning Adoption
B	Breather Membrane	Generation	Length-side	By using more membrane overlap than required	7.0%	Manual Work Inaccuracies
B	Breather Membrane	Avoidance	Width-side	By using breather membrane width that matches the required panel height	0.0%	Standard Size Alignment
B	Breather Membrane	Generation	Openings	By cutting out the membrane layer that was initially fitted over the openings.	14.0%	Lack of precision-adaptive application
B	Breather Membrane	Avoidance	Others	By cutting 2700 mm membrane roll precisely into the 300 mm as required	0.0%	Effective Manual Nesting
C	Timber Framing	Generation	430 mm	By using a timber section that spans more than two stud spaces	6.3%	Lack of custom-size ordering
C	Timber Framing	Generation	25 mm	By conducting a trim cut to the new timber sections	0.5%	Inconsistent Material Quality
C	Timber Framing	Generation	Others	By cutting different lengths of different timber sections	2.1%	Lack of Effective Nesting
C	OSB Sheathing	Generation	Length-side	By using OSB boards larger than the required panel height	6.0%	Limited Standard Size Alignment
C	OSB Sheathing	Reduction	Width-side	By cutting the last OSB board in each panel only	2.0%	Standard Size Alignment
C	OSB Sheathing	Generation	Openings	By cutting out the OSB layer fitted over the openings	19.0%	Lack of Cut Planning
C	Rigid Insulation Board	Generation	Length-side	By using full-length panels of 2400 mm which more than the required 2178 mm	8.0%	Lack of custom-size ordering
C	Rigid Insulation Board	Generation	Width-side	By cutting various widths required to fit the varying panel cavity sizes	10.0%	Lack of Effective Nesting
C	Breather Membrane	Generation	Length-side	By using more membrane overlap than required	3.0%	Manual Work Inaccuracies
C	Breather Membrane	Generation	Width-side	By using a standard membrane width bigger than required	11.0%	Lack of custom-size ordering

C	Breather Membrane	Generation	Openings	By cutting out the membrane layer that was initially fitted over the openings.	16.0%	Lack of precision-adaptive application
D	Timber Framing	Generation	646 mm	By cutting 2949 mm stud out of 3600 mm timber	7.4%	Poor choice of material size
D	Timber Framing	Generation	20 mm	By conducting a trim cut to the new timber sections	0.6%	Inconsistent Material Quality
D	Timber Framing	Generation	Others	By cutting different lengths of different timber sections	3.6%	Lack of Effective Nesting
D	OSB Sheathing	Generation	Length-side	Offcuts generated from cutting the length-side of sheathing boards	8.0%	Limited Standard Size Alignment
D	OSB Sheathing	Generation	Width-side	Offcuts generated from cutting the width-side sheathing boards	13.0%	Limited Standard Size Alignment
D	OSB Sheathing	Avoidance	Openings	By cutting and fitting the required OSB cuts around the openings	0.0%	Cut Planning Adoption
D	Rockwool Insulation	Generation	Whole	Overstuffing rock wool insulation into wall cavities	9.0%	Manual Work Inaccuracies

Appendix F: Observation Notes

Observation Sheets: Factory A

General Information	
Factory	A
Session	A01
Component Observed	Structural Frame Components
Date & Time	14 August 2024, 12:00 pm
Product Type	Steel Frame Modular
Material Waste-Generation Description	
No waste generation was observed, as these components are outsourced and only arrive at the factory for assembly. Observations indicate that outsourcing enables the commissioning of complex assembly manufacturing to specialised manufacturers, which in turn enhances production speed and overall production flow.	

General Information	
Factory	A
Session	A02
Component Observed	Floor Decking
Date & Time	15 August 2024, 10:30 pm
Product Type	Steel Frame Modular
Material Waste-Generation Description	
For floor decking, 18 mm-thick, 1200 mm-wide, and 2400 mm tongue-and-groove plywood sheets were used. Two waste-related instances were identified: 1. Length-side cutting: Each module required two and more than a half plywood boards. The remaining offcut was directly reused as a starting piece for the same module. This indicates that workers had sufficient experience to implement efficient material nesting without compromising production efficiency. 2. Width-side cutting: Each module required two and a half boards across the width. The remaining half-boards were reused as starting pieces for subsequent modules. This practice reflects an efficient design approach that accounts for standard material sizes or their multiples.	

General Information	
Factory	A
Session	A03
Component Observed	Roof Sheet
Date & Time	15 August 2024, 11:45 pm
Product Type	Steel Frame Modular
Material Waste-Generation Description	
For the roof, 100 mm-thick and 1000 mm-wide Kingspan roof sheets were used. Two instances of waste avoidance were identified: 1. Length-side offcut avoidance: Roof sheet sections were ordered and delivered in the exact required lengths, eliminating the need for factory cutting. This approach avoided material waste and enhanced production flow. 2. Width-side offcut avoidance: Each module required exactly three sheets across the width. Consequently, no width-wise cutting was necessary, preventing offcuts and further promoting production flow. This practice reflects an efficient design approach that accounts for standard material sizes.	

General Information	
Factory	A
Session	A04
Component Observed	Rigid Insulation Panels
Date & Time	15 August 2024, 12:30 pm
Product Type	Steel Frame Modular
Material Waste-Generation Description	
As an external sheathing layer, rigid insulation panels measuring 50 mm in thickness, 1220 mm in width, and 3000 mm in length were used. Two instances of waste avoidance/reduction were identified: 1. Width-side offcut reduction: Each module required five panels plus a small strip of rigid insulation. The remaining offcut was directly reused as a starting piece for the subsequent module. This indicates that workers possessed sufficient experience to implement efficient material nesting without compromising production efficiency. 2. Length-side offcut avoidance: The standard lengths of the rigid insulation panels used in this project exactly matched the specified module width, eliminating the need for cutting and thereby promoting production flow. This practice reflects an efficient design approach that accounts for standard material sizes.	

General Information	
Factory	A
Session	A05
Component Observed	Rockwool Insulation
Date & Time	16 August 2024, 11:00 pm
Product Type	Steel Frame Modular
Material Waste-Generation Description	
Rockwool insulation was supplied in 150 mm-thick, 1160 mm-wide, and 6065 mm-long rolls for the roof and floor, and 50 mm-thick, 600 mm-wide, and 1200 mm-long blocks for the walls. The primary source of material loss was overstuffing, whereby more insulation was installed than required to fill the cavities. Observations indicated that workers did not spend time on precise measurements; instead, they applied a positive tolerance to ensure that minimum insulation requirements were met quickly and efficiently. Consequently, additional rockwool insulation was consumed due to limited installation precision and the operational need to maintain production speed.	

General Information	
Factory	A
Session	A06
Component Observed	Plasterboard
Date & Time	16 August 2024, 12:00 pm
Product Type	Steel Frame Modular
Material Waste-Generation Description	
Different plasterboard sizes were used to finish the module ceilings and walls. Boards of 2700 mm length were used for the walls, while 3000 mm-long boards were used for the ceilings. The observed waste-related instances are summarised as follows: 1. Ceiling plasterboard offcut reduction: Only negligible offcuts were generated, as the supplied plasterboard sizes closely matched the design requirements. This reflects a design-aware approach that aligns layouts with standard material sizes, thereby promoting material efficiency and enhancing production flow. 2. Length- and width-side wall plasterboard offcuts avoidance: No waste was generated in either the length or width directions, as the supplied plasterboard sizes exactly matched the design specifications, eliminating the need for further cutting. This reflects an efficient design approach that considers standard material sizes, supporting both material efficiency and production flow. 3. Wall opening-related plasterboard offcuts: Significant offcuts were generated around openings (e.g. windows and doors). The assembly process involved installing full boards across openings and subsequently cutting out the plasterboard covering these areas. This practice can be attributed to a lack of detailed design information for plasterboard layouts around openings. However, although this approach causes significant offcut generation, it is more productive, as it avoids time-consuming pre-cutting and assembly around openings, which would otherwise prioritise material efficiency over production flow.	

General Information	
Factory	A
Session	A07
Component Observed	Cladding Panels
Date & Time	16 August 2024, 02:15 pm
Product Type	Steel Frame Modular
Material Waste-Generation Description	
This composite insulation layer was supplied in 100 mm thickness and 1190 mm width. The observed waste-related instances are summarised as follows: 1. Length-side cladding panel offcut avoidance: No waste was generated in the length direction, as the supplied panel sizes were specially sourced to match the design specifications, eliminating the need for further cutting. This reflects an efficient procurement approach that aligns material supply with design requirements where feasible, thereby supporting both material efficiency and production flow. 2. Width-side cladding panel offcuts: Significant offcuts were generated from the final panel required to achieve the specified module height. Unlike the length direction, custom-sized panels were not sourced to avoid these offcuts. 3. Cladding panel opening-related offcuts: Significant offcuts were generated around openings (e.g. windows and doors). The assembly process involved installing full panels across openings and subsequently cutting out the material covering these areas. This practice can be attributed to a lack of detailed design information for cladding layouts around openings.	

