Offsite Timber Systems Multi-Factor Productivity Index

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This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

Signed: Цветомила

Date: 07/06/2019

I dedicate this thesis to Heimlich Dunchev, my shining star.

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Table of contents

ABSTRACT **1**

CHAPTER 1: INTRODUCTION **2**

CHAPTER 2: LITERATURE REVIEW **7**

2.1 UK ECONOMIC CONTEXT 7
2.2 OFFSITE TIMBER SYSTEMS 12
2.3 OFFSITE CONSTRUCTION MARKET 29
2.4 PRODUCTIVITY MEASUREMENT IN CONSTRUCTION 34
2.6 LIMITATION TO EXISTING KNOWLEDGE 45

CHAPTER 3: METHODOLOGY **46**

3.1 RESEARCH AIM AND OBJECTIVES 48
3.2 RESEARCH DESIGN 49
3.3 USE OF ANALYTICAL SOFTWARE TOOLS 50
3.4 MFP VARIABLES 52
3.5 SAMPLING 52
3.6 ETHICS 53
3.7 CHRONOLOGICAL SEQUENCE 53
3.8 SCIENTIFIC LIMITATIONS 54

CHAPTER 4: MARKET PERCEPTIONS SURVEY **55**

4.1 RESEARCH DESIGN 55
4.2. QUESTIONNAIRE RESULTS AND DISCUSSION 60
4.3. INTERVIEW RESULTS AND DISCUSSION 68
4.4. FOCUS GROUPS RESULTS 82
4.5. MARKET PERCEPTIONS SURVEY SUMMARY 83

CHAPTER 5: MANUFACTURING SURVEY **85**

5.1 RESEARCH DESIGN 85
5.2 PROJECT MANAGEMENT AND PRODUCTIVITY 90
5.3 FACTORY OPERATION PROCESSES 109
5.4 EUROPEAN AND UK MANUFACTURING ANALYSIS AND DISCUSSION 123
5.5 ADDITIONAL INTERNATIONAL EXAMPLES 136
5.6 MANUFACTURING SURVEY SUMMARY 146

CHAPTER 6: CONSTRUCTION PRODUCTIVITY PILOT CASE STUDY: LOW-RISE RESIDENTIAL **149**

6.1 METHODOLOGY 149

6.3 Productivity results and analysis 154
6.4 VTC and OTP case studies summary 164

CHAPTER 7: CONSTRUCTION PRODUCTIVITY DETAILED COMPARATIVE CASE STUDY: MID-RISE RESIDENTIAL 165

7.1 Introduction 165
7.2 Case study buildings 166
7.3 Productivity results 168
7.4 Productivity analysis 177
7.5 CLT and CTP case studies summary 198

CHAPTER 8: DISCUSSION 203

8.1 Multi-factor productivity analysis of offsite timber systems 203
8.2 Offsite timber systems multi-factor productivity index: a theoretical framework 214
8.3 Offsite timber systems multivariate analysis 221
8.4 Offsite timber systems MFP index summary 224

CHAPTER 9: CONCLUSION 226

9.1 Multi-factor productivity of offsite timber systems 228
9.2 Productivity differences between offsite timber systems 230
9.3 Further work 231

REFERENCES 234

APPENDICES 251

Appendix 4A - Market survey questionnaire 251
Appendix 4B - Interview questions 262
Appendix 4C - Full questionnaire responses 264
Appendix 4D - Questionnaire statistical analysis 277
Appendix 5A - Questions for interviews with factory tours of volumetric/panelised timber manufacturers 299
Appendix 6A - Data availability low-rise case studies 301
Appendix 6B - Data collection and analysis method development process 303
Appendix 6C - Constructability results and analysis 316
Appendix 7A - Data availability mid-rise case studies 322
Appendix 7B – CLT and CTP case studies constructability results 324

Please note that Appendices were numbered according to the chapter number they support with capital letters utilised to distinguish their sequence. E.g. Appendix 4A is the first appendix utilised to support Chapter 4, and Appendix 6B is the second appendix supporting Chapter 6.

List of figures

FIGURE 1. PERCENT CHANGE IN UK GDP: CONSTRUCTION PRODUCTIVITY STAGNATION. DATA SOURCE: (ONS, 2017) 2
FIGURE 2. EMBODIED CARBON IN COMMON UK BUILDING MATERIALS. DATA SOURCE: (BRE, 2014). ... 4
FIGURE 3. INTERNATIONAL LABOUR PRODUCTIVITY COMPARISON. DATA SOURCE: (OECD, 2017)........ 7
FIGURE 4. CONSTRUCTION INDUSTRY VALUE LEVERAGE OPPORTUNITIES BETWEEN 2017 AND 2027, UK IN ABSOLUTE VALUE. ADAPTED FROM (UK GOVERNMENT, 2017). 8
FIGURE 5. PERMANENT DWELLINGS IN THE LAST 20 FINANCIAL YEARS (ENDING 1996-2016). DATA SOURCE: (DEPARTMENT FOR COMMUNITIES AND LOCAL GOVERNMENT, 2016:PT.209)............... 10
FIGURE 6. FIRST-YEAR TRAINEES IN CONSTRUCTION ACROSS THE UK. DATA SOURCE: CITB (WISEMAN, ROE & PARRY, 2016). 11
FIGURE 7. CONSTRUCTION AND DEMOLITION WASTE IN THE EUROPEAN UNION 2011. SOURCE: (EUROPEAN COMMISSION, 2016) 12
FIGURE 8. OFFSITE TIMBER CONSTRUCTION SYSTEMS WITH DIFFERENT LEVELS OF PREFABRICATION. SOURCE: AUTHORS' ORIGINAL WORK. AUTHOR'S OWN WORK BASED ON (SMITH, 2011). 13
FIGURE 9. 2D OFFSITE TIMBER SYSTEMS WITH INCREASING LEVEL OF PREFABRICATION. AUTHOR'S OWN IMAGES.......... 14
FIGURE 10. 3D OFFSITE TIMBER SYSTEMS. AUTHOR'S OWN IMAGES, E.CORE POD ADAPTED FROM: (TRADA, 2014).......... 15
FIGURE 11. DISTRIBUTION OF COSTS IN VOLUMETRIC CONSTRUCTION ACCORDING TO (NAO, 2005). .. 17
FIGURE 12. ON-SITE WIND- AND WATER-TIGHT COMPARISON (LAWSON, OGDEN & GOODIER, 2014)... 19
FIGURE 13. THE EFFECT OF OFFSITE SYSTEMS ON TYPICAL CONSTRUCTION PROJECT WASTE MATERIALS, CASUAL LOOP DIAGRAM ADAPTED FROM (LI, SHEN & ALSHAWI, 2014)...................................... 22
FIGURE 14. IDEAL BUILDING LIFE-CYCLE, IN WHICH DESIGN FOR MANUFACTURE AND ASSEMBLY (DFMA) AND DESIGN FOR DISASSEMBLY (DFD) PRINCIPLES ARE COMBINED TO ACHIEVE A CIRCULAR BUILDING ECONOMY THROUGH OFFSITE TIMBER CONSTRUCTION. THIS DOES NOT REFER TO RIBA STAGES. AUTHOR'S OWN WORK. 24
FIGURE 15. GREENHOUSE GAS EMISSIONS ASSOCIATED WITH TRADITIONAL AND MODULAR BUILDING METHODS OF A THREE-BEDROOM DETACHED HOUSE IN THE U.S.A. DATA SOURCE: (QUALE *ET AL.*, 2012).......... 26
FIGURE 16. OFFSITE SECTOR SEGMENTS GROSS VALUE OUTPUT (TURNOVER) DISTRIBUTION FOR 2008. DATA SUMMARISED FROM (TAYLOR, 2010). 30
FIGURE 17. GVA INCREASE RESULTING FROM PROJECTED OFFSITE UPTAKE TO 25% OF CONSTRUCTION IN THE PLANNED HEATHROW EXPANSION. DATA SOURCE: (WPI ECONOMICS, 2017). 31
FIGURE 18. SCOTTISH OFFSITE SECTOR PRODUCTIVITY, SECONDARY DATA CALCULATIONS BASED ON FINDINGS FROM (SMITH *ET AL.*, 2013). 1 UNIT = 1 HOME = 1 HOUSE OR 1 APARTMENT. 33
FIGURE 19. RESEARCH METHODOLOGY. 47

FIGURE 20. TOTAL MAIN MARKET SURVEY SAMPLING DISTRIBUTION BY PROFESSION (QUESTIONNAIRE AND INTERVIEWS). 59
FIGURE 21. PARTICIPANTS' KNOWLEDGE OF OFFSITE SYSTEMS, COMBINATION OF TWO QUESTIONS WITH AVERAGED VALUES FOR 2D SYSTEMS (FAÇADE PANELS, OPEN PANELS, CLOSED PANELS) AND 3D SYSTEMS (BATHROOM PODS, KITCHEN PODS, VOLUMETRIC STEEL AND VOLUMETRIC TIMBER) WITH CALLED OUT FAMILIARITY WITH VOLUMETRIC TIMBER SYSTEMS. 60
FIGURE 22. PERCEPTION OF TIME AS AN ADVANTAGE OR DISADVANTAGE COMPARED TO TRADITIONAL CONSTRUCTION METHODS. 61
FIGURE 23. PERCEIVED RELEVANCE OF COST AS A BARRIER AND FACTOR TO INCREASE VTC SPECIFICATION. 62
FIGURE 24. PERCEPTIONS REGARDING SELECTED VTC DEMAND FACTORS. 63
FIGURE 25. PERCEIVED RELEVANCE OF BUILDING SYSTEMS IN THE UK GROWING MARKET CONTEXT OF THE NEXT 5-10 YEARS. 64
FIGURE 26. PERCEPTIONS OF ENERGY EFFICIENCY AND BUILD QUALITY AS POTENTIAL ENABLERS. 65
FIGURE 27. DESIGN FLEXIBILITY PERCEPTIONS AS A BARRIER (N RESPONSES=22) AND AS A POTENTIAL ENABLER (N RESPONSES=21) TO VTC SPECIFICATION IN THE UK. 65
FIGURE 28. PERCEPTIONS OF BIM VARIABLES. 66
FIGURE 29. PERCEPTIONS REGARDING WORKING KNOWLEDGE. 67
FIGURE 30. INTERVIEW PARTICIPANTS' DEFINITIONS OF VTC. 69
FIGURE 31. TYPES OF PARTICIPANTS' PREVIOUS EXPERIENCES. 69
FIGURE 32. PERCEPTIONS OF VTC PROJECT TIMES VS CONVENTIONAL CONSTRUCTION. 70
FIGURE 33. PERCEPTIONS OF THE COST OF VTC COMPARED TO CONVENTIONAL CONSTRUCTION. 71
FIGURE 34. PERCEPTIONS OF THE COST OF VTC COMPARED TO CONVENTIONAL CONSTRUCTION IN MORE DETAIL AND DIVIDED INTO PROFESSIONAL GROUPS. 71
FIGURE 35. PARETO DIAGRAM OF PERCEIVED BARRIERS TO VTC IMPLEMENTATION, WHERE THE RED LINE IS USED TO DETERMINE THE MOST IMPORTANT FACTORS BY DRAWING A PERPENDICULAR DASHED LINE. 72
FIGURE 36. PERCEIVED SUITABILITY OF BUILDING TYPES FOR VTC. 73
FIGURE 37. PERCEIVED CHANGES IN THE BUILDING REGULATIONS IN THE UK IN THE NEXT 5-10 YEARS. 75
FIGURE 38. PERCEPTIONS OF VTC DESIGN FLEXIBILITY. 77
FIGURE 39. PERCEIVED PROJECT MANAGEMENT STRATEGY CHANGES NEEDED FOR VTC. 77
FIGURE 40. PERCEIVED COMPLIANCE OF VTC WITH BUILDING REGULATIONS BY (A) TYPE AND (B) THEME. 78
FIGURE 41. PARETO DIAGRAM (AMERICAN SOCIETY FOR QUALITY, 2016) OF PERCEIVED OPPORTUNITIES PRESENTED BY VTC, WHERE THE RED LINE IS USED TO DETERMINE THE MOST IMPORTANT FACTORS BY DRAWING A PERPENDICULAR DASHED LINE. 79
FIGURE 42. PERCEIVED IMPORTANCE OF BIM IN THE NEXT 5-10 YEARS. 80
FIGURE 43. PERCEIVED CONNECTION BETWEEN BIM AND VTC BY TYPE. 81