Observation Sheets: Factory B

General Information	
Factory	B
Session	B01
Component Observed	Timber Framing
Date & Time	19 August 2024, 09:00 am
Product Type	Timber Frame Panelised
Material Waste-Generation Description	
Timber frame sections were produced using 4800 mm and 5400 mm timber lengths. The observed waste-related instances are summarised as follows: 1. 50 mm offcuts: A significant number of timber offcuts of approximately 50 mm were observed. The apparent purpose of this consistent trimming practice was to ensure a square and clean starting edge without requiring additional inspection or extensive measurement. 2. 435 mm offcuts: A substantial number of offcuts of approximately 435 mm were generated when cutting two studs of 2453 mm from 5400 mm timber lengths. These offcuts could have been reduced if 5100 mm standard timber lengths had been available. 3. 2290 mm offcuts: A considerable number of offcuts of approximately 2290 mm were generated when cutting a single stud of 2453 mm from 4800 mm timber lengths. These offcuts could have been avoided if 5400 mm timber lengths had been available at the time of cutting. However, an apparent logistics delay necessitated the use of 4800 mm timber in order to maintain the production schedule. 4. Other offcuts: Additional offcuts of varying sizes were observed throughout the production session. These appear to result from a prioritisation of cutting speed over the integration of cuts to improve material efficiency.	

General Information	
Factory	B
Session	B02
Component Observed	OSB Boards
Date & Time	19 August 2024, 11:00 am
Product Type	Timber Frame Panelised
Material Waste-Generation Description	
The standard dimensions of the OSB boards used were 9 mm in thickness, 1200 mm in width, and 2400 mm and 2700 mm in length. The observed waste-related instances are summarised as follows: 1. Length-side OSB board offcuts: A significant number of OSB strips of approximately 115 mm were consistently generated. These offcuts were primarily driven by the need to achieve the required panel height specified by the design. This indicates an apparent misalignment between the design dimensions and standard OSB board lengths. 2. Width-side OSB board offcuts: A substantial number of offcuts of varying widths were generated due to the requirement to cut OSB boards into different widths to match design-specified sections. The main constraint on the width side was the presence of structural openings, which were not designed in alignment with the standard OSB width or its multiples. 3. Opening infill OSB offcuts: Additional offcuts were generated when cutting OSB boards to form door and window headers. As these sections had to be produced sequentially in line with the production schedule, limited attention was given to material nesting, resulting in increased offcut generation. 4. OSB opening offcut avoidance: In contrast, offcuts around window and door openings were entirely avoided where detailed shop drawings were provided and pre-cutting activities were carried out to fabricate and assemble smaller sections around the openings. This highlights the effectiveness of detailed design information and pre-planning in preventing offcut generation.	

General Information	
Factory	B
Session	B03
Component Observed	Vapour Barrier
Date & Time	21 August 2024, 02:00 pm
Product Type	Timber Frame Panelised
Material Waste-Generation Description	
The standard width of the polyethene vapour barrier used was 3000 mm. The observed waste-related instances are summarised as follows: 1. Width-side vapour barrier offcuts: Approximately 500 mm-wide offcuts were consistently generated due to a mismatch between the designed panel height and the supplied polyethene width. The apparent cause of this waste was the lack of procurement coordination to source custom-width polyethene roll, likely due to cost or lead-time constraints. 2. Length-side vapour barrier offcuts: Approximately 250 mm of offcuts were consistently generated in the length direction. This waste is attributed to the practice of rapidly unrolling the vapour barrier with a positive tolerance to ensure full coverage, followed by fixing the far end without undertaking precise measurement, in order to maintain production speed. 3. Vapour barrier opening-related offcuts: After the entire panel was covered and the vapour barrier was fixed around the edges, the material covering window and door openings was cut out, generating significant offcuts.	

General Information	
Factory	B
Session	B04
Component Observed	Rockwool Insulation
Date & Time	20 August 2024, 12:00 pm
Product Type	Timber Frame Panelised
Material Waste-Generation Description	
Rockwool insulation was supplied in 100 mm thickness, 600 mm width, and 1200 mm length. The primary source of insulation volume loss was overstuffing, whereby more material was installed than required to fill the cavities. Observations indicated that workers did not allocate time for precise measurement; instead, a positive tolerance was applied to ensure that minimum insulation requirements were met quickly and efficiently. Consequently, additional rockwool insulation was consumed due to limited installation precision and the operational need to maintain production speed.	

General Information	
Factory	B
Session	B05
Component Observed	Brick Slips
Date & Time	21 August 2024, 12:00 pm
Product Type	Timber Frame Panelised
Material Waste-Generation Description	
Brick slips were used as a false brick façade layer, with each slip comprising 20 standard-sized bricks (equivalent to approximately one-third of a square metre). The observed waste-related instances are summarised as follows: 1. Half-brick façade corner offcuts: These offcuts were consistently generated in the form of half-brick pieces. The primary cause was the need to cut return bricks to fit around openings and corners. Such offcuts could have been avoided if custom-shaped brick slips had been sourced from the supplier, which would both eliminate waste generation and enhance production flow. 2. Other brick slip offcuts: A substantial number of offcuts were generated, many of which were retained for potential future reuse. However, due to time pressures to complete the work, only a minimal proportion of these offcuts were reintegrated into subsequent assemblies. The accumulation of waste appears to result from limited emphasis on material nesting, which was treated as a lower priority than maintaining production speed.	

General Information	
Factory	B
Session	B06
Component Observed	Timber Battens
Date & Time	20 August 2024, 02:00 pm
Product Type	Timber Frame Panelised
Material Waste-Generation Description	
Timber batten sections measuring 60 × 35 mm and 3000 mm in length were used to provide a ventilated cavity and support for the external cladding layer. The observed waste-related instances are summarised as follows: 1. 178 mm offcuts: These offcuts were consistently generated due to the need to achieve the panel height specified by the design. This indicates an apparent misalignment between the design dimensions and the standard timber batten length. 2. Other offcuts: Additional offcuts of varying lengths were generated as the batten sections were produced sequentially in line with the production schedule. As a result, limited attention was given to material nesting, leading to increased offcut generation.	

General Information	
Factory	B
Session	B07
Component Observed	Cladding Boards
Date & Time	19 August 2024, 02:00 pm
Product Type	Timber Frame Panelised
Material Waste-Generation Description	
The standard dimensions of the cladding boards used were 9 mm in thickness, 1200 mm in width, and 2400 mm and 2700 mm in length. The observed waste-related instances are summarised as follows: 1. Length-side cladding board offcuts: A substantial number of offcuts of varying lengths were generated due to the need to cut cladding boards to match design-specified sections. The main constraint in the length direction was the presence of structural openings, which were not designed in alignment with the standard cladding board lengths or their multiples. 2. Width-side cladding board offcuts: Significant quantities of cladding board offcuts of approximately 760 mm were consistently generated. These offcuts were primarily driven by the requirement to achieve the panel height specified by the design. This indicates an apparent misalignment between the design dimensions and the standard cladding board width or its multiples. 3. Opening infill cladding board offcuts: Additional offcuts were generated when cutting cladding boards to form door and window headers. As these sections had to be produced sequentially in line with the production schedule, limited attention was given to material nesting, resulting in increased offcut generation. 4. Cladding board opening offcut avoidance: In contrast, offcuts around window and door openings were entirely avoided where detailed shop drawings were provided and pre-cutting activities were undertaken to fabricate and assemble smaller sections around the openings. This highlights the effectiveness of detailed design information and pre-planning in preventing offcut generation.	

General Information	
Factory	B
Session	B08
Component Observed	Breather Membrane
Date & Time	20 August 2024, 11:00 am
Product Type	Timber Frame Panelised
Material Waste-Generation Description	
The standard breather membrane roll width used was 3000 mm. The observed waste-related instances are summarised as follows: 1. Width-side breather membrane excess overlap avoidance: This form of waste was entirely avoided, as the 3000 mm-wide breather membrane matched the required panel height of 2850 mm, allowing for a controlled overlap of 150 mm. The avoidance of waste in this case is attributed to effective design alignment with the standard membrane roll width. 2. Length-side breather membrane excess overlap: Waste was generated along the panel length where the membrane was cut with a greater overlap than required, exceeding the standard 150 mm overlap on each side. In practice, overlaps of approximately 350 mm were applied on both sides, resulting in an excess of around 400 mm of membrane per panel in vertical overlaps. This waste is attributed to the practice of rapidly unrolling the membrane with a positive tolerance to ensure full coverage, followed by fixing the far end without precise measurement, in order to maintain production speed. 3. Breather membrane opening-related offcuts: After the entire panel was covered and the breather membrane was fixed around the edges, the material covering window and door openings was cut out, generating significant offcuts. 4. Breather membrane opening overlap offcut avoidance: In contrast, 300 mm-wide membrane strips were installed around window and door frames to ensure appropriate overlaps. These strips were prepared in a manner that generated zero offcuts, demonstrating efficient material use. Specifically, a 2700 mm-wide membrane roll was cut into nine strips, each 300 mm wide, thereby producing membrane sections of the exact width required for overlapping at window and door frames with the external membrane.	

Observation Sheets: Factory C

General Information	
Factory	C
Session	C01
Component Observed	Timber Framing
Date & Time	6 November 2024, 01:00 pm
Product Type	Timber Frame Panelised
Material Waste-Generation Description	
Timber frame sections were produced using 4800 mm and 5400 mm timber lengths. The observed waste-related instances are summarised as follows: 1. 25 mm offcuts: A significant number of timber offcuts of approximately 25 mm were observed. This consistent trimming practice appears to serve the purpose of ensuring a square and clean starting edge, without requiring additional inspection or extensive measurement. 2. 430 mm offcuts: A substantial number of offcuts of approximately 430 mm were generated when cutting two studs of 2180 mm from 4800 mm timber lengths. These offcuts could have been reduced if 4500 mm standard timber lengths had been available. 3. Other offcuts: Additional offcuts of varying sizes were observed throughout the production session. These appear to result from a prioritisation of cutting speed over the integration of cuts to enhance material efficiency.	

General Information	
Factory	C
Session	C02
Component Observed	OSB Boards
Date & Time	6 November 2024, 12:00 pm
Product Type	Timber Frame Panelised
Material Waste-Generation Description	
The standard dimensions of the OSB boards used were 9 mm in thickness, 600 mm, 800 mm, and 1200 mm in width, and 2400 mm and 2700 mm in length. The observed waste-related instances are summarised as follows: 1. Length-side OSB board offcuts: A significant number of OSB strips of approximately 141 mm were consistently generated. These offcuts were primarily driven by the need to achieve the panel height specified by the design, indicating an apparent misalignment between the design dimensions and standard OSB board lengths. 2. Width-side OSB board offcut reduction: Compared with Factory B, width-side offcuts were significantly reduced due to the specification and use of a range of standardised OSB widths, including half-, two-thirds-, and full-board sizes. This reflects effective design–procurement coordination, resulting in reduced offcut generation and more streamlined robotic assembly operations. 3. OSB opening-related offcuts: These offcuts were generated when OSB layers, initially assembled and nailed using robotic arms, were subsequently cut over window and door openings. Unlike Factory B, where smaller OSB sections were specified by design and prepared in advance to avoid openings, this factory did not adopt a similar approach, apparently in order to streamline robotic operations.	

General Information	
Factory	C
Session	C03
Component Observed	Rigid Insulation
Date & Time	5 November 2024, 11:00 am
Product Type	Timber Frame Panelised
Material Waste-Generation Description	
This insulation layer was supplied in 80 mm thickness, 1200 mm width, and 2400 mm length panels. The observed waste-related instances are summarised as follows: 1. Length-side rigid insulation offcuts: These offcuts were generated when approximately 222 mm was cut from 2400 mm rigid insulation panels to infill the internal cavity height of 2178 mm. This indicates an apparent misalignment between the design dimensions and the standard rigid insulation board lengths. 2. Width-side rigid insulation offcuts: Offcuts were generated due to the need to cut varying widths from the 1200 mm side of the rigid insulation panels to match the required cavity widths. As the required cut widths varied considerably, cutting decisions were largely optimised based on the saw operator's experience to maximise material use. However, because these sections had to be produced sequentially in line with the production schedule, limited attention was given to material nesting, resulting in increased offcut generation.	

General Information	
Factory	C
Session	C04
Component Observed	Breather Membrane
Date & Time	5 November 2024, 12:00 pm
Product Type	Timber Frame Panelised
Material Waste-Generation Description	
The standard breather membrane roll width used was 2700 mm. The observed waste-related instances are summarised as follows: 1. Width-side breather membrane overuse: Waste occurred because the standard membrane width exceeded the actual required width. Specifically, the required membrane width was 2406 mm (including a 150 mm overlap), whereas the membrane used was 2700 mm. This resulted in an excess of approximately 300 mm of membrane per panel. This overuse can be attributed to an apparent misalignment between the specified and supplied membrane widths. 2. Length-side breather membrane excess overlap: Additional waste was generated along the panel length where the membrane was cut with a greater overlap than required, exceeding the standard 150 mm overlap on each side. In practice, overlaps of approximately 300 mm were applied, resulting in an excess of around 150 mm of membrane per panel. This waste is attributed to the practice of rapidly unrolling the membrane with a positive tolerance to ensure full coverage, followed by fixing the far end without precise measurement, in order to maintain production speed. 3. Breather membrane opening-related offcuts: After the entire panel was covered and the breather membrane was fixed around the edges, the material covering window and door openings was cut out, generating significant offcuts.	

Observation Sheets: Factory D

General Information	
Factory	D
Session	D01
Component Observed	Timber Framing
Date & Time	18 October 2024, 10:00 am
Product Type	Timber Frame Panelised
Material Waste-Generation Description	
Timber frame sections were produced using a 3600 mm standard timber length. The observed waste-related instances are summarised as follows: 1. 20 mm offcuts: A significant number of timber offcuts of approximately 20 mm were observed. This consistent trimming practice appears to serve the purpose of ensuring a square and clean starting edge, without requiring additional inspection or extensive measurement. 2. 646 mm offcuts: These offcuts were generated when cutting a single stud of 2949 mm from the 3600 mm standard timber length. Shorter timber lengths were not sourced, as the production team considered that most of these offcuts could be reused as noggins. 3. Other offcuts: Additional offcuts of varying sizes were observed throughout the production session. These appear to result from a prioritisation of cutting speed over the integration of cuts to enhance material efficiency.	

General Information	
Factory	D
Session	D02
Component Observed	OSB Boards
Date & Time	18 October 2024, 11:00 am
Product Type	Timber Frame Panelised
Material Waste-Generation Description	
The standard dimensions of the OSB boards used were 9 mm in thickness, 1200 mm in width, and 2400 mm in length. The observed waste-related instances are summarised as follows: 1. Length-side OSB board offcuts: These offcuts were generated from cutting a 625 mm piece from the 2400 mm side of the OSB board. The 625 mm cut was required, together with a full board length of 2400 mm, to cover the total panel length of 3025 mm. These offcuts can be attributed to limited consideration of standard OSB board length multiples (e.g. quarters) during the design process. Designing the wall height to require a second cut of 600 mm instead of 625 mm would allow a single OSB board to be reused four times with no offcuts. 2. Width-side OSB board offcuts: These offcuts were generated only when the designed panel width fell below the standard OSB board width of 1200 mm. Hence, the apparent source of these offcuts is limited consideration of standard material sizes during design. 3. OSB opening offcut avoidance: Offcuts at window and door openings were entirely avoided where detailed shop drawings were provided and pre-cutting activities were undertaken to fabricate and assemble only the required OSB sections around the openings. This highlights the effectiveness of detailed design information and pre-planning in preventing offcut generation.	

General Information	
Factory	D
Session	D03
Component Observed	Rockwool Insulation
Date & Time	18 October 2024, 12:00 pm
Product Type	Timber Frame Panelised
Material Waste-Generation Description	
These insulation blocks were supplied in 100 mm thickness, 1200 mm width, and 3700 mm length. The primary source of insulation volume loss was overstuffing, whereby more material was installed than required to fill the cavities. Observations indicated that workers did not allocate time for precise measurement; instead, a positive tolerance was applied to ensure that minimum insulation requirements were met quickly and efficiently. Consequently, additional Rockwool insulation was consumed due to limited installation precision and the operational need to maintain production speed.	

Appendix G: Sample Interview Transcripts (Anonymised)

Interview with Interviewee A09

Transcript

22 October 2024, 15:34 pm

Researcher: Yeah, it is recording now. Sorry for the interruption.

Interviewee A09: Yeah.

Researcher: Okay. Yeah, you can go on.

Interviewee A09: Okay.

Interviewee A09: Yes, so the frames are generally outsourced, historically along with the steelwork. We have a lot of cold-rolled galvanized sections within the frames. In our manufacturing facilities, we don't have the scope to weld anything galvanized. So, welding has historically been done off-site to eliminate any issues with galvanized fumes. The box frames and wall panels are generally procured and made off-site because they are part of the companies we work with, and we use their own systems. For instance, we use Supplier A, who have their own system, and Supplier B, who use theirs. Everything comes to us assembled and pre-built.

Researcher: Okay, exactly as needed, every single section?

Interviewee A09: Yes, everything that's needed. End walls come at three meters or whatever size is required. Cables come in the correct size, so everything fits within the cube.

Researcher: Okay. Do you produce shop drawings for them?

Interviewee A09: Yes, we do.

Researcher: Let's move on to the roof plasterboard. This is the section from Project A, right? The net ceiling dimensions are 6 by 3 meters. My understanding is that 3-meter plasterboards are used, based on the data I received. Is my assumption correct that they are being installed in this direction?

Interviewee A09: Yes, as you mentioned. That's correct. So, it's a full board from that end. That's correct.

Researcher: Okay, and is there a closing strip that should be cut and left for on-site installation? I'll show you what I mean.

Interviewee A09: Yes, some buildings require a joint, which is what you've got back there.