Figure 44. Perceived connection between BIM and VTC by theme. 81
Figure 45. Total survey sampling by profession. 87
Figure 46. Examples of timber stud systems – closed panels (left) and volumetric (right). 90
Figure 47. Construction detail examples. 94
Figure 48. Generalized factory management hierarchical system. 106
Figure 49. Examples of automated (UKP) and manual working environments (UKV, EUV). 106
Figure 50. Generalized panel and volumetric manufacturing lines. 110
Figure 51. Number of manufacturing lines per company. 111
Figure 52. Manufacturing types: static production (left) and dynamic production (right). 111
Figure 53. Generalized panel manufacturing flow, indicating a high potential for automation. 111
Figure 54. Generalized volumetric manufacturing flow, indicating mostly manual tasks. 113
Figure 55. Framing station (semi-automated production) with annotated highlights. ... 114
Figure 56. Automation use per manufacturing line. 115
Figure 57. Nailing bridge example with 2 nail guns, which move along support beams on 3 axis and automatically nail the OSB sheet to the timber frame in seconds. 115
Figure 58. Example of a CNC saw, which cuts intricate shapes accurately and quickly and reduces the risks of working with sharp cutting tools. 115
Figure 59. Mechanisation per manufacturing line. 116
Figure 60. Example of an indoor crane, attached to a floor cassette and a vacuum machine. 116
Figure 61. Example of a butterfly table, which rotates the panel from horizontal to vertical on one steel frame 'wing', the timber panel is then transferred onto the opposite wing and rotated back to horizontal position, 180° flipped from its starting position. 117
Figure 62. Manufacturing stages without use of automation nor mechanisation. 118
Figure 63. Examples of manual production activities, bespoke panels assembly with a manual nail gun and installation of insulation. 118
Figure 64. Space saving strategies per manufacturing stage. 119
Figure 65. Examples of rail storage and inventory control examples. 119
Figure 66. Waste reduction strategies observations per manufacturing stage. 120
Figure 67. Example of material type segregation for recycling. 120
Figure 68. Variety of waste reduction strategies observed per main manufacturing stage. 121

FIGURE 69. OFFSITE SYSTEMS CLASSIFICATION COMPARATIVE REVIEW ACCORDING TO BUILDING ELEMENTS COMPLETION IN THE FACTORY (GIBB & ISACK, 2003; OLIVEIRA *ET AL.*, 2017; SMITH, 2011; HAIRSTANS, 2015; MMC WALES, 2008). 124
FIGURE 70. OFFSITE AND ONSITE BUILDING COMPLETION PERCENTAGE CALCULATED VALUES. 125
FIGURE 71. PILOT 1-BEDROOM LIVING UNIT EQUIVALENT VISUALISATIONS. AUTHORS' OWN WORK, INCLUDES ADAPTED TRIMBLE SKETCH UP STOCK FURNITURE MODELS AND IS BASED ON PUBLICLY AVAILABLE DATA (SINTEF, 2013). 129
FIGURE 72. LIVING UNIT-EQUIVALENT SELECTION METHODOLOGY APPLIED IN THIS RESEARCH. 130
FIGURE 73. HOUSEHOLD DISTRIBUTION IN THE UK: A) ENGLAND AND WALES, B) SCOTLAND. DATA SOURCES: (OFFICE FOR NATIONAL STATISTICS, 2018; NATIONAL RECORD OF SCOTLAND, 2013). 131
FIGURE 74.COMPARATIVE PRODUCTIVITY ANALYSIS FOR 2-BEDROOM LIVING UNIT EQUIVALENT, WHERE THE GOLD COLOUR INDICATES THE DATA AVERAGE. 134
FIGURE 75. BENCHMARK OF LABOUR PRODUCTIVITY RESULTS (SMITH *ET AL.*, 2013). 135
FIGURE 76. EXAMPLE TYPICAL VOLUMETRIC HOUSE INTERIOR AND EXTERIOR. 137
FIGURE 77. LAMINATED STRAND LUMBER PANELS AND A MODULAR ROOF OBSERVED IN CANADA. .. 138
FIGURE 78. COMMUNITY HEALTH CENTRE IN CANADA: EXTERIOR SHOWING ORGANIC PROFILE. 140
FIGURE 79. COMMUNITY HEALTH CENTRE IN CANADA: INTERIOR SHOWING GLULAM BEAMS. 140
FIGURE 80. LEAN TOOL DEVELOPED BY A VOLUMETRIC TIMBER MANUFACTURER IN SWEDEN. AUTHOR'S OWN IMAGES. JUNE 2017. 141
FIGURE 81. VOLUMETRIC TIMBER MANUFACTURING PROCESS IN SWEDEN: PANELISED AND MODULES. AUTHOR'S OWN IMAGES. JUNE 2017. 142
FIGURE 82. CLOSED TIMBER PANEL PRODUCTION IN SWEDEN: AUTOMATED ASSEMBLY LINE AND MANUAL BENCHES. AUTHOR'S OWN IMAGES. JUNE 2017. 144
FIGURE 83. HOTEL WITH LIGHTWEIGHT CLT EXTENSION OF FOUR STOREYS. AUTHOR'S OWN IMAGES. JUNE 2017. 145
FIGURE 84. CLT MANUFACTURING EXAMPLES: SORTING, AND ADHESIVE & PRESSURE MACHINE. AUTHOR'S OWN IMAGES. JUNE 2017. 145
FIGURE 85. VTC AND OTP CASE STUDIES OVERVIEW. 151
FIGURE 86. OTP CASE STUDY AS PROPOSED CONSTRUCTION. ADAPTED FROM CONTRACTOR'S PROGRAMME. 155
FIGURE 87. SUMMARY TASK LEVEL DATA ENTRY AND REPORTING PILOT: VOLUMETRIC CASE STUDY. 156
FIGURE 88. TASK LEVEL DATA ENTRY AND REPORTING PILOT: VOLUMETRIC CASE STUDY WITH MINOR BUGS IN C12 AND C52. 157
FIGURE 89. SUB-TASK LEVEL DATA ENTRY AND REPORTING PILOT: VOLUMETRIC CASE STUDY, WHERE _1 TO _5 IDENTIFY CONSTRUCTION PROJECT PHASES 1 TO 5. 157
FIGURE 90. HAND-DRAWN SKETCH PLAN SKETCH OF ACTUAL VOLUMETRIC UNIT INSTALLATION DATES. 158
FIGURE 91. WASTE TYPE DISTRIBUTION ON AVERAGE FOR VTC CASE STUDY, 02/2016 TO 05/2017... 161

Figure 92. High-risk activity near-miss installation scenario instance marked in red. .. 162
Figure 93. Example visual management boards used in the VTC and OTP case studies. ... 163
Figure 94. CLT project: overview, typical layout and during construction. 167
Figure 95. CTP project: overview, typical layout and during construction...................... 168
Figure 96. CLT as planned C11-level coded programme. 169
Figure 97. CLT percent work complete per task, actual values on 23/10/2017. 170
Figure 98. Actual CLT Gantt Chart with original completion date marked using a red line.. 171
Figure 99. CLT Actual work and remaining work for 23/10/2017, and total work per resource. 173
Figure 100. CTP project actual Gantt chart. 174
Figure 101. Closed timber panel project work (labour-hours) per resource. 176
Figure 102. CLT task group duration: planned versus actual, measured in working days. 177
Figure 103. CLT task duration comparison as planned versus actual, measured in working days. 179
Figure 104. Task group CLT start and end date difference comparison, measured in working days. 180
Figure 105. Selected tasks start and end date difference comparison, measure in working days. 181
Figure 106. Task productivity and duration per task, measured in hours per plot 186
Figure 107. Labour-hour utilisation per work group as a percentage of overall project labour-hours.. 187
Figure 108. Task group productivity comparison: CTP and CTP projects. 188
Figure 109. Total working days per plot. 190
Figure 110. Total labour-hours per plot. 190
Figure 111. Base task group cost and labour-hours: CLT vs CTP case studies. 193
Figure 112. Waste distribution on average per plot. 196
Figure 113. Construction project productivity conceptual model for offsite timber systems. Author's own work 2017. 219
Figure 114. Spider diagram used to communicate the differences between offsite and onsite construction. Adapted from (Miles & Whitehouse, 2013)................................. 220
Figure 115. Proposed visualisation of Offsite timber Systems MFP index: single-project or stage, and multiple project or stages. 220
Figure 116. Comparative analysis of four construction case studies, on a project level with emphasis on the offsite system installation stage. 222

Abstract

The construction industry in the UK has been characterised in recent years by stagnating productivity. Offsite methods of construction which involve building in a factory environment, have been suggested as part of the solution to this issue. Within the current economic context, this thesis focussed on timber systems and examined the existing literature relating to their Multi-Factor Productivity (MFP) measurements, identifying a gap in knowledge relating to comparative MFP index for different offsite timber systems. A subsequent market perception survey amongst built environment professionals highlighted an opportunity for offsite timber systems to increase efficiency. However the responses indicated the importance of examining advanced offsite timber systems such as Volumetric Timber Construction (VTC) in comparison to established in the UK market panelised timber systems. A manufacturing survey was then undertaken which compared the productivity of VTC manufacturers in the UK and mainland Europe with open and closed timber panel manufacturing techniques in the UK. The main findings from the survey were that the European VTC and UK panelised manufacturers had similarly high productivity and the UK VTC manufacturers had potential for growth. The MFP of four timber construction projects was then analysed: two low-rise residential projects (using open timber panel and VTC), and two mid-rise residential developments (one using closed timber panels and one using cross-laminated timber). The results revealed that increased offsite completion in the factory could result in increased construction productivity however external and internal works were still a major challenge to efficiency. The overall analysis was used to outline a theoretical framework for an innovative MFP index with five key quantified variables and five secondary qualitative variables. This index facilitates the measurement and comparison of construction productivity between a variety of different structural systems and is one of the unique contributions to knowledge generated in this thesis.

Chapter 1: Introduction

The UK construction-economic context is characterised by pressing challenges in labour productivity, energy-efficiency, waste materials and digitisation, amplified by uncertainty resulting from Brexit (The Economist, 2018). Indeed, the productivity of construction in the UK has stagnated in recent years as shown in **Figure 1** (ONS, 2017), in line with international trends of low construction productivity compared to other industries (O'Connor, 2018). Within this context, annual home completions have been routinely significantly lower than the estimated national housing demand and therefore the UK industry is faced with the challenge of building more homes with fewer labour resources.

Figure 1. Percent Change in UK GDP: construction productivity stagnation. Data source: (ONS, 2017)

Today's challenges are routed in historic events from the 20th century. For instance, in 1934 Alfred Charles Bossom published one of the first in a series of critical reviews of the construction industry (Bossom, 1934). Bossom discussed the unstructured business-as-usual processes of the construction industry. He stated that the built environment negatively impacted the economy by causing process waste. Sixty years later in the UK, Latham discussed the same topic, and hypothesised that the process wastes of construction could be resolved by educated clients (Latham, 1994). Terminology now connected to BIM was also highlighted in the Latham report, such as the recommended use of 'Co-ordinated Project Information'. Throughout the report the focus was on contractual relationships and the need for clients to select tenders not only on cost, but also with consideration to final product quality. Furthermore, these topics were re-iterated in a different format in the subsequent 'Rethinking Construction' report, where the UK construction industry was urged to improve quality of builds, increase efficiency and profitability (Construction Task Force, 1998). This was underpinned by a need for investment in skills development across all occupations and professions.