That's your board cut back. So, when the building gets installed on-site, we have an infill piece that spans the two modules.

Researcher: Okay, so does that mean that this building needs the strip cut out or not?

Interviewee A09: No, it's not needed for this building.

Researcher: So, it's going to be installed like this, with no cutting?

Interviewee A09: Yes, that's right.

Researcher: Got it. So, how does this impact the exact amount of waste generated? Is there an arrangement between design and standard material sizes?

Interviewee A09: Yes, our suppliers of the plasterboard have a relationship with us. If we need plasterboard at 3 meters or 3.6, they will cut it to the required size. So, in this case, there's no waste other than the offcut piece from your last board.

Researcher: So, this one fits exactly because 6 meters is an exact multiple?

Interviewee A09: Yes, that's right.

Researcher: And does the design adjust the dimensions to avoid waste in both directions?

Interviewee A09: No, not really. The design is based on the client's needs, and we design the plasterboard around that.

Researcher: So, it's just by coincidence that it works out this way?

Interviewee A09: Yes, just by luck.

Researcher: Okay. What about the closing strip? We don't need it here at all?

Interviewee A09: No, not for this building.

Researcher: What's the main purpose of the closing strip?

Interviewee A09: The closing strip is for fire encasement detail. When two modules come together, we have to fully encase the steelwork to meet fire safety standards.

Researcher: Okay, and are there other sizes of plasterboard available?

Interviewee A09: Plasterboard can be bought in whatever size we need, but common sizes are 2.4m, 3m and 3.6m.

Researcher: For this project, the wall panels are 3 meters wide and 2.7 meters high. Are the 2.7-meter plasterboards used here?

Interviewee A09: Yes, that's correct. Closing strips are needed on the wall panels.

Researcher: And this means that in the factory, there is no waste?

Interviewee A09: Correct. There's no waste unless we cut a window or a door out of the plasterboard.

Researcher: What is the range of closing strip sizes?

Interviewee A09: For this project, 300mm is typical, but when installed on-site, we use a 600mm jump board for the bay-to-bay joints.

Researcher: That's great for waste reduction. Minimal waste, right?

Interviewee A09: Yes, minimal waste.

Researcher: Can you clarify why no waste is generated in this case?

Interviewee A09: Since the plasterboard fits perfectly between the modules, no waste is generated. We also buy custom-sized boards from the supplier to ensure minimal waste.

Researcher: So, does your procurement team ensure that custom sizes are ordered to avoid waste?

Interviewee A09: Yes, our procurement team works closely with suppliers to get the right sizes for each project.

Researcher: Okay, perfect. So now moving on to the rigid insulation. Based on the design, we have three meters by 6.3 meters from the bottom. The boards are used in dimensions of three meters by 1220 millimeters. Am I right in assuming they are installed in this direction?

Interviewee A09: Yes, you're right. That's correct.

Researcher: Okay. So this means we have about five full boards, and then we need a small strip to be cut, around 200 millimeters. Is that right?

Interviewee A09: Yeah.

Researcher: So we'll generate a bit of offcuts that can be reused for other bays?

Interviewee A09: Generally, the offcut is reused on the next bay to start the module. So on your next module, where you start with your 1220, you'd use your offcuts. You might start

with a smaller piece next time. Your offcuts are always used as starter panels after the first module is built.

Researcher: Okay, so this piece can be reused within the next module?

Interviewee A09: Yes, that piece will start at the far end and begin your next floor.

Researcher: Perfect. And no waste is generated in the length direction because the design and the standard panel length are aligned, right?

Interviewee A09: Yeah, that's correct. The only waste we generate is from the end of the module where we cut the length. But any offcuts we generate are used in the next module.

Researcher: Okay.

Interviewee A09: The design is procured and reviewed alongside what materials we can purchase for the module. If the module were slightly wider, we might have to adjust the layout of the panel sizes—maybe laying them horizontally instead of vertically.

Researcher: So is this the only standard size available for rigid insulation?

Interviewee A09: No, you can buy 2.4 or 3-meter panels.

Researcher: So there are only two options?

Interviewee A09: Yes, for rigid insulation, just two options.

Researcher: Same width?

Interviewee A09: Yes, same width.

Researcher: And regarding the width, since it's not an exact multiple of the module length, it's not a design concern to get an exact fit?

Interviewee A09: No, it's not a major design concern.

Researcher: So my understanding is that the three-meter size is more about standard material availability, not the length.

Interviewee A09: Yes, that's correct.

Researcher: And for the floor decking, my understanding is that it's 6.3 meters by 3 meters, installed in this direction. Is that correct?

Interviewee A09: That's right.

Researcher: So we have offcuts here—two pieces and a strip to be cut. Why is it necessary to cut these pieces? Couldn't we use different dimensions to avoid the need for cuts?

Interviewee A09: The 2.4-meter length is based on your joist centers, which are normally 600 millimeters apart. Standard flooring plywood comes in 2.4 meters. The offcut from your 600-millimeter cut can be used on the next floor, as long as you alternate the tongue and groove as your starting point.

Researcher: Okay. And I see the offcut in the 600-millimeter direction can be reused on the next bay?

Interviewee A09: Yes, it can be reused on the next floor.

Researcher: So my understanding is that the design is intended to reduce waste as much as possible?

Interviewee A09: Yes, it is. The way it's set up—full sheet, half sheet—helps minimize waste. Your offcut can be used on the next floor.

Researcher: What are the available standard sizes of tongue-and-groove plywood?

Interviewee A09: Tongue-and-groove plywood typically comes in 2.4 by 1200 millimeters. You can also buy square-edge plywood in 3-meter lengths, but you lose the benefits of the tongue-and-groove feature.

Researcher: Okay, so similar options for square-edge as well. Now, moving on to external cladding—I believe it's IsoClad. I noticed that the panels are sourced from the supplier at the exact length needed, but not the width. For example, for a door reveal or a window reveal, the width of each panel is 1190 millimeters, but we need to cut off 395 millimeters. Why don't we source the exact width needed instead of cutting and wasting material?

Interviewee A09: Historically, when we used Kingspan before Grenfell disaster, you could order any size panel you needed. With Rockwool panels, they generally come in one or two sizes. So we've lost the ability to get them cut to size. Everything we buy now has to be cut at the factory, and unfortunately, that offcut becomes waste.

Researcher: So it can't be sourced in a different width?

Interviewee A09: No, but the supplier offers a service where they can cut the panels for you, though you'd pay a premium for that.

Researcher: I see.

Interviewee A09: Whether we cut the panels or the supplier does, that piece becomes waste.

Researcher: Okay. Moving on to the second layer—the offcuts for the reveals. Why didn't we just buy pieces cut to size for the reveals instead of installing full panels and then cutting openings?

Interviewee A09: In some cases, you could do that, but the top of the door head where the cladding line is might not always match up exactly. You sometimes have to cut into the top panel to fit the door properly. The bottom panel usually needs to be cut out to form the door sill.

Researcher: So the bottom panel ends up being waste?

Interviewee A09: Yes, and the same applies for windows. The cut doesn't always fall neatly between two panels.

Researcher: Even though the design shows it should line up?

Interviewee A09: Designers do try to make it so the window falls below the top joint line, but it doesn't always work that way. Sometimes the window or door needs to be adjusted on-site, which can cause waste.

Researcher: Couldn't we reduce waste by getting these measurements right from the start?

Interviewee A09: You're often governed by setting-out points on site, like the ground level or other factors. Lead times for cladding can also be quite long, and sometimes the final design isn't ready by the time you need to order the cladding panels, so you might end up with offcuts.

Researcher: I see. How would you describe the fact that no cuts are needed on the length because the panels are pre-cut by the supplier to custom sizes? How does that fit into the procurement process?

Interviewee A09: That's part of the early-stage design and procurement process. The design drawings are provided to the supplier, who then cuts the panels to the exact size. This is all planned during the design and bill-of-materials (BOM) stage.

Researcher: Regarding the roof sheet, I see zero waste here. The panels are 12 meters long and one meter wide. The length is custom, and the width is standard. Is there anything you'd like to add about that?

Interviewee A09: No, it's similar to the cladding. Everything is designed and procured early on, so the supplier provides the correct sizes.

Researcher: Lastly, I noticed from my observations that overstuffing of mineral wool insulation can lead to 7-8% wastage. Overstuffing also reduces insulation efficiency. Why does this happen?

Interviewee A09: Like with any manual work, there's some variability in cutting. The insulation rolls come in at 1200 millimeters, and they're cut by hand with a saw. You sometimes get variation in width—600, 620, or 650 millimeters—depending on the cut. This can lead to overstuffing.

Researcher: So, it's due to manual cutting imperfections?

Interviewee A09: Yes, if we could order 400- or 600-millimeter-wide rolls, it would eliminate some of that. But with standard 1200-millimeter rolls, there's always some manual cutting involved.

Researcher: Okay, I understand. Is there anything else you'd like to add? I think I've covered all my questions.

Interviewee A09: No, I think you've covered everything really well.

Researcher: Thank you very much for your time. I really appreciate it. I'll see if I can access the recording.