In recent years the ambitions of the UK Government have echoed the past themes of cost and efficiency, and emphasised the importance environmental impact (HM Government, 2013). Critically, the Farmer Review compared the current practices of the construction industry were analogised to a lethal disease, whose only possible cure was modernisation (Farmer, 2016). Among the ten target areas recommended for disruptive improvement were productivity, profitability, skills and the predictability of project time and cost.

One of the solutions to these complex and multi-factor issues requires a diversion from traditional construction methods and a decision to move towards Modern Methods of Construction (MMC). The term is used more and more frequently today and originates from the 1998 Egan report (Lawson, Ogden & Goodier, 2014). MMC and can be defined as follows:

> *Modern Methods of Construction (MMC) are defined as those which provide an efficient product management process to provide more products of better quality in less time. It has been defined in various ways: pre-fabrication, off-site production and off-site manufacturing (OSM). But while all OSM is MMC not all MMC is OSM.*
>
> Home Builders Federation in (Burwood & Jess, 2005)

Offsite construction is one of the building methods that can be used to achieve MMC. Offsite construction can be described as an umbrella term for construction systems, which transfer a percentage of the construction process from the building site to a controlled factory environment, also known as ‘smart’, or ‘industrialised’ construction (Hairstans, 2015). Other variations in terminology include ‘Prefabrication’ and ‘prefab’, which tend to be outdated terms and can be associated with stigma from the post-war period, when residential construction aimed for the skies (Pepper, 2017; Nadim & Goulding, 2011; Edge *et al.*, 2002). These events may have made a lasting impression on the generation of built environment professionals, however today there is a strive towards an improved perception of offsite systems through emphasis on technological advancements, or ‘smart construction’ (HM Government, 2017).

Indeed, numerous publications and case studies have demonstrated that offsite construction can have significant efficiency advantages over traditional methods of construction (Hairstans, 2010; Krug & Miles, 2013). Frequently cited benefits of offsite construction including reduced time on site, waste reduction and improved quality, have been proposed to help alleviate the current need for housing (McCallie & Barton-Maynard, 2015). This thesis investigated these and other offsite construction productivity variables in the current economic context by collecting primary data from offsite designers, manufacturing plants and construction projects.

Due to the global need to reduce carbon dioxide (CO_2) emissions, timber was selected in this thesis as the main building material for offsite systems in this thesis (United Nations, 2015). Timber was identified as the only renewable material, which sequesters carbon, as shown in **Figure 2** (BRE, 2014).

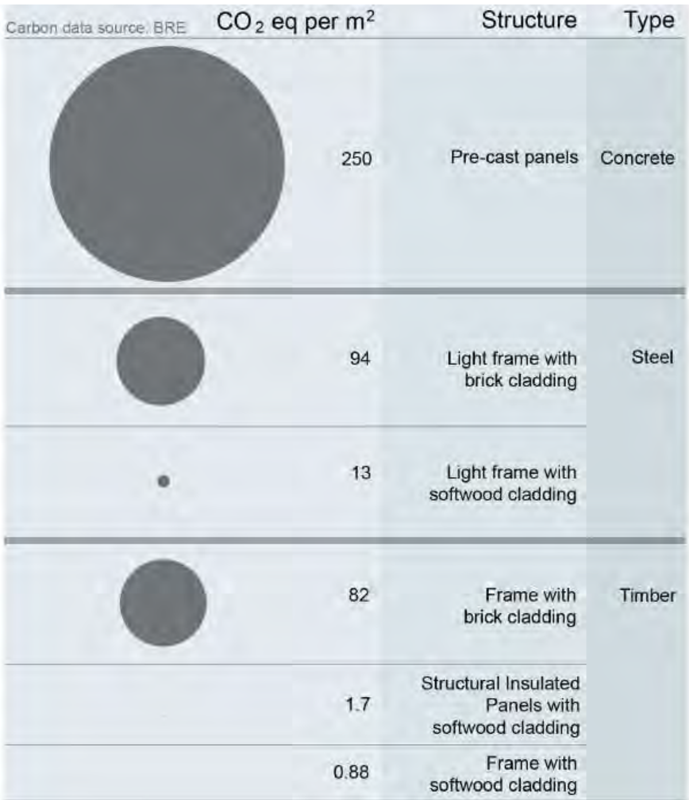


Figure 2. Embodied carbon in common UK building materials. Data source: (BRE, 2014).

Timber was also selected because forests can be managed sustainably to produce more timber resource overall than the amount felled for construction, packaging, paper, pulp and bio-fuel as, therefore creating a replenishable natural building resource (Forestry Commission, 2014). At the time of writing, the UK forested area was estimated at 3.17

million hectares, of which the highest concentration was found in Scotland, where trees covered 20% of land in 2018 (Forest Research, 2018b). From these forests, 11.2 tonnes of wood were produced for UK sawmills, mainly for production of fencing and pallets, however in addition £7.8 billion-worth of wood products were imported in the UK, mainly for use in construction (Forest Research, 2018a). Therefore, there is a need to utilise more home-grown timber in construction, and for research which demonstrates what high-value products could be produced from timber.

Bringing all the above themes together, this doctoral thesis has investigated the multi-factor productivity (MFP) of Volumetric Timber Construction (VTC) in the context of both emerging and established offsite timber systems within the UK market, namely Open Timber Panels (OTP), Closed Timber Panels (CTP) and Cross-Laminated Timber (CLT). The comparative productivity of the different offsite timber systems was explored through a mixed methods methodology with six subsequent research phases summarised in **Table 1**, to each of which a separate chapter is dedicated within this thesis. A mixed methods methodology may be defined as one which 'focuses on collecting, analysing, and mixing both quantitative and qualitative data in a single study or series of studies', and its main benefits is a better understanding of issues from several perspectives than may be possible by using only qualitative or quantitative methods alone (Creswell & Clark, 2007; Zou, Sunindijo & Dainty, 2014)

Table 1. Main opportunities and challenges associated with offsite timber systems (non-exhaustive list with only top 10 aspects identified from the reviewed literature).

Research phase	***Knowledge gap***	***Contribution to knowledge***
Literature review	Combined review of the current UK economic context, offsite timber systems and productivity measures (Mtech Group & Gibb, 2007; Smith *et al.*, 2013).	Identification of ten MFP variables for MFP analysis of offsite timber systems, as a theoretical framework. The justification for this may be found in Chapter 2.
Market survey	A lack of data on the perception and knowledge of built environment designers regarding advanced offsite timber systems, specifically VTC (Goulding & Arif, 2013).	A snapshot in time of the perceived opportunities and challenges of VTC in the context of panelised timber systems, and the most effective offsite timber knowledge dissemination strategies. The justification for this may be found in Chapter 4.
Offsite Timber manufacturing survey	No technical guidance on the manufacturing processes of advanced offsite timber systems existed to inform designers and project stakeholders (SINTEF, 2013; Pan, Gibb & Dainty, 2005).	In-depth comparative product, process and productivity analysis of UK timber panels, UK volumetric and EU volumetric timber manufacturers. The justification for this may be found in Chapter 5.

Research phase	*Knowledge gap*	*Contribution to knowledge*
Construction case studies: low-rise	No specific data collection and analysis tools proposed for comparative productivity and constructability analysis of offsite timber systems (The Chartered Institute of Building *et al.*, 2011; Isaac & Navon, 2013).	Explorative use of BIM tools, data collection and analysis spreadsheets and project management software for comparative offsite construction productivity measures, with developed Work Breakdown Structure (WBS). The justification for this may be found in Chapter 6.
Construction case studies: medium-rise	Lack of data on offsite timber systems constructability and productivity within the entire project build process, from foundations to completion (Buildoffsite, 2010; Court *et al.*, 2009; Hairstans & Smith, 2017)	Comparative full-project bottom-up labour productivity analysis of CLT and CTP systems, with ten-variable MFP analysis (five primary and five secondary variables). The justification for this may be found in Chapter 7.
Multi-factor productivity index proposal for offsite timber systems	No existing method for comparatively evaluating and effectively disseminating the multi-factor productivity performance of offsite timber systems within the UK market (Jorgenson, 2017; O'Mahony & Timmer, 2009).	Synergy of the findings from the previous research stages into a unique and original comparative productivity analysis method according to ten MFP variables, of which five were categories as 'main' and quantitative, and five were categorised as 'secondary' and qualitative. The justification for this may be found in Chapter 8.

Although every effort has been made to ensure a high sample diversity and a rigorous methodological approach, the findings from this thesis should not be generalised to all instances of offsite timber projects in all international economic contexts, however they do provide a robust overview of state-of-the-art trends in UK offsite timber construction.

With future research, the conclusions of this thesis could be extended with multi-factor productivity research at a national and potentially global scale. Further work could include applied modelling and simulation of offsite timber systems design, manufacture and construction processes in order to optimise specific project criteria. Thus, the proposed MFP index could be refined using nominal composite variables for comparative evaluations.

Chapter 2: Literature review

2.1 UK economic context

2.1.1 UK productivity context

Productivity is conventionally defined as the "the ratio of (the product's) output to (the product's) input" (Fried, Lovell & Schmidth, 1993:p.4). Although this is not a perfect definition with some limitations, it was preferred over others such as relating to the 'efficiency' of a machine, person and process. The OECD adopts a separate definition in its productivity database, 'labour productivity per hour' (Freeman, 2008). A country's productivity dictates its citizens' standard of living (Mankiw & Taylor, 2010). Productivity statistics and benchmarks are often measured in monetary output per unit of time worked. In general, when a country's productivity decreases, more labour is utilised, whereas when productivity increases, the country's labour is more efficient, i.e. they achieve more output with fewer labour hours. For example, France's economy was characterised in 2016 by a decrease in labour utilisation and a corresponding increase in labour productivity, shown in Figure 3. Therefore, France's workforce was considered more labour efficient, achieving more with less. A similar trend was observed in Canada's economy, albeit to a smaller degree. In contrast, in the UK economy in 2016 there was an increase in labour utilisation, which led to a decrease in labour productivity. The effect on the economy was similar in extent to that of France, however in the opposite direction, i.e. in the UK economy across all sectors, more labour use achieved less output.

Figure 3. International labour productivity comparison. Data source: (OECD, 2017).

Despite the differences in national economies, the productivity of the construction industry across the USA, Italy, Mexico, Japan and other countries has plateaued internationally during the course of the last decade (The Economist, 2017). This issue was acute in the UK, where there has been a historic trend of low construction productivity percentage-changes with associate criticisms of the construction industry, discussed in **Chapter 1** (ONS, 2017).

2.1.2 UK digitisation context

The stark difference in productivity between the construction, manufacturing and services industries can be explained in part by the use of digitisation. Technology improvements in computers and personal devices have had a positive impact on our personal productivity ranging from quicker document processing to increased heart rate control. Globally, construction was the second-lowest industry according to technology uptake (before agriculture and hunting) (Agarwal, Chandrasekaran & Sridhar, 2015). In contrast, industries such as Wholesale Trade and Finance & Insurance have been among the top five industries with high digitisation. Within this context, the UK was one of the countries with the slowest digitisation across all industries, expressed mainly through use of websites, e-purchases and supply chain management technologies (CBI, 2017). Therefore, across in all industries and especially in construction, there could be significant potential to increase productivity through the adoption of existing and emerging technologies (SMAS, 2017). Approximately £89 billion could be added to the industry from the construction industry through increased efficiencies and digitisation between 2017 and 2027 (UK Government, 2017). Construction's estimated contributions are shown in **Figure 4**, it had the highest potential for value added among all the UK industries (which are not shown in the figure).

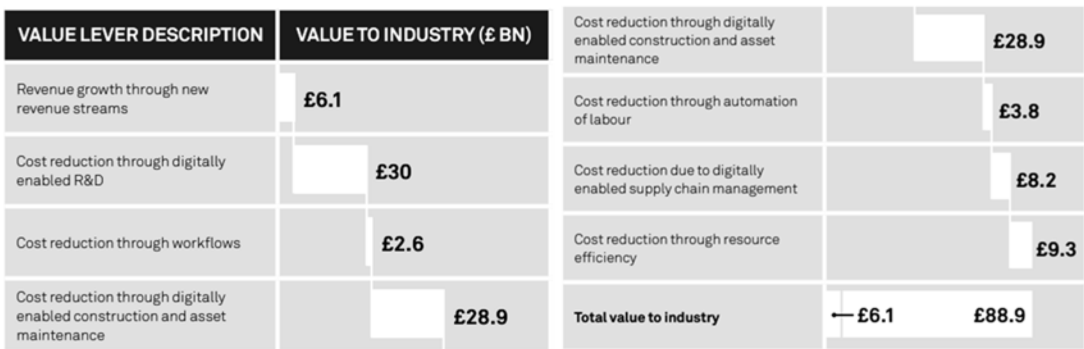


Figure 4. Construction industry value leverage opportunities between 2017 and 2027, UK in absolute value. Adapted from (UK Government, 2017).

2.1.3 UK Building Information Management (BIM) context

The UK Government recognised the global importance of Building Information Management (BIM) and in an agenda to establish the UK as a world leader in BIM, required that from April 2016 all centrally-funded construction projects complied with BIM Level 2 (HM Government, 2012). Within the BIM definition the emphasis falls on the 'I' for 'information', and BIM level 2 can be defined by "an information exchange process which is specific to that project and coordinated between various systems and project participants" (NBS, 2018). This may include 3D models with attached component information but can also be carried out using any combination of software packages (Scottish Futures Trust, 2018). Moreover, British Standards guidelines have been published to guide built environment professionals in their BIM journey (BSI Standards Limited, 2007). The aim of the guidance is to progress towards BIM Level 3, defined as an integrated design with a building model which is single source of truth. UK digital ambitions have been further emphasised in the 2017 British Industrial Strategy, which highlighted smart construction investments in digital construction skills, artificial intelligence (AI), clean smart energy and efficiency improvements (HM Government, 2017).

2.1.4 Housing demand and supply

In England alone there has been an urgent requirement to construct approximately 240,000 houses per year in order to alleviate what is being termed the "housing crisis" (de Castella, 2015; Miles & Whitehouse, 2013). In Scotland and Wales there are similar requirements, such as the Scottish Government's commitment to building 50,000 affordable homes by 2021 with a £3bn investment to reach this target (Scottish Government, 2017). At present the UK industry is only estimated to have maximum capacity to deliver approximately 150,000 out of the required more than 260,000 homes per year, shown in **Figure 5**. Therefore, implementation of Modern Methods of Construction, specifically offsite construction methods, has been suggested as an essential component of the solution to the shortage in dwelling completions (Miles & Whitehouse, 2013).

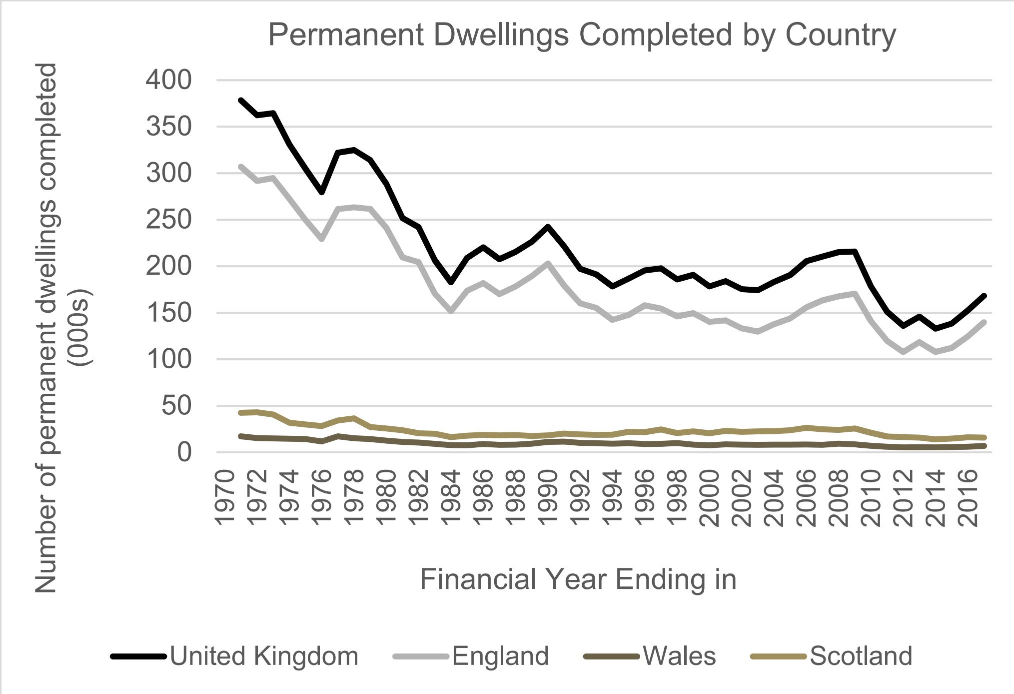


Figure 5. Permanent dwellings in the last 20 financial years (ending 1996-2016). Data source: (Department for Communities and Local Government, 2016:pt.209).

2.1.5 UK skills context

The above housing delivery challenge for the industry is being further exacerbated by a widely reported skills shortage (Farmer, 2016). The skills shortage in the UK construction industry can be illustrated using the statistics for first-year trainees across all trades according to the Construction Industry Training Board (CITB), shown in **Figure 6** (Wiseman, Roe & Parry, 2016). In the decade between 1994 and 2005 there was an upward trend in trainees' intake in construction, whereas from 2006 to 2012 there was a sharp downward trend, mostly reduced in 2009 due to the recession. Positively there has been a slight upward trend in recent years. However, because of the cumulative effect of the previous years, approximately 20% of construction businesses reported a skill gap. The 2016 data stated that the occupations most affected by the skills gap were the following: scaffolders among the trades; architects among the services and managers/directors among the businesses operations skills.

Figure 6. First-year trainees in construction across the UK. Data source: CITB (Wiseman, Roe & Parry, 2016).

2.1.6 UK waste materials sent to landfill context

The latest available data from 2014 on construction waste in the UK showed that construction, demolition and excavation waste from buildings and infrastructure represented 59% of all waste in the UK, or nearly 120 million tonnes (DEFRA, 2018). Because of the large contribution of the built environment to waste materials in the UK, small waste reduction measures in construction have the potential to have a large impact. Waste separation and recycling can reduce waste materials in construction and in fact the UK was among the top countries for recycling percentage of built environment waste, shown in **Figure 7** despite the high proportion of construction waste sent to landfill (European Commission, 2016). In addition, it has been estimated that only 1% (21,600 tonnes) of the timber waste in the UK is recycled, and the rest is sent to landfill because of issues with metal fixings and chemical treatments which prevent timber recyclability (Voulvoulis, 2014).

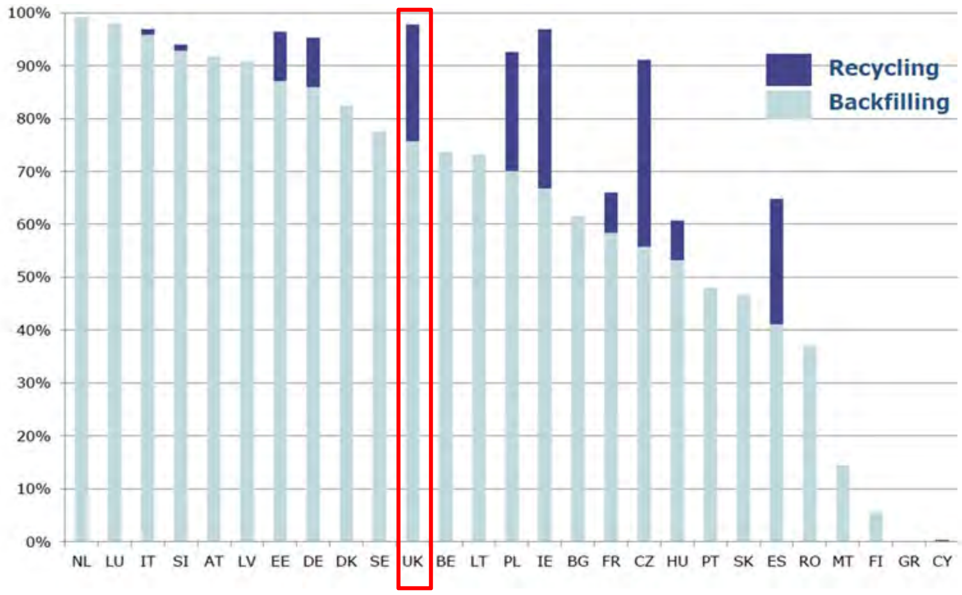


Figure 7. Construction and demolition waste in the European Union 2011. Source: (European Commission, 2016)

2.1.7 UK economic context summary

Overall the reported data in the sections above showed a significant potential for productivity increase in the historically under-performing construction industry, and the issue of labour-productivity should not be viewed in isolation (McKinsey, 2017). The above discussion demonstrated that productivity issues were interconnected with other economic drivers such as digitisation, housing delivery, the skills shortage and waste materials. For example, increased uptake of technology in offsite construction to manufacture buildings, could have a positive impact on the productivity in construction (measure GVA), similar to those observed in the manufacturing industry (UK Government, 2017). It would be important to underpin this with development of skills in offsite construction, to achieve an increase in housing completions to tackle what has been referred as the 'housing crisis' in the UK. In addition, with resource-efficiency improvement techniques from the manufacturing industry, the economic and environmental sustainability of construction can be reduced by optimising the use of materials. Yet the extent of these impacts would depend on the type of offsite timber systems, and their multi-factor productivity characteristics.

2.2 Offsite timber systems

2.2.1 Offsite timber systems classification

Not all offsite timber systems share the same qualities, typically different systems are classified according to the product's level of offsite completion when leaving the factory.

Open panels, closed panels and volumetric modular systems have increasing levels of prefabrication, as shown in **Figure 8**, with the lower levels of prefabrication involving more work onsite. With lower level of offsite completions, there are increased opportunities for changes to the design, specification and details after construction has started. In contrast, with higher the level of prefabrication, more work is done offsite and more opportunities are created for manufacturing process optimisations and increased product quality control.

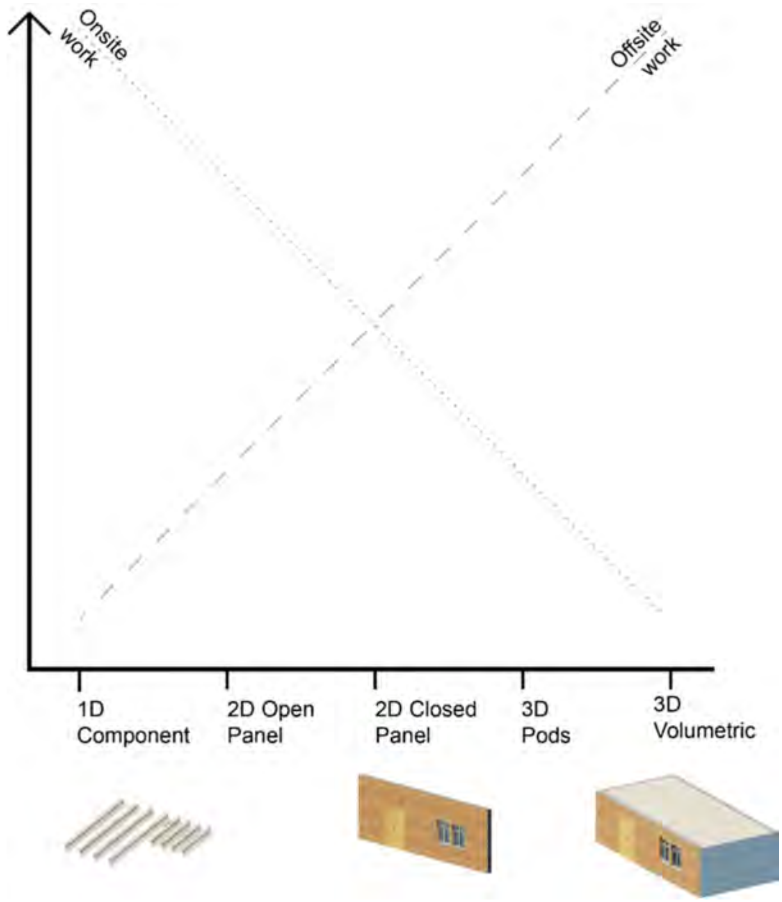


Figure 8. Offsite timber construction systems with different levels of prefabrication. Source: authors' original work. Author's own work based on (Smith, 2011).