Interviewee A09: If I stop recording now, you should be able to access it.

Researcher: Hopefully, yes. Thank you. See you later.

Interview with Interviewee B07

Transcript

October 25, 2024, 9:01 AM

Researcher started transcription

Researcher 0:08

Yeah. Is it showing?

Interviewee B07 0:12

It is showing

Researcher 0:13

Yeah, yeah. So what I did, I analyzed each material in isolation — each in terms of quantity and root cause. But now, for the root causes, I need your help because identifying them based on lean principles is important for finding solutions to simulate improvements with your support.

Interviewee B07 0:43

OK.

Researcher 0:44

To make practical solutions. So, starting with the studs, I observed during my visit: initially, we used like 5.4 studs to cut 2 studs for each panel — yeah, 2405, three, two pieces. Then, of course, we had 400 mils, 435. So, why did we use the 5.4 timber instead of 5.1? What's the main reason?

Interviewee B07 1:27

We generally buy timber in two sizes — 4.8 or 5.4. For apartments, we use 5.4 since we can't get two lengths out of 4.8. Although 5.1 might work, it has a longer lead time. We'd need drawings available well in advance to know which size to order. 4.8 and 5.4 are standard sizes. 5.1 is OK as long as it's preordered with a long lead time.

Researcher 2:24

So, it takes more time to be purchased and delivered to the factory?

Interviewee B07 2:29

Yes, the procurement schedule for 5.1 is longer than for 5.4 and 4.8.

Researcher 2:37

Is there any cost implication with using 5.1? Is it more expensive?

Interviewee B07 2:46

No, it's priced by length in meters. The price for 5.1 would be similar to 5.4.

Researcher 2:59

OK.

Interviewee B07 2:59

Only 4.8 is slightly cheaper; 5.1 and 5.4 are priced the same.

Researcher 3:11

Got it. If we have plans ahead, do you think it's a good idea to order 5.1 to reduce both cost and waste?

Interviewee B07 3:28

Yes, we've ordered 5.1 before, but only with finalized project drawings and a long lead time before manufacture. We'd need drawings ready about 12 weeks in advance to plan for 5.1 instead of 5.4. The default for apartments, though, is 5.4 to get two studs.

Researcher 4:08

Makes sense.

OK, another question about the 50 mils being consistently cut from each timber section. Why is this small piece trimmed?

Interviewee B07 4:37

To ensure the stud end is square. It's the first step in calibrating the saw. Although the timber is ordered at 5.4, lengths can vary slightly, so the CNC saw does an initial cut to set the pusher and blade calibration, ensuring the next cut is exactly 2453 millimeters.

Researcher 5:20

Is it about the cleanliness of the first cut or defects? I noticed some...

Interviewee B07 5:29

It's primarily for cleanliness and calibration of the CNC pusher to the saw blade.

Researcher 5:42

OK.

Interviewee B07 5:48

If 5.4 or 5.1 timber was just enough for two studs, that initial cut could be reduced to 10mm.

Researcher 6:02

So it's about the machine calibration?

Interviewee B07 6:07

Yes, to calibrate the saw blade with the material pusher.

Researcher 6:13

Understood.

Interviewee B07 6:18

It's about calibrating those two components.

Researcher 6:18

Not about defects on the timber edges, like cracks?

Interviewee B07 6:25

No, but it ensures a 90° square cut at the bottom for the framing machine.

Researcher 6:36

Got it.

Interviewee B07 6:37

It's good practice and ensures the saw is calibrated for length variations since 5.4 is a nominal length.

Researcher 6:45

Understood.

Interviewee B07 6:53

The 5.4 is a minimum length but can vary slightly. When cutting studs, multiple layers of timber are cut at once. Both pieces are flush at the pusher end, but there might be a slight step at the saw end, so we take that initial cut as a datum for the cycle.

Researcher 7:29

Makes sense.

Do you think newer saws could reduce this waste?

Interviewee B07 7:48

An initial cut is generally needed to ensure both the saw blade and pusher align, allowing the CNC to measure 2453mm accurately.

Researcher 8:11

Got it.

So, for other cuts — I noticed at the beginning, since 5.4 wasn't available, we used 4.8, which left a 2.29 piece to be reused. Not wasted, but set aside.

Interviewee B07 8:39

Yes, that piece can fit other parts of window modules or as a standard stud elsewhere. It's used to keep production going until the 5.4 material is delivered.

Researcher 8:43

Is this due to logistics delays for 5.4?

Interviewee B07 9:11

Yes.

Researcher 9:12

Understood.

Interviewee B07 9:14

5.4 should be available at the saw before the job starts.

Researcher 9:20

And the 2.29 piece wasn't used in the same job?

Interviewee B07 9:29

Not for the same job.

Researcher 9:32

Right. So, this is mostly a logistics issue?

Interviewee B07 9:45

Yes, either the 5.4 material isn't available in the factory, or we're waiting for transport to bring it to the saw — it's all logistics.

Researcher 10:04

So, coordination is needed between the cutting team and the materials team?

Interviewee B07 10:20

That's normally communicated in advance, and it should have been swapped over. It surprises me that happened on that job.

Researcher 10:32

Not a lot, just a few.

Interviewee B07 10:33

Right. But that throws off our bills of materials.

Researcher 10:41

Yeah.

Interviewee B07 10:41

The whole job was costed based on using 5.4 timber.

Researcher 10:48

Right.

Interviewee B07 10:49

Then, when we get to stocktake, we end up with more 5.4 than expected and less 4.8. A month later, no one understands why.

Researcher 10:54

Got it. It only happened for about six or seven studs, I think — six sections.

Interviewee B07 11:08

Was that at the start or end of your exercise?

Researcher 11:17

It was at the beginning before 5.4 was available to cut.

Interviewee B07 11:20

OK. The operator should have waited instead of cutting those six or seven studs until the right material arrived.

Researcher 11:31

Yeah.

Interviewee B07 11:33

But he saw you standing there and cut some 4.8 to stay busy. That shouldn't happen.

Researcher 11:43

Understood. Now, about the OSB boards — we talked about the 100-mil trim that's cut from each board because of the apartment height. Have you considered sourcing custom-sized boards?

Interviewee B07 12:00

Yes.

Researcher 12:06

Right.

Interviewee B07 12:07

Boards come in standard sizes, typically 2400 or 2700. Ordering custom sizes would mean changing the supplier's manufacturing process, which would be costly. With apartments, we have two options: use a standard 2.4 board, but that means cutting a timber nogging into every panel at the 2.4-meter mark to support the board with a small trim at the top.

Researcher 12:51

Exactly, yeah.

Interviewee B07 12:56

So, for apartments, we factor in some waste and trimming at the top of the OSB boards. The alternative — cutting and adding timber noggins — would be costlier and more wasteful than that 115-mil trim.

Researcher 13:28

OK. Have you compared costs if you sourced custom boards in advance, given cutting also takes time and generates waste?

Interviewee B07 13:54

We've tried sourcing pre-cut boards, but suppliers just make the standard board and charge us a premium to cut it. The waste remains the same.

Researcher 14:17

Understood.

Interviewee B07 14:17

We'd just incur the additional cost at the supplier instead of managing it here by buying standard boards.

Researcher 14:27

So, we'd still have to cut it to the required height.

Interviewee B07 14:31

Right. It's made in set molds for standard boards and is commonly cut to size at the point of use in the industry.

Researcher 14:32

Got it. On another point with OSB — I noticed that every cut maximizes the width, which leaves a lot of 200 to 500-mil offcuts.

Interviewee B07 15:19

Yes.

Researcher 15:21

So, why are OSB width cuts always maximized?

Interviewee B07 15:34

We use full-width boards at 1200 wherever they fit in the panel. Width cuts often happen near structural openings like windows or doors. So, depending on the panel layout, there might be a 700-mil width left before a window. About 90% of those offcuts get reused.

Researcher 16:26

Got it. My observation, though, is that the reuse rate for these offcuts within the same job is lower. In one job, I noticed it wasn't efficient for the eight panels.

Interviewee B07 16:44

They're not reused within the same job. The OSB is a standard thickness board, especially for timber frames. When they assemble the ground floor, floor panels cover the 245-mil depth joining the two panels.

Researcher 17:09

Makes sense.

Interviewee B07 17:10

We provide site materials, like 2.4-meter lengths of OSB at 245mm for assembly. So, any offcuts here are reused at the site fit stage.

Researcher 17:32

Ah, I see.

Interviewee B07 17:46

And anything below 245mm is repurposed into flat-pack braces that hold panels together. Not for the same project necessarily, but for other projects. They're also used on external walls of flat-pack products during transport to prevent membrane damage.

Researcher 18:12

Got it.

Interviewee B07 18:13

So, reuse is high overall, even if it wasn't evident in those specific panels.

Researcher 18:30

OK, that makes sense.

One last thought — instead of maximizing every width cut, could we optimize cuts to be smaller? It might increase reuse within the same job, though it would require more labor for nailing different pieces.