Panelised timber systems

Two-dimensional timber frame panel systems, as shown in **Figure 9,** have become mainstream in the UK domestic sector, especially in Scotland during the last 30-40 years, where the challenging weather conditions dictate a need to reduce time on site (The NHBC Foundation, 2016). Applications of laminated timber products have moreover provided new opportunities for application of panelised timber construction in tall timber buildings (Hairstans, 2018).


Cross-laminated timber panel Closed timber panel

Figure 9. 2D offsite timber systems with increasing level of prefabrication. Author's own images.

Open timber panels

Open timber panels are typically manufactured manually in the UK, and include the timber frame with a sheathing on one side, such as an OSB board (Hairstans, 2015). The timber frame may be manufactured either manually on assembly benches, or using semi-automated equipment such as frame assembly stations. Open timber panels represent the lowest level of offsite completion on the factory for panelised timber systems.

Closed timber panels

Closed timber panels can also be referred to as 'enhanced', and can have different levels of work completed in the factory (Hairstans, 2015). In the UK closed timber panels typically include insulation, sheathing on both sides and in the more enhanced products, with optional windows and doors can be included. Similar to the open panels, they may be manufactured either manually or semi-automatically with use of butterfly tables for rotating the timber frame elements so that insulation may be fitted.

Laminated timber

Laminated timber panels can also be referred to as 'mas timber' or 'engineered timber' and originate from Germany, where Glue-Laminated Timber (Glulam) was first developed (Mueller, 2010). To create a long-spanning, timber planks were finger-jointed and glued (laminated) together to create beams whose strength properties were greater than those of the individual elements.

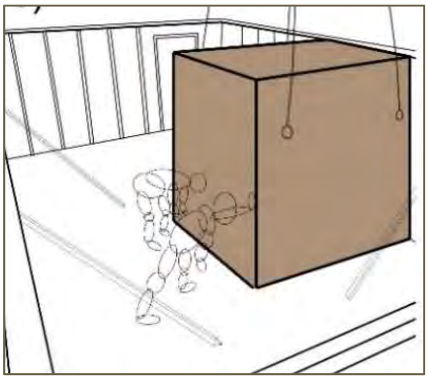
Another type of laminated timber system is Cross-laminated timber (CLT). Because timber is strong in compression only along the direction of the grain, in the production of CLT timber planks are arranged with altering directions of the grain (parallel and perpendicular)

(Hairstans, 2018). Increasingly taller buildings have been constructed across the globe using CLT, the tallest of which at the time of writing is a 17-storey CLT and Glue-laminated timber buildings with a ground concrete storey at the University of British Columbia, Vancouver, Canada (Ravenscroft, 2016). CLT has been used in the UK in residential projects such as the 1999 9-storey apartment block in Murray Grove, Hackney, London and in 2017 for a 10-storey residential building in London (CABE, 2011; Pearson, 2016).

Nail-laminated timber (NLT) and Dowell-laminated timber (DLT, Brettstrapel), are similar to CLT, but the adhesives are replaced with nails and hardwood dowels, respectively.

Volumetric timber systems

Among the timber offsite timber systems, VTC has the highest percentage of activities transferred to the factory environment. At the end of the manufacturing lines, the modules can include the structural frame, insulation, sheeting, glazing, internal finishes, as well as mechanical, electrical and plumbing (MEP) services and cladding (Lawson, Ogden & Goodier, 2014). The 3D modules are then transported to the construction site and assembled using a crane, typically with few labour resources. Finally, the modules are 'stitched' together, filling the gaps in floor surfaces, wall surfaces, cladding, etc. for seamless connections. Two types of timber volumetric systems are shown in **Figure 10**: a smaller pod with services for a home made from laminated timber, and a larger volumetric unit forming half of a semi-detached house made from SIPs.



Nail-laminated timber pod

Volumetric timber module

Figure 10. 3D offsite timber systems. Author's own images, E.core pod adapted from: (TRADA, 2014).

2.2.2 Offsite timber systems characterisation

Because VTC allows for the highest percentage of labour and materials use to be transferred to the factory environment, it could be hypothesised that VTC should offer the greatest opportunity for labour and materials productivity optimisation among the offsite timber systems (Court *et al.*, 2009; Khalili & Chua, 2014; Gibb, 2001). The attributes of VTC could be hypothesised to be shared with other offsite systems such as open, closed and laminated timber panels, however with potentially more extreme values due to the higher offsite completion level. Therefore, offsite timber systems attributes are discussed comparatively in this thesis, to identify novel nuances in their characteristics. This approach is in contrast to the typical examination of offsite systems as one construction method, exemplified in the study of decision-making in house-building, where the most relevant offsite factors were identified as cost, time, health and safety (Pan, 2006). The offsite timber variables are summarised in **Table 2** and are relevant to the identification of MFP variables for comparative analysis offsite timber systems' productivity**,** and each is discussed in turn below. It should be noted that although this were the main characteristics identified relevant to MFP of offsite timber systems, others also existed such as level of investment to set up factories, perceptions, structural and social aspects. However these were considered not directly relevant to MFP measurement and were therefore omitted from the table.

Table 2. Main opportunities and challenges associated with offsite timber systems (non-exhaustive list with only top 10 aspects identified from the reviewed literature).

Rank	Variable	Type	Offsite timber systems reaction
1	Time	Opportunity	Housing demand and supply through increased predictability and efficiency
2	Cost	Opportunity & Challenge	Housing demand and supply through increased predictability and improved cash flow; initial investment can be a barrier
3	Labour	Opportunity	Productivity stagnation and skills shortage through new technical roles
4	BIM	Opportunity	Advances in BIM and smart construction methods such as volumetric timber manufacturing are closely interconnected
5	Waste	Opportunity	The biggest contributor to UK waste is construction and with volumetric systems there are increased materials and process efficiencies with opportunities for closed-loop flows of key materials as timber.
6	Logistics	Opportunity & Challenge	Road transport legislation limits the size of modules in different contexts, however the number of and carbon footprint of people and materials transport is reduced with volumetric timber systems
7	Low carbon construction	Opportunity	The climate change impact potential of volumetric timber systems is much lower than traditional methods, but other forms of engineered timber may be superior
8	Specification guidelines	Challenge	There is no single technical guideline resource for designers and specifiers of volumetric timber in the UK
9	Build quality	Opportunity	Targets the low carbon agenda and wasteful snagging processes reduction through automation and quality management systems (QMS)
10	Health & Safety	Opportunity	Improved conditions due to a controlled factory process and equipment use can help mitigate the construction skills shortage

Time

There is a general consensus within the literature that volumetric timber construction can reduce project time by manufacturing modules in the factory simultaneously with the construction of the foundations, therefore reducing the time spent on site and the overall duration of the project (Smith, 2011; Hairstans, 2015; Lawson, Ogden & Goodier, 2014). Studies have estimated that with volumetric construction, the overall construction programme can be reduced by 60%, compared to only 20% using panelised methods, when benchmarked against traditional brick and block construction in the context of affordable housing (NAO, 2005; RLB, 2018). Other authors have estimated the overall programme savings with volumetric as 60% (Krug & Miles, 2013), approximately 50% (Smith, 2011) and between 30% and 50% (Lawson, Ogden & Goodier, 2014). This may be associated with the rapid installation of volumetric modules on site, indeed some sources have estimated that between 6 and 12 modules can be installed in a single working day (Lawson, Ogden & Goodier, 2014). It can therefore be hypothesised that volumetric systems have higher time-saving potential (approximately 50%), compared to panelised systems (approximately 20%).

Cost

In volumetric construction the cost for the production of the modules in the factory typically accounts for between 50% and 70% of the overall building cost (Lawson, Ogden & Goodier, 2014). The cost for transportation of the volumetric units were moreover estimated to be £800 assuming a 150-mile journey, or approximately £25/m^2 (2% of the overall build costs). Whereas crane costs can be estimated at £1,000 per day. Onsite material costs represent 15% of the overall project costs, onsite labour 10% and the offsite manufacturing approximately 75% (NAO, 2005), as summarised in **Figure 11**. The offsite components can be further sub-divided into manufacturing material costs, approximately 30-35% of the overall costs, and 40% for labour and operational costs.

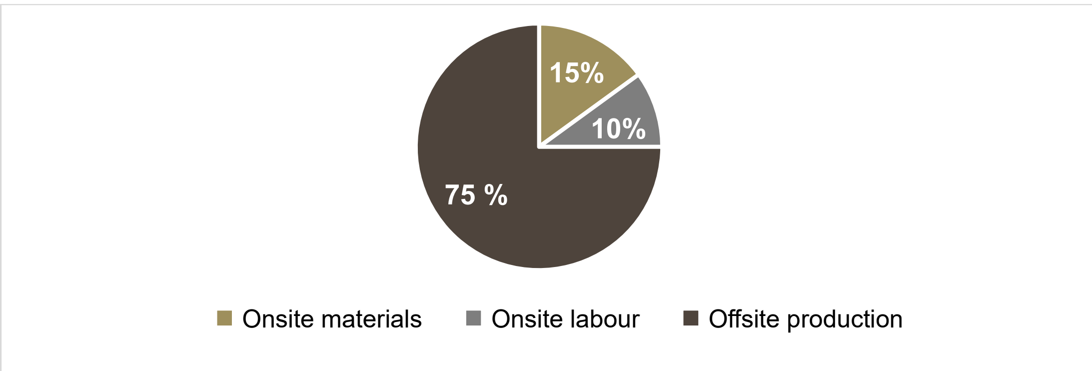


Figure 11. Distribution of costs in volumetric construction according to (NAO, 2005).

As a consequence of the early completion of volumetric buildings, there are opportunities to start collecting revenue early and to reduce the length of investment loans, which can lead to 5% savings of the overall build costs in buildings such as hotels (Lawson, Ogden & Goodier, 2014). Reductions in requirements for workers' support premises and equipment resulting from decreased on-site labour needs have been estimated to lead to additional 5 to 8% savings. Further reductions in costs could be made from reduced scaffolders' and bricklayers' utilisation, estimated to be half of those required in traditional methods of construction, and the reduced need for site supervision staff, all in all approximated at 10%. In comparison, panelised timber systems were proven to be cost-neutral compared to traditional masonry construction for home-building (RLB, 2018). In previous studies, panelised timber systems were estimated to be approximately 3% lower than the cost of concrete construction (Pan & Sidwell, 2011).

Yet volumetric systems can also be associated with higher costs due to the comparatively higher equipment costs (Polat *et al.*, 2006). Therefore, the high upfront costs for volumetric manufacturing facilities should also be considered. In an English context, a lightweight steel modular factory would typically require a £5-10 million investment, whose repayment would be susceptive to fluctuations in the market demand and the cyclical nature of the construction industry (Lawson, Ogden & Goodier, 2014). In contrast, panelised timber factories in the UK are often set up with manual working processes, where the up-front investment for equipment is lower and the labour resources are easier to reduce during economic downturns (Hairstans, 2010).