Interviewee B07 19:10

You'd lose the structural integrity of the sheathing. Panels are designed with full-width boards for strength, which the designer specifies through nailing centers. Using multiple smaller pieces would either reduce strength or require changing nailing centers, increasing material use and costs.

Researcher 20:02

I see. OK, let's move on.

Researcher 20:14

The next point is on the polythene vapor barrier. I noticed we always leave around 250 to 300 mils extra along the edge. As you can see here, what's the reason for that?

Researcher 20:34

Why is this side of the cut always being generated and cut out?

Interviewee B07 20:48

We generally have an overlap on every side of the panel.

Researcher 21:01

OK.

Interviewee B07 21:02

Since it's a panelized system joined together on-site, to keep the vapor barrier waterproof, there's a minimum 150mm overlap that's stapled on-site.

Researcher 21:16

No, sorry, I mean the part being cut and thrown away.

Interviewee B07 21:23

Are you asking about the polythene?

Researcher 21:26

Yes, polythene, exactly.

Interviewee B07 21:28

Oh, I thought you meant the external membrane.

Researcher 21:32

Yes, yes.

Interviewee B07 21:35

On the sides, that's an error. It's waste that doesn't need to be there.

Researcher 21:42

Got it.

Interviewee B07 21:43

On the top and bottom, it's due to the polythene sizes available for purchase.

Researcher 21:53

And is it because they need to work quickly without measuring the exact amount?

Interviewee B07 22:04

It's often a quick cut with a Stanley knife from the last roll, which might leave a jagged edge, so they leave excess over the panel.

Researcher 22:10

OK, OK.

Interviewee B07 22:17

Then they pull the polythene tight, staple it, and cut off the excess.

Researcher 22:21

Got it.

Interviewee B07 22:22

But yes, 250-300mm is extra waste on the sides, though we can't do much on the top and bottom.

Researcher 22:36

On the width side, there's about 500mm excess. Why use 3,000mm polythene instead of 2.7 or 2.6 if that's available?

Interviewee B07 22:49

We currently source polythene in two sizes: 3 meters and 4 meters.

Researcher 23:04

OK.

Interviewee B07 23:05

The 3-meter width is used for panels, including narrow ones between houses and apartments. The 4-meter width is for wrapping the packs for waterproofing.

Researcher 23:27

Have you considered sourcing 2.7 or 2.6 meters, closer to what's needed?

Interviewee B07 23:40

No, we haven't tried that.

Researcher 23:42

Do you think it would cost more to get the exact width?

Interviewee B07 23:51

Exact sizing would be costly, as we make five or six different projects each week with varying panel sizes.

Researcher 24:13

Understood.

Interviewee B07 24:13

There might be some benefit to a 2.7-meter roll for panels, as it's rare for internal panel sides

to exceed that width. However, some projects specify flush cuts, while others require an overlap for permanent vapor barrier functionality.

Researcher 25:01

OK, OK. Regarding insulation, I noticed it's sometimes overstuffed into cavities. Not only does it waste material, but it can also reduce insulation performance by compressing it. Here, for example, about 20mm extra is being forced in unnecessarily. Why is that?

Interviewee B07 25:46

The insulation comes in a 600mm slab, but the standard cavity for a 1.2 board is 578mm.

Researcher 25:51

Right.

Interviewee B07 26:06

So they'll force it in to fit rather than waste material by cutting.

Researcher 26:19

Got it. How do you think we could reduce this? Though small, it adds up significantly over time.

Interviewee B07 26:38

For the Product A, we can use some offcuts to create a single layer of insulation since it has two layers. But using smaller pieces alone would reduce thermal efficiency due to gaps.

Researcher 27:02

Understood.

Interviewee B07 27:05

Currently, insulation is applied with an answer to keep up with the plant cycle time, though it doesn't always give the cleanest edge.

Researcher 27:20

Would sourcing a specific width directly help?

Interviewee B07 27:30

Every project varies due to window and door positions and building dimensions.

Researcher 27:39

Right.

Interviewee B07 27:39

It's similar to OSB boards with structural openings. Sourcing 578mm insulation could raise costs, as most insulation is manufactured in 600mm slabs.

Researcher 28:10

Yes, makes sense. Please continue.

Interviewee B07 28:12

The standard is 600mm slabs. Making the cavity exactly 600mm wouldn't align with OSB board sizes.

Researcher 28:18

Exactly, yes.

Interviewee B07 28:21

Larger pieces are sometimes reused, but smaller pieces don't maintain cavity consistency for insulation.

Researcher 28:57

Understood. And lastly, about the brick slips — why are they around reveals in exact multiples of a full brick length? There's no half or quarter brick; it's all full bricks.

Interviewee B07 29:31

Do you mean the full brick length?

Researcher 29:36

Yes, exactly. No small cuts, just whole bricks.

Interviewee B07 29:52

We purchase them as corners. Did you see waste generated from cutting corners to make the reveals?

Researcher 30:01

Yes, all the corner pieces.

Interviewee B07 30:06

All those are cut from corner profiles.

Researcher 30:09

Understood.

Interviewee B07 30:15

So we have corners for corners, and for the reveal, it already has the 50 mil required on the internal reveal face to minimize waste.

Researcher 30:33

OK, OK. And about the battens, just a quick one — I noticed cut optimization across different panels. Why were different cuts integrated, even though they were in separate panels? Is that due to worker skill or something else?

Interviewee B07 31:04

It's because your standard 74mm battens are used under windows for structural openings. Structural openings stay aligned in building elevations, so even if they're not in one panel, they will be in the next one or the one after that.

Researcher 31:41

And the worker knows to integrate these, right?

Interviewee B07 31:48

Yes, because...

Researcher 31:50

That could be a key difference.

Interviewee B07 31:53

It's a standard cut list, and all that info is on the same drawing they're cutting from.

Researcher 32:02

Got it, and that's the difference between cutting battens and timber studs — there's better optimization here.

Interviewee B07 32:12

Yes, it's done on a more panel-by-panel basis rather than multi-wall groups cut simultaneously.

Researcher 32:22

Understood.

Interviewee B07 32:31

We buy battens in three lengths: 2400, 2700, and 3000.

Researcher 32:41

OK, that's great for flexibility and waste reduction.

Interviewee B07 32:48

Exactly.

Researcher 32:51

Regarding sheathing boards, specifically glass rock, I noticed cuts are maximized for every piece. Sometimes, optimizing instead of maximizing could allow reuse within the same job.

Interviewee B07 33:14

They're stored for reuse, especially around windows and doors for reveals. The 1200 boards must be installed horizontally. Any offcuts then serve as top pieces, like the 300mm rip at the top.

Researcher 33:57

Right, the 760mm part?

Interviewee B07 34:04

Yes, the 700mm on this one. But cutting generates waste, particularly for apartment heights, with about 440mm offcuts around the building perimeter.

Researcher 34:24

Exactly. Is there an attempt to source custom sizes, like 760mm?

Interviewee B07 34:32

The next project could require 740 or 780 due to varied wall heights from architects. Anything over 2400mm must be cut as a rip. Ideally, I prefer if it's less than 600mm for multiple rips from the same board.

Researcher 35:12

Why don't designers standardize dimensions?

Interviewee B07 35:20

We work with various architects, adapting their designs into a panelized system without dictating house types. Engaging with clients sooner might standardize designs, but currently, clients bring their designs to us.

Researcher 36:00

Makes sense.

Interviewee B07 36:03

We incorporate the associated cost and waste into quotations.

Researcher 36:08

Understood. One last point on breather membranes. Is it 150mm?

Interviewee B07 36:29

It's 150mm for Product A, 250mm for Product B, and up to 400mm for brick slip jobs. For external membranes on traditional timber frames, there's a minimum 150mm overlap.

Researcher 36:56

OK.

Interviewee B07 36:58

For brick slip systems, the membrane attaches back onto the panel end, wraps around the internal side, and aligns with an adjoining membrane, ensuring waterproofing.

Researcher 37:39

Understood.

Interviewee B07 37:39

This requires up to 205mm overlap for sealing. Excess up to 350mm may occur, and we're looking at ways to achieve cleaner cuts for reuse.

Researcher 38:15

Got it. Just a quick final point on the window and door reveals. Couldn't we reuse offcuts for these reveals?

Interviewee B07 38:55

Ideally, a continuous piece is necessary to prevent moisture ingress, maintaining a full vapor and moisture control layer.

Researcher 39:00

Understood.

Interviewee B07 39:12

Using patchwork pieces around windows and doors would cause issues on-site.

Researcher 39:20

Lastly, I noticed you cut the breather membrane roll into smaller pieces, like into ten pieces, for coverage. What's the reason?

Interviewee B07 39:39

We can't purchase narrower widths than 540mm for breather membranes and 600mm for reflective ones. Cutting them down increases production flow and minimizes material waste.

Researcher 40:03

So, you developed this to improve efficiency?

Interviewee B07 40:05

Yes, we cut a full roll into ten pieces for easier handling.

Researcher 40:11

Understood. Thank you, for your time and insights. Apologies for extending the meeting.

Interviewee B07 40:21

Some very useful findings.

Researcher 40:25

I'll validate the data and return with more findings before proposing solutions.

Interviewee B07 40:35

That would be helpful. Thank you.

Researcher 40:36

Thank you so much. I appreciate it.

Interview with Interviewee C09

Transcript

13 March 2025, 10:00 am

Researcher (0:04):

OK. Can you see the screen now?

Interviewee C09 (0:15):

Yeah, we can see that. Yeah, that's fine.

Researcher (0:17):

Perfect, thank you. So, I just need to quickly review and validate the initial findings so far, starting with the design package. I analysed the automated design package, and this is just an example—one panel without openings and one with an opening.

So, starting with timber studs and the cutting practice: we typically use 4.8-metre lengths.

Interviewee C09 (0:23):

OK. Yeah.

Researcher (0:45):

One thing I noticed across different factories, including yours, is an initial trim cut of up to around 50 millimetres—sometimes 40, sometimes 20.

Interviewee C09 (0:45):

Yeah, yeah.

Researcher (0:57):

From the study so far, the explanation is that this cut is required because of the nominal length of the timber, to establish a precise reference point and ensure accuracy for subsequent cuts. Is that correct?

Interviewee C09 (1:24):

Yes. We can turn that facility off if needed, but generally we do a trim cut at the beginning.

Researcher (1:32):

I noticed it's fairly regular, but the thickness varies—20, 30, or 40 millimetres—depending on the timber length.

Interviewee C09 (1:44):

It depends what we're getting out of it. If we need, say, a 4.775-metre piece, we might only do a 5-millimetre trim. Normally, it's about 25 millimetres.

Researcher (1:57):

OK. So is this mainly because of the nominal timber length, or because the saw can't precisely measure that length?

Interviewee C09 (2:12):

No, the saw can measure it precisely. To be honest, most of the time we turn the trim cut off. The timber's already cut anyway, and a slightly rough edge is acceptable for our panels. We only trim if the operator sees damage or chipping—say, if there's 100 millimetres damaged at the end.

Researcher (2:39):

OK. And typically, the first stud is cut at around 2.18 metres, then the second piece, leaving a leftover of about 400 millimetres from each timber length.

Interviewee C09 (2:55):

Yep.

Researcher (3:02):

The explanation from the findings and interviews is that ordering custom lengths like 4.4 metres instead of 4.8 isn't feasible because it's more expensive and takes longer to source. Is that fair?

Interviewee C09 (3:16):

Yeah, that's bang on. Timber comes in certain sizes—normally 600-millimetre increments—so you get 4.2, 4.8, 5.4, and so on. A custom 4.4 would definitely be higher cost.

Researcher (3:36):

Moving on to rails and headers: studs are mass-cut together because they share the same length, but rails and headers vary per panel, so they're cut sequentially, panel by panel.

Interviewee C09 (4:14):

Yep.

Researcher (4:37):

That means there's limited optimisation across panels—we prioritise maintaining production flow over global material optimisation. Is that correct?

Interviewee C09 (4:47):

I'd say that's right. We cut in panel order for the line. Offcuts get reused for noggins and other walls, but there's definitely room to improve optimisation at source.

Researcher (5:08):

Moving on to OSB sheathing. The first step is fitting a full-size 1.2×2.4 -metre board. On the automated line, the robotic arm places the full board and then cuts out the excess.

Interviewee C09 (5:16):

Yep.

Researcher (5:33):

For example, about 140 millimetres is cut off here, and similar cuts occur elsewhere. This happens because the panel height is customer-defined and not always aligned with standard board sizes.

Interviewee C09 (6:03):

Exactly. We design on 600-millimetre centres so standard boards can be used, but the wall height is customer-driven. We can buy 2.4, 2.7, or 2.9 boards, but height is dictated by the client.

Researcher (6:43):

At the far end, only a small strip is generated, which is limited because of the standardised layout.

Interviewee C09 (7:19):

Yes. We use as many full boards as possible. The end board is the only one that needs to be smaller, and that's again driven by customer panel size.

Researcher (9:30):

Where openings exist, significant opening-related offcuts are generated because full boards are installed first and then cut out, rather than pre-cutting around openings.

Interviewee C09 (9:57):

Yes. We place a full board because it's easier and faster, then reuse the cut-out pieces elsewhere in the factory.

Researcher (10:06):

So this is production flow-driven rather than material-efficiency-driven.

Interviewee C09 (10:09):

Yep.

Researcher (10:16):

For rigid insulation, offcuts of around 220 millimetres are generated because the panel height doesn't align with standard insulation sizes.

Interviewee C09 (10:42):

Yes, absolutely. That section will be an offcut.

Researcher (12:33):

A global optimisation approach could reduce this further, but panel-by-panel cutting supports production flow.

Interviewee C09 (12:50):

If you optimised across 20 panels, you'd definitely reduce waste further.

Researcher (13:09):

For the breather membrane, the panel height is 2.25 metres, but a 2.7-metre membrane is used to allow for overlaps.

Interviewee C09 (13:36):

Yes. We wouldn't cut that off—it's overlapped and still usable on site.

Researcher (14:33):

Manual cutting introduces imprecision, so overlaps can exceed the standard 150 millimetres.

Interviewee C09 (14:36):

Yes, that's spot on.

Researcher (14:53):

Why are noggins not always included in the design?

Interviewee C09 (14:59):

Some panels have noggins, some don't—it depends on the design. Internal walls usually have them.

Researcher (16:01):

Could the precision of automated OSB installation reduce the need for noggins?

Interviewee C09 (16:37):

Essentially, yes. But we can still fit them manually where required. I'd need to check the design criteria.

Researcher (19:31):

Would automated labelling and sorting make global cutting optimisation more feasible?

Interviewee C09 (21:04):

Absolutely. We already label panels, so labelling components by panel number would help.

Interviewee C09 (21:27):

One more thing—we can create “multi-walls” by combining smaller and larger panels on the line, then trimming them at the end. That helps optimise timber length.

Researcher (21:54):

Thank you. I'll prepare the report and share it with you. I appreciate your time.

Interviewee C09 (22:39):

No problem at all. I'll check on the noggins and get back to you.

Interview with Interviewee D05

Transcript

10 March 2025, 01:20 PM

Interviewee D05 (0:03):

When you do a cut—your first cut—your third piece that comes off is like your offcut.

It cuts from the **throat**. So yes, when the blade comes up, that's the calibration point, but it might not necessarily

Researcher (0:24):

Sorry, I can't hear you very well. Can you come closer to the mic? Sorry.

Interviewee D05 (0:39):

Is that better?

Researcher (0:44):

Yes, better.

Interviewee D05 (0:46):

So your first cut—say you want to cut something at **1000 mm**—you calibrate, and the cut would be **2600** (if you like). It's not always **15 mm**; it can be anything.

Researcher (0:58):

Exactly, yes.

Interviewee D05 (0:59):

That's it—just make sure you understand that.

Researcher (1:05):

So is it accurate to say we need that because of the **nominal timber length**, so we need to establish a reference point?

Researcher (1:16):

So the first cut will be the stud at **2.95 m** for this design package. Then we'll have a leftover of about **600 mm**.

The root-cause explanation I assumed is: this leftover happens because we did not order **3 m timber**, and we didn't order it because it is expensive and needs longer lead time. To what extent do you agree?

Interviewee D05 (1:58):

That piece of timber isn't redundant. That piece would go to a **noggin**. If you go to panel one—

Researcher (2:10):

I agree—I'm not saying it gets thrown away. I'm saying: to avoid it, is there any opportunity to source 3 m timber?

Interviewee D05 (2:26):

No, because I still need that **600 mm** piece to get the noggin. It wouldn't be worth buying 3 m timber, because you still need that excess for the noggin. If you bought 3 m timber, you'd have to buy excess material for the noggins anyway.

Researcher (2:33):

Got it.

Interviewee D05 (2:47):

It covers your timber and the noggin—because it covers, you see.

Researcher (2:52):

Understood. But can you clarify: is 3 m more expensive and slower to source, or is it available in the market?

Interviewee D05 (3:09):

It's a very broad market, but it's viable—however we wouldn't order it because it wouldn't be cost effective.

Researcher (3:17):

So it's not viable for your case because you need that piece.

Interviewee D05 (3:19):

Because we need that piece, yes.

Researcher (3:23):

Now moving to rails and noggins: first we have calibration cuts. Then we cut top rail, bottom rail, and there's a piece left. This piece will be stored for future reuse, right?

Interviewee D05 (3:45):

Yes. It'll be used for two more noggins.

Researcher (3:55):

Okay. I'm assuming: if we cut panel-by-panel, and we're not integrating cuts across panels (e.g., taking noggins for panel 7 while cutting panel 1), that reduces optimisation—unless you are integrating.

Interviewee D05 (4:22):

The sequence?

Researcher (4:27):

The priority for sequence?

Interviewee D05 (4:29):

Yeah—the sequence you've got is wrong. Because you've got all... [unclear]. Your knowledge of the ordering is off.

Researcher (4:44):

So you cut noggins from offcuts, not from new timber?

Interviewee D05 (4:47):

That's it.