Labour productivity

In volumetric timber construction, productivity is most often measured as production of modules per labour unit and number of people required on site. With volumetric building the onsite labour can be reduced by approximately two-thirds compared to traditional construction methods (NAO, 2005; Lawson, Ogden & Goodier, 2014).

In the context of the USA it has been estimated that approximately 250 labour-hours were required to produce one module with area of approximately 55 m^2, equalling 5 labour-hours per m^2 (Mullens, 2011). Although, productivity improvements in volumetric manufacturing can be challenging to evaluate and the factory processes could be hypothesised to be twice as efficient as onsite processes (Lawson, Ogden & Goodier, 2014).

Moreover, volumetric building could be made water- and win-right in a fifth of the time, compared to traditional methods; whereas panelised systems required half the time, as shown in **Figure 12** (Lawson, Ogden & Goodier, 2014). This can aid the on-site labour productivity by proving an opportunity to start the internal works sooner, and to streamline their operations.

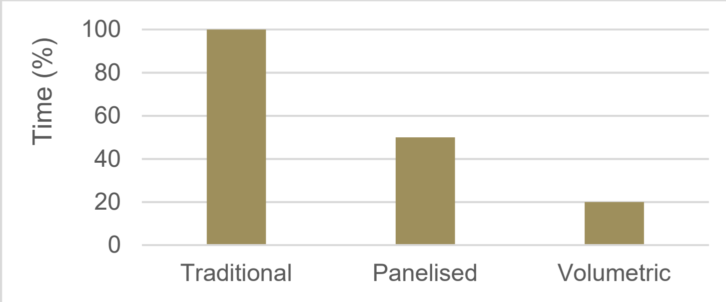


Figure 12. On-site wind- and water-tight comparison (Lawson, Ogden & Goodier, 2014).

Digitisation

Building Information Management (BIM)

The utilisation of BIM in combination with volumetric construction should theoretically be able to provide even greater optimisation opportunities, due to the integration of a factory production culture with increased efficiencies in information management (Goulding & Arif, 2013). Four-dimensional BIM (3D +time) has been utilised within a volumetric manufacturing setting to optimise the environmental sustainability and productivity of the production process (Lee & Kim, 2017). This was also achieved through provision of accurate and timely information in the production facility, and in addition through provision of more complex multi-factor data such as material quantities, equipment throughput and process structure. In precast concrete volumetric systems delivered for the Ministry of Justice, BIM was integrated in the process to deliver a building 14 weeks ahead of schedule and with zero defects, demonstrating time and build quality advantages (Bayliss, n.d.).

There are however also challenges to BIM implementation in construction, such as upskilling of staff, cost of new hardware and software items, the labour-intensive process of building information models generation and maintenance, and the uncertainty of collaborative contractual frameworks (Babič, Podbreznik & Rebolj, 2010; Tulenheimo, 2015). The implementation of BIM technologies in volumetric and panelised timber manufacturers remains un-quantified to the best of the author’s knowledge. Thus, there is a gap in knowledge to identify which BIM tools and methods would bring the biggest advantages to volumetric and panelised timber manufacturing and construction.

Automation

Volumetric manufacturing systems which utilise automation through combination of Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) can benefit from standardised product quality and reduction of rework as a result from human error (Gibb, 1999). Although manufacturing tend to be unique to each company, there are three key components to volumetric assembly lines: framing stations, working tables and turning tables (Lawson, Ogden & Goodier, 2014). Volumetric timber manufacturing strategies could be categorised as manual, where traditional building methods are transferred to an enclosure; those with some CAM applications; and the technologically extreme, whereas automated digital manufacturing techniques are transplanted from the manufacturing industry to the offsite manufacturing process. These automation levels could be said to differ across borders, for example in Japan the manufacturing of housing is highly automated and volumetric construction is regarded as the highest-quality product on the residential property market (Dalgarno, 2015; Buntrock, 2017).

Waste

Due to the scale of waste generated from construction related activities, guidance has emerged on strategies to minimise waste in construction, and offsite construction has repeatedly been outlined as a method to achieve good practice materials waste management strategies (WRAP, 2014a, 2014b, 2009). This was partly due to opportunities to optimise materials use and stock controls in a factory environment, as compared to onsite construction where materials are exposed to the weather and stocks control is manual (Smith, 2011; Hairstans, 2011; Goulding & Arif, 2013).

Research studies have been conducted in different economic contexts to evaluate the waste minimisation potential of offsite systems, as summarised in **Table 3**. Overall the literature agrees that offsite systems lead to reductions in waste materials, varying between a 40% and 90% reduction potential according to research in different offsite systems. In volumetric construction, measurement units vary between waste weight per metre squared, percent weight sent to landfill, and percent reduction compared to traditional construction. Estimates of waste reduction potential for volumetric construction vary from 64% to 90%, with volumetric steel manufacturers sending only 2% to landfill (Nahmens & Ikuma, 2012). However, in addition the increased utilisation of materials in double walls and floors needs to be considered, as they could account for 25% of the overall materials. In contrast, closed timber panels were estimated to reduce waste materials by 40% (WRAP, 2008a). To better understand what the waste reduction potential of offsite timber systems, the effect of offsite on the project waste materials process can be explored using a simulation model, as shown in **Figure 13** (Li, Shen & Alshawi, 2014). This figure is a useful representation of construction waste loops and the timber elements have been highlighted with circles.

Table 3. Offsite materials waste reduction evaluations review.

Category	Reference & Location	Main findings
Offsite	(Jaillon, Poon & Chiang, 2008) Hong Kong	Offsite waste materials reduction potential was **52%** (both inert and non-inert materials), based on 7 case study high-rise buildings.
Timber frame panels	(WRAP, 2008a) U.K.	Timber frame can reduce waste materials by **40%.** In a manufacturer case study less than **2%** of all materials were sent to landfill. Specific material savings: Timber (8%), OSB (9%), Joists (8%), Lorry Movements (5% to 10%).
Precast offsite panels	(Lachimpadi *et al.*, 2012) Malaysia	Precast offsite systems can lead to only **5.9%** of all waste materials sent to landfill, generating 0.016 tons/m^2. Based on 8 high-rise, medium-cost residential case study buildings grouped in 3 categories, traditional, traditional + offsite & offsite.
Offsite	(Li, Shen & Alshawi, 2014) China	Dynamic **model to quantify** the waste reduction potential of offsite technology on construction sites. Validated using one case study building. Recommend subsidy for adoption of prefabrication as the most influential environmental sustainability **policy** direction.
Volumetric steel	(WRAP, 2008b) U.K.	Volumetric has potential to reduce waste sent to landfill by **90%** compared to traditional construction. In a lightweight steel volumetric manufacturer case study, less than **2%** of materials were sent to landfill. Specific material savings: Design (50%), racking packaging (100%), Floor deck timber (100%), Steel structure (100%), steel joist & beam (100%), timber for steel studs (80%), roof steel (5%), roof packaging (100%), finishes packaging (80%).
Volumetric	(Nahmens & Ikuma, 2012) U.S.A.	Lean in combination with volumetric can lead to **64%** materials waste reduction in residential construction projects.
Volumetric	(Quale *et al.*, 2012) U.S.A.	The efficiency in waste materials in volumetric manufacturing surpasses that of traditional building methods and waste materials were reduced by **17%**. However, in volumetric manufacturing double walls lead to an approximate **25%** material utilisation increase; therefore roughly mitigating the effect of each.

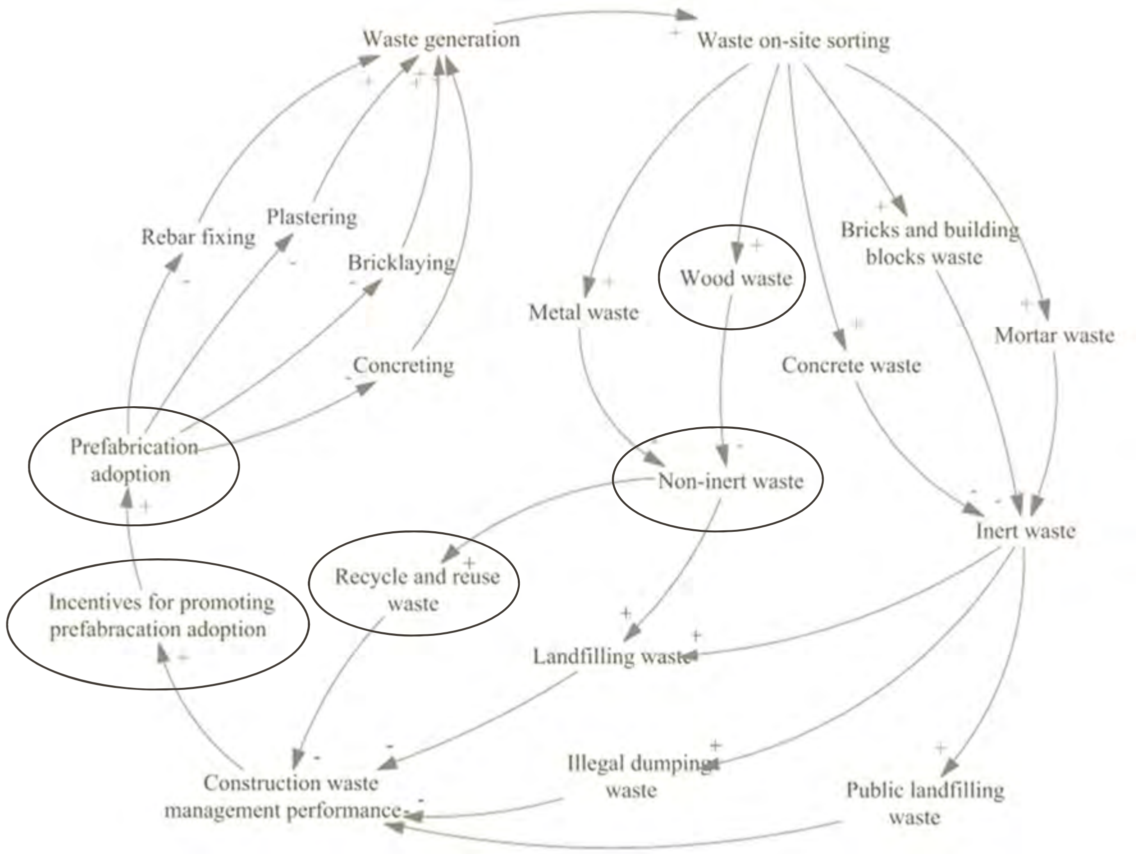


Figure 13. The effect of offsite systems on typical construction project waste materials, casual loop diagram adapted from (Li, Shen & Alshawi, 2014).

Lean

Recent publications have investigated the effects of Lean strategies on offsite manufacturing. Lean process improvement aims to reduce ‘muda’ (Japanese for ‘waste’) within manufacturing, management and supply chain processes (Womack & Jones, 2003). There are eight key ‘muda’ types in construction: ‘transportation, inventory, motion, waiting, over-production, over-processing, defects and skills misuse’ (Corfe, 2013). A research study by Meiling et al. (2015) which surveyed two volumetric timber manufacturers in Sweden indicated that all surveyed staff felt that they were active participants in the newly implemented Lean 5S strategy and therefore suggested that continuous process improvements could be planned in the long-term (Meiling, Fredrik Backlund & Johnsson, 2015). However, the research discovered differences in the perceptions of management and production staff regarding the production processes, which suggested clarification and communication is needed between management and production personnel.

Furthermore, a case study of a Canadian volumetric manufacturer revealed that companies who originated as on-site traditional contractors and subsequently transferred to or branched out to offsite manufacturing, tended to implement onsite management strategies in the factory environment (Yu *et al.*, 2013). Therefore, there was additional potential to improve factory processes using the Lean 5S system. Indeed, results from a half year pilot implementation project demonstrated an increase in production and productivity with simultaneous reduction in labour-hours.

Yet, a knowledge gap was identified in the implementation of Lean tools and techniques to improve the productivity (in Lean terms the 'flow'), of UK volumetric timber manufacturing and construction processes. This was explored further in the manufacturing survey and construction case studies.

DfMA and DfD

Design for Manufacture and Assembly (DfMA) is a recently introduced strategy for material and labour optimisation, and its principles are generally applied by offsite manufacturers in the UK (Hairstans, 2015). In accordance with DfMA, products are designed for optimum cost efficiency in the manufacture process. The optimisation can include reduction in part numbers, use of standard parts or reduction of time required to assemble the product (Boothroyd, 1994).

A shortcoming of DfMA is that it does not include considerations for the product's full life-cycle stages, such as adaptation, maintenance and disposal. However, Design for Disassembly (DfD) principles can be used in conjunction with DfMA to create products adaptable to functional change or upgrade, and with optimum re-use of components at the end of the products' life-cycle. DfD in combination with DfMA can therefore be used to implement circular economy principles in the construction industry, as shown in **Figure 14**. In this figure the typical stages of an offsite timber construction project are shown, starting with the frame assembly on the left and continuing onto building construction on the right. The arrows in both directions indicate that after the building has been constructed, they with DfD principles, the components could be broken down to their parts and the process may restart with use of these used components to the maximum degree possible.

Circular economy is a concept in which products and materials are re-used, repaired or recycled before disposal, therefore reducing waste and improving resource-efficiency (Sinclair, Wood & Mccarthy, 2013). DfD is a familiar technique in the automotive industry, which is often used as a comparator to offsite construction (Bogue, 2007). There seems to be a gap in DfD application in the technical design of buildings (Crowther, 1999; Thormark, 2001), despite the suitability for off-site methods for Design for Manufacture, Assembly & Disassembly (DfMA&D) principles (Hairstans, 2010).

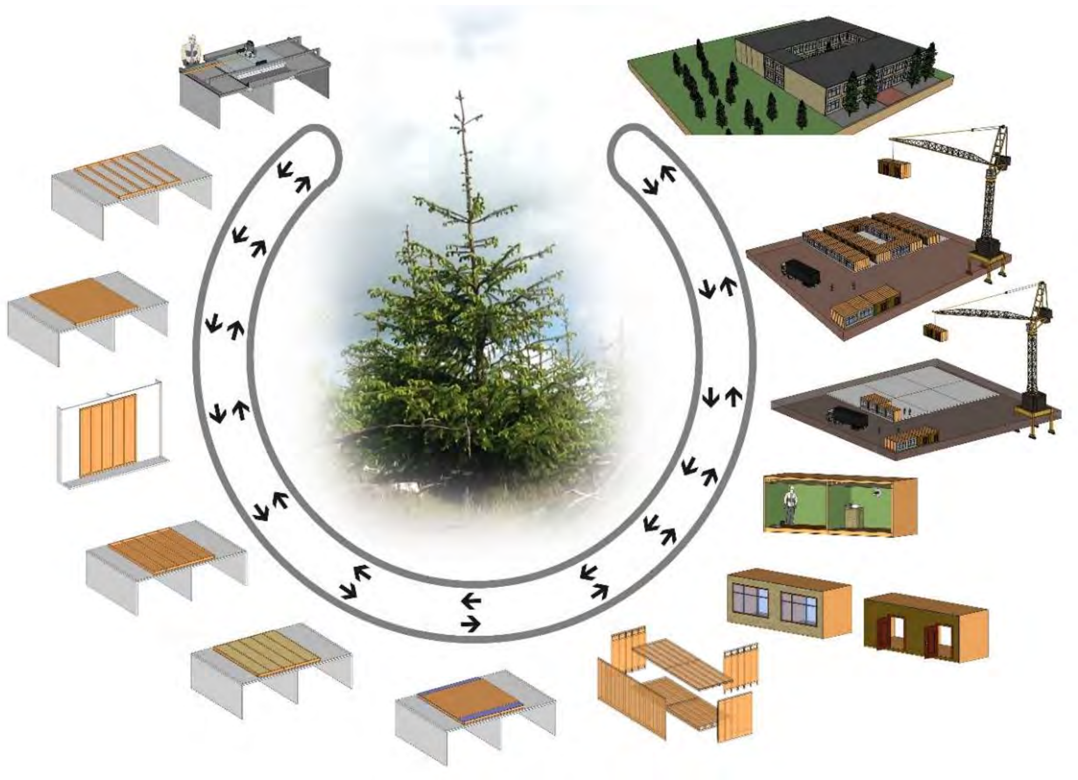


Figure 14. Ideal building life-cycle, in which Design for Manufacture and Assembly (DfMA) and Design for Disassembly (DfD) principles are combined to achieve a circular building economy through offsite timber construction. This does not refer to RIBA stages. Author's own work.

Logistics

Logistics can be both an opportunity and challenge for volumetric timber construction. The main advantages are associated with reduced number of transport vehicle movements to site, resulting in reduced disruption to the local area and therefore increasing the social sustainability of the project (Krug & Miles, 2013). However, with volumetric construction road load transportation legislation has been identified as a barrier to implementation, because of limitations to module sizes and legislative requirements when transporting oversized loads, as well as physical access limitations for remote sites (Goulding & Arif, 2013). In contrast, panelised offsite timber systems are typically delivered flat-packed, reducing the need to transport air in 3D form, and simplifying transport law compliance (Hairstans, 2010).

Regardless, volumetric timber manufacturing simplifies the logistics of materials deliveries to site because of the increased control and stock tracking in manufacturing facilities compared to construction sites (Quale *et al.*, 2012). Indeed more efficient supply chain management has been hypothesised as the keystone to material waste reductions, and a more integrated supply chain is one of the key benefits of offsite timber systems (Dainty & Brooke, 2004).

Specification guidelines

Because of the international difference in building regulations and transportation legislation, volumetric systems tend to differ between regions and countries. As identified above, in the UK lightweight volumetric steel modules are most often specified for high-rise buildings in South-East England. The RIBA DfMA overlay provides an introduction to the differences in design workflow for volumetric construction (RIBA, 2013), however to understand the in-depth aspects to designing and specifying volumetric buildings, built environment professionals would need to source information from other sources such as the 'Design in Modular Construction' book (Lawson, Ogden & Goodier, 2014). This text describes lightweight steel systems, however it does dedicate less than a page to volumetric timber construction.

In Norway each building system manufacturer is required to apply for a Technical Approval, which outlines the dimensions of the volumetric units, their build-ups, their energy performance and build quality (SINTEF, 2013). Unfortunately, In the UK there is no equivalent resource to provide technical specification guideline information for volumetric timber systems, despite the benefits that have been demonstrated when buildability and design are synergised (Rupnik, 2017).

The design, manufacturing and construction of timber frame and laminated timber panel systems is less ambiguous, i.e. plentiful information and specification guidance has been produced by industry bodies and specific manufacturers, to inform designers in the UK (CCG, 2015; Reynolds & Enjily, 2005; John Gilbert Architects, 2005).

Low carbon construction

Offsite timber systems have a lower climate change impact potential than traditional building methods when analysed using the cradle-to-site Life Cycle Analysis (LCA) framework (Monahan & Powell, 2011). A typical UK 3-bedroom semi-detached case study house was found to have 34.6 tonnes embodied carbon, which was approximately a third less than the traditional building method case study. Proposals have been made for integration of the carbon cycle process with offsite timber technologies to minimise the carbon impact of buildings, by creating a closed-loop materials flow throughout the lifecycle of the building (Jaillon & Poon, 2014). Yet greater opportunities for embodied carbon reduction are embedded in solid laminate timber systems, such as CLT. CLT systems have for example been identified as advantageous in urban infill plots for low carbon medium-rise construction (up to 10 storeys) (Lehmann, 2013).

The environmental impact of volumetric construction methods has been evaluated by several studies. The findings vary from those in which the global warming potential of volumetric residential buildings has been determined as approximately 5% less than that of traditionally constructed residential buildings; to those in which volumetric construction leads to more than 40% reduction in embodied carbon (Kamali & Hewage, 2016). In one research study specification and utilisation data from three volumetric timber manufacturers was analysed to demonstrate that the Greenhouse Gas emissions of volumetric versus traditional construction were a third less and were distributed as shown in **Figure 15** (Quale *et al.*, 2012). The Greenhouse gas emissions (kg CO_2e) of traditional methods were dominated by energy use on site and workers' transport to site with some impact emerging from materials production and waste management. In contrast, the volumetric construction option's kg CO_2e impact was mainly due to energy used in the factory, whereas the energy use on site was drastically reduced, and there were additional GHG contributions from the workers' transport to the factory and the modules' transport to site. Yet in the volumetric option the workers' transport to the factory and site combined represented only a third of workers' transport to site in the traditional building method.

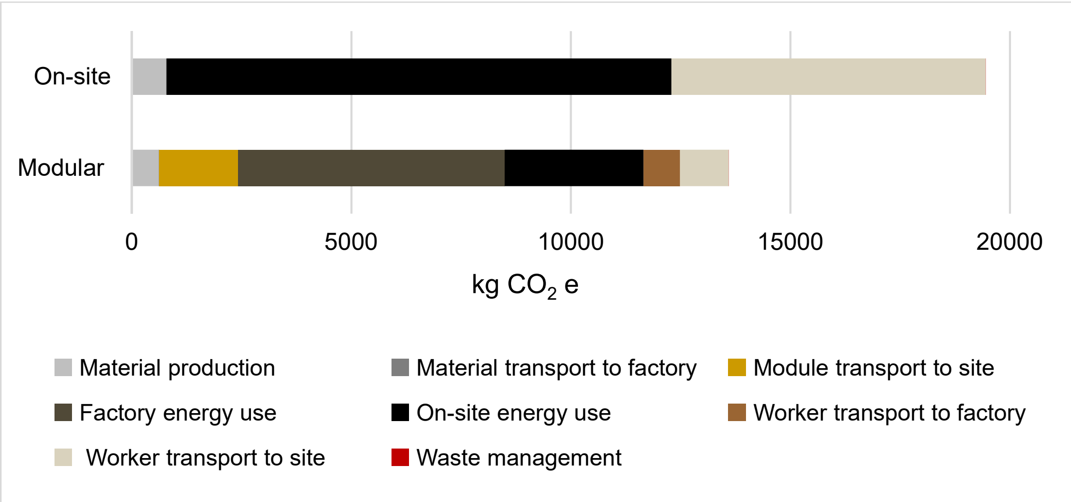


Figure 15. Greenhouse gas emissions associated with traditional and modular building methods of a three-bedroom detached house in the U.S.A. Data source: (Quale *et al.*, 2012).

The scope of the environmental impact comparison was later extended to cover modelling of traditional timber frame, CLT and volumetric timber construction in the context of Sweden (Dodoo, Gustavsson & Sathre, 2014). The building method with the lowest environmental impact was the CLT panel option, whose material production and energy utilisation were 6% less than those of the volumetric option, and 16% less than the traditional timber frame option. The results were in part influenced by the lower air infiltration rate of 0.2 l/m^2, twice lower than rates of the timber frame and volumetric systems. The sensitivity analysis demonstrated that a decrease in the air infiltration rate to 0.2 l/m^2 was due to enhanced detailing, and this generated operational energy savings from heating of 15% in both systems. Additional operational energy carbon equivalent savings could be made with installation of low-energy lighting fittings and appliances. Further research in low carbon construction has proposed the integration of carbon with cost, into the formation of a carbon economy value for evaluation of projects (Zhang & Wang, 2015; Kuittinen, 2015).