Researcher (4:44):

So the priority is production flow—keeping the line running—rather than maximising integration?

Interviewee D05 (4:47):

Yeah.

Interviewee D05 (5:16):

Just one: I can see on your screen you've got three total rails.

You've got an upright and a noggin, upright and a noggin, upright and a noggin—are you with me?

Researcher (5:32):

Yes—those noggins are here.

Interviewee D05 (5:34):

Then with the fourth piece of timber, you'd get a top, a bottom, and a noggin—it would make—

Researcher (5:42):

About the sequence: do you cut the whole batch of studs first, or do you complete one panel (studs, noggins, top and bottom rails) and then move to the next?

Interviewee D05 (6:00):

That's correct (panel-by-panel).

Researcher (6:02):

Okay.

Interviewee D05 (6:06):

But if you had, say, five panels the same, you would probably cut fifteen uprights first so you wouldn't have to change the size on the saw.

Researcher (6:18):

Yes.

Interviewee D05 (6:19):

So basically you cut all fifteen, put them on the floor, and stack them.

Researcher (6:40):

So that happens only when multiple panels are similar (e.g., panel 1 similar to panel 7, panel 11, etc.).

Researcher (6:40):

Now OSB: here we have two panels—one full OSB at 1.2 m, and here we have about 800 mm.

A full sheet fits exactly here, but on this side we'll have offcuts. We'll need a whole piece of OSB.

Interviewee D05 (7:19):

Yes, that's correct.

Researcher (7:30):

So the explanation is: required OSB cuts do not align with standard sizes or multiples. If this was 600 (not 606.25), then 2.4 is 4×600 , and we can reuse the offcut more efficiently.

So using multiples/approximations in design is important to reduce offcuts.

Interviewee D05 (8:53):

That will be pulled down and used up until it's gone across panels throughout the project.

Researcher (8:59):

So you can reuse this piece?

Interviewee D05 (9:03):

Yes—still on the same project. When they go to the next panel, they'll put a full sheet on. If they need 700 or 600, they'll go back to the offcut from the previous sheet.

Researcher (10:25):

So panel widths being “random” increases offcuts, but you don't always have the option because that's what the software produces, and the architects specify it.

Interviewee D05 (10:25):

Yeah—we don't have the option here. That's what the software produces. We're always—[unclear]—I know the architects. That's what it produces.

Researcher (10:40):

Now panels with openings: my understanding is you fit whole OSB, then cut out the opening. Is that correct?

Interviewee D05 (11:28):

Yeah—we would... we would cut up to the bottom cell. Go back to the previous drawing.

Researcher (11:42):

So do you cut a piece for the bottom and another for the top? What about pieces around windows?

Interviewee D05 (11:46):

For the top, we're just using offcut.

Researcher (11:55):

Okay.

Interviewee D05 (11:58):

Because it goes through that and tries to cut the hole out.

Researcher (12:03):

That's good practice—you're saving material by planning cuts around openings, rather than fitting a full piece like other factories.

Researcher (12:37):

Now mineral wool: in another factory I observed that cutting is not flush/neat, with some overstuffing because manual cutting is imprecise.

In your case, with a 1.2 m roll and external width 1.2 m, if we cut into two halves (600 + 600), the internal cavity width is about 453 mm each (total less than 1.2 by about 55 mm).

So there is "wasted" area in the form of overstuffed insulation that remains in the panel. I'm not saying it is thrown away—it stays in the panel.

The explanation is: manual measurement and cutting imprecision causes unseen volumes to be overstuffed. To what extent do you agree?

Interviewee D05 (15:07):

Yeah—and the reason is we do it like that as well because we want it a little bit over so it stays in the panel—tight in the panel—so it doesn't fall out. That's why you want it slightly overstuffed.

Researcher (15:20):

Understood.

Researcher (15:50):

Why is panel width not greater than 1.2 m? Is it transport, factory space constraints, or operational agility?

Interviewee D05 (16:30):

All three reasons—plus the weight of the panel.

Researcher (16:33):

So transportation?

Interviewee D05 (16:47):

Yes—we try not to go over 1200. Sometimes we do, but not often. The lorry bed is 2.4 m. So you can put two stacks of 1200 on it.

If you had 1500, you'd only get one stack, because you can't fit two.

Factory space constraints, manual labour lifting, and on-site manoeuvring—it's harder when it's bigger than 1200.

Researcher (17:33):

How does operational agility help?

Interviewee D05 (17:38):

By operational agility—smaller panels made [provide more flexibility] [unclear].

Researcher (17:41):

I'm assuming smaller panels give more flexibility for complex shapes?

Interviewee D05 (17:56):

You mean the building and how we design the buildings?

Researcher (18:01):

Yes.

Interviewee D05 (18:02):

If you make small batches, you'd have to make four panels.

Researcher (18:21):

Yes—exactly.

Interviewee D05 (18:27):

Sort of like 500 by 3 m panels are near the maximum you can manoeuvre. But I can build that quick, compared with 2600 by 1500 panels.

Researcher (18:36):

What happens when you must produce larger panels—what is the maximum?

Interviewee D05 (18:55):

About 1500–1600 wide. Basically, we just send it out of the building as a different entity.

You'd likely have higher transport costs to site. You'd need to check that.

Researcher (19:30):

Finally—why are many panels less than 1.2 m? I understand the 1.2 m logic, but many panels are 500, 700, 800, etc. Why?

Interviewee D05 (19:55):

That'll be down to design—when you come into windows, and where you've got glulam landing across the head of plates and whatnot.

Researcher (20:08):

So it's design-driven. Would you criticise the automated design tool for that?

Interviewee D05 (20:19):

Yes.

Interviewee D05 (20:39):

If a lot of things are 500, then it's all the same—but you do that, so... [unclear].

Interviewee D05 (20:51):

I can show you my wall panel layout—dimensions of the wall panels at the front.

Researcher (21:17):

Yes, I have it. You mean this one? Let me show it quickly.

Interviewee D05 (21:38):

That's the manufacturer panel—let me share the screen.

Researcher (21:45):

Okay.

Interviewee D05 (22:58):

Can you see that?

Researcher (22:58):

Yes, that's very helpful.

Interviewee D05 (23:02):

Can you see it?

Researcher (23:05):

It wasn't showing—now it is.

Interviewee D05 (23:23):

So that explains... [unclear] ...but you can look at ES1, EX2, EX3, EX4, EX5, EX6/7. Then you come to the end and you have a smaller one.

Researcher (23:41):

Is that automated—by Tool A?

Interviewee D05 (23:45):

Yes.

Researcher (23:51):

Can I get this for the same design package?

Interviewee D05 (23:54):

Yes—what we'll do is send you that and send the wall panel layout again. Then you can align them: which is 1, 2, 3, 4, etc.

Researcher (24:04):

That would be great—thank you.

Researcher (24:04):

Thanks for your time. I'll adjust the initial findings and produce a report for your use. My calculations will be approximate since I didn't observe directly, but I'll estimate offcut generation. I appreciate that you reuse a lot of offcuts, but I'm focusing on offcuts at the first instance. Thanks again.

Interviewee D05 (25:00):

I was just going to say—

Researcher (25:02):

Bye, cheers.

Researcher stopped transcription.

Appendix H: Ethics Approval



Faculty of Computing, Engineering & the Built Environment Research Office
Millennium Point, Curzon Street
Birmingham
B4 7XG

BCU_ethics@bcu.ac.uk

30/Jan/2024

Mr Ali Hadi

ali.hadi@mail.bcu.ac.uk

Dear Ali ,

Re: Hadi /#12541 /sub2 /R(B) /2024 /Jan /CEBE FAEC - The Development of Predictive Building Circularity Index: Exploring Off-Site Construction Dynamics for Enhanced Embodied Carbon Circularity Metrics

Thank you for your application and documentation regarding the above activity. I am pleased to take Chair's Action and approve this activity.

Provided that you are granted Permission of Access by relevant parties (meeting requirements as laid out by them), you may begin your activity.

I can also confirm that any person participating in the project is covered under the University's insurance arrangements.

Please note that ethics approval only covers your activity as it has been detailed in your ethics application. If you wish to make any changes to the activity, then you must submit an Amendment application for approval of the proposed changes.

Examples of changes include (but are not limited to) adding a new study site, a new method of participant recruitment, adding a new method of data collection and/or change of Project Lead.

Please also note that the Computing, Engineering and the Built Environment Faculty Academic Ethics Committee should be notified of any serious adverse effects arising as a result of this activity.

If for any reason the Committee feels that the activity is no longer ethically sound, it reserves the right to withdraw its approval. In the unlikely event of issues arising which would lead to this, you will be consulted.

Keep a copy of this letter along with the corresponding application for your records as evidence of approval.

If you have any queries, please contact BCU_ethics@bcu.ac.uk

If you would like to provide feedback on the ethics process, please complete the feedback form using [this link](#).

I wish you every success with your activity.

Yours Sincerely,

Professor Sharon Cox

On behalf of the Computing, Engineering and the Built Environment Faculty Academic Ethics Committee