Build quality

As determined in the previous section, the build quality of volumetric timber systems is a critical consideration when aiming to reduce the environmental impact of buildings through improved air tightness detailing (Dodoo, Gustavsson & Sathre, 2014). The argument for increased build quality for air tightness detailing is based on the systematic assembly line of the modules, where membranes can be installed accurately and the process can be quality inspected at each stage of the manufacturing line (Lawson, Ogden & Goodier, 2014).

A further consequence of the quality inspections and the third-party quality accreditations with offsite methods (volumetric and panelised), are reductions or indeed eliminations of defects in the handover stage, also known as snagging (Bayliss, n.d.; Krug & Miles, 2013).

The cost savings from the defects reduction have been estimated to be approximately 1-2% of the overall build costs with volumetric projects (Lawson, Ogden & Goodier, 2014). Moreover, areas with high servicing and surfaces standards such as bathrooms in hotels, have been identified as some of the most beneficial areas for volumetric manufacturing in construction (Pan, Gibb & Sellars, 2008).

Lower defects in volumetric timber compared to traditional timber construction have been determined using two cases of volumetric timber manufacturers and eight case study onsite constructed residential buildings in Sweden (Johnsson & Meiling, 2009). Yet the defect reduction in construction, even in factory assembly-line based volumetric timber manufacturing, has been demonstrated to be prone to human errors and surface cracks from the lifting process. The research study utilised existing quality documents conventionally produced by construction firms for auditing purposes, which were recommended as a data source in further studies with a view to continuously improve the build quality of volumetric timber systems; and to generalize the findings via case study research in other economic contexts.

Health & Safety

Volumetric construction is generally accepted to provide improved Health and Safety (H & S) compared to traditional onsite construction methods due to the transfer of up to 80% of the activities to a factory environment with higher levels of control and use of automation to reduce manual handling (Goulding & Arif, 2013; Lawson, Ogden & Goodier, 2014; Hairstans, 2015). Moreover on construction sites there are fewer operatives who work in ergonomic work cells and work with basic tools to perform assembly rather than construction tasks, based on a lightweight steel volumetric healthcare case study (Court *et al.*, 2009). However, the health and safety impact of volumetric timber construction needs to be investigated in greater detail for each step of the manufacturing and construction processes, and quantified in further research.

2.2.3 Offsite timber systems summary

Overall, the following key issues regarding offsite timber systems in today's economic context were identified:

- Offsite systems' factory production provides opportunities for increased digitisation.
- Among these, volumetric have the highest level of offsite completion in the factory, and therefore could have significant productivity improvement potential.
- Further research is needed to identify specific opportunities for productivity improvement in offsite timber systems according to their different categories of completion in the factory.
- Although the potential of volumetric construction to reduce waste material to landfill was demonstrated by research by WRAP, there is a gap in knowledge on the Lean tools and techniques most applicable to improvement of flow in volumetric (and offsite) timber systems.
- There is unlocked potential to combined DfMA and DfD principles (DfMA+D) to create volumetric timber systems adaptable to changes over time and whose components can be re-used or re-cycled in a circular economy framework.

- There is a lack of technical guidance for volumetric timber designers in the UK, an under-appreciation for their high-technological 'smart' aspects of VTC. Therefore, research is needed to bring to light and objectively comparatively analyse different manufacturer's strategies and products.

2.3 Offsite construction market

Measurement of the value of the offsite sector is a challenging task, because offsite construction can be included in either manufacturing or construction statistics due to its dual nature. The diversity of the terminology used makes the definitions of the scope of work difficult to interpret unless clear definitions or preferences terms are stated. Classifications of the offsite sector according to products and services are typically inconsistent between different market valuation studies. A common example is the differentiation between building materials and the proportion of work completed offsite. For instance, in a given study panelised systems can be presented as a single category, whereas another source could differentiate between steel, timber and concrete panels, and a further research study could in addition differentiate between open timber panels, closed timber panels and engineered timber panels. Therefore, although the most up to date data and scientific rigour are applied in studies which evaluate the sector, the cited figures should not be taken at face value.

2.3.1 UK offsite market

UK offsite sector size

A holistic sector valuation study with data from 2008 presented the estimated gross output value of the offsite sector as £5.7 bn (Taylor, 2010). Within this study, the output of open timber panels was £528 m, whilst closed panels had an output of only £20 m and Structurally Insulated Panels (SIPs) only £3 m. Taylor presented data for two types of volumetric systems, permanent and temporary with combined value of £329 m, but without distinguishing between different structural materials. Therefore, it is not clear how many percent of the £329m volumetric output were timber. Taylor's results are summarised in **Figure 16** below.

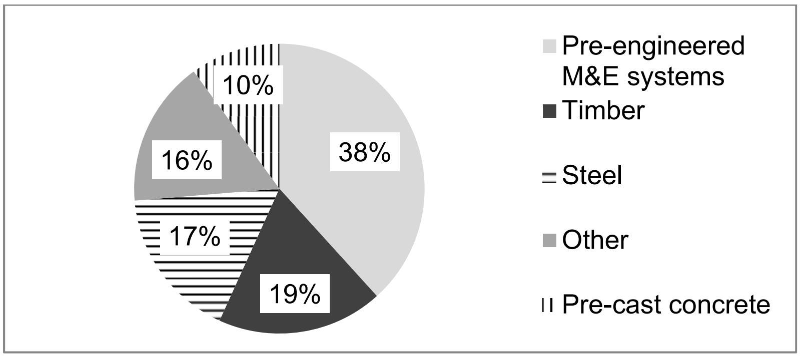


Figure 16. Offsite sector segments gross value output (turnover) distribution for 2008. Data summarised from (Taylor, 2010).

Taylor forecasted that the total output of the offsite sector would be below £5 bn in 2013, whereas other sources have indicated values ranging from below £1 bn to £6 bn (Gambin *et al.*, 2012). In 2006, the total value of the UK offsite construction market was evaluated at approximately £6 bn (4.5%) out of £131bn construction industry output in 2006 (ONS, 2016b; Mtech Group & Gibb, 2007). Overall, there seems to be a consensus in literature that the valuation of the offsite sector is challenging because of its geographic fragmentation and its position in both manufacturing and construction, but it can be estimated at 7% of construction output (UKCES, 2013).

UK offsite sector productivity

Because of uncertainty of the actual value and size of the offsite construction industry in the UK, the measurement of the productivity of the sector in terms of Gross Value Added (GVA) per employee or average m^2 of building components per employee in offsite manufacturing companies remains to be established. Despite this, it is generally understood that offsite manufacturing has the potential to increase productivity, specifically achieving a higher output of homes with a lower input of resources than traditional construction. Indeed, Eastman and Sacks (2008) proved that in the USA context, the value added per employee of offsite manufacturing was 43% higher compared to onsite construction. They also estimated that offsite had a growth rate of approximately 0.9% more than onsite.

The projected positive effect of offsite uptake on construction productivity growth was moreover recently confirmed in a UK context. As part of a research project for the Heathrow Airport expansion, the productivity effect of offsite construction uptake was modelled using two growth projections: 25% and 50% of all construction work to be completed offsite (WPI Economics, 2017). This study utilised assumptions for productivity improvement ranging between 10% and 30%. The authors identified a 25% increase in offsite uptake and a 20%

productivity increase, as the most probable values for the next 5-10 years of UK economic development. This offsite utilisation was projected to result in additional Heathrow-expansion related GVA of approximately £4.3 billion, split between the UK market regions as shown in **Figure 17**. However, these estimates were based on exemplar off-site case studies and qualitative data, which portrayed the benefits of offsite timber construction with few considerations for any of the challenges such as increased complexity of logistics co-ordination. Moreover, it was limited to the context of Heathrow airport and further research is needed to quantify the impact of offsite timber systems' utilisation on UK productivity.

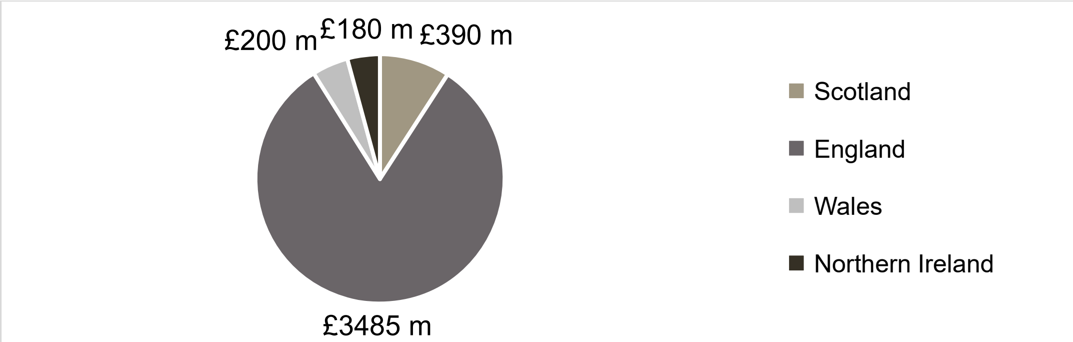


Figure 17. GVA increase resulting from projected offsite uptake to 25% of construction in the planned Heathrow Expansion. Data source: (WPI Economics, 2017).

UK market gap analysis

Recently, the NHBC evaluated the use of different offsite methods amongst registered new build completions and collected qualitative and quantitative data from companies who cumulatively constructed a third of new build homes in 2015 (The NHBC Foundation, 2016). Although not representative of the overall construction industry, their findings provided an insight into the use of offsite systems with different levels of prefabrication in residential construction, in context of traditional construction methods. For example, between 2008 and 2015 approximately 70% of new build dwellings were in the UK were constructed using traditional masonry methods, whereas in Scotland 75% were constructed using timber frame (or open panel) construction. The construction methods most used by the surveyed companies in the UK were sub-assemblies (60%) and panelised methods (40%). Among the panelised building systems, open timber panel was used by 70% of surveyed companies, closed timber panels by nearly 40% and CLT by only circa 15%. Volumetric modules and pods (irrespective of building material), were utilised by approximately 5% each, and approximately 60% of the surveyed companies had no intentions of considering volumetric systems for homebuilding. Moreover, volumetric systems were recorded only in London and its surroundings, typically in building over 10 storeys using steel modules.

Therefore, there are opportunities for open timber panel market size expansion in England and Wales, and moreover for volumetric construction market expansion in other urban centres across the UK following the model of London, such as in Birmingham and Manchester. Volumetric construction could moreover be utilised more in rural or island areas, where remote locations and adverse weather favour reduction the percentage of work done onsite.

2.3.2 Scottish offsite market

Scottish offsite sector size and productivity

The Scottish offsite sector was most recently reviewed by Smith and colleagues on behalf of the Scottish Government, and the value of the participating companies represented £125 m, with potential to grow to £230 m excluding increases in numbers of manufacturing facilities in 5 to 10 years' time (Smith *et al.*, 2013). The sector at the year of study (2012) produced 6,000 homes per annum, however the existing facilities had capacity to produce 16,500 homes per annum in 5 to 10 years' time. In addition, the number of people employed by surveyed offsite companies was 1,450, with potential to grow to 2,000 people in 5 to 10 years' time.

From these statistics the Scottish offsite sector in productivity at the time can be calculated in output per person using the definition "the ratio of (the product's) output to (the product's) input" shown in **Equation 1** (Fried, Lovell & Schmidth, 1993:p.4) introduced in Chapter 1:

$$Productivity = \frac{Output}{Input} \qquad \text{Equation 1}$$

Where:

Input= people employed

Output = number of homes produced (gross output) or annual turnover (capital)

Therefore, the productivity of the sector could be estimated at approximately 4.13 homes output per person, or £86,200 annual turnover output per person employed per annum for 2012. Combined with employee growth numbers, within Equation 1 resulted in 8.5 homes per person, or £155,000 annual turnover output per person per annum. These estimates are visualised in **Figure 18,** where the x-axis shows number of homes output per person, the y-axis shows the annual turnover output per person, and the size of the bubble indicates the number of employees. Further information on productivity measures in construction may be found in section 2.4.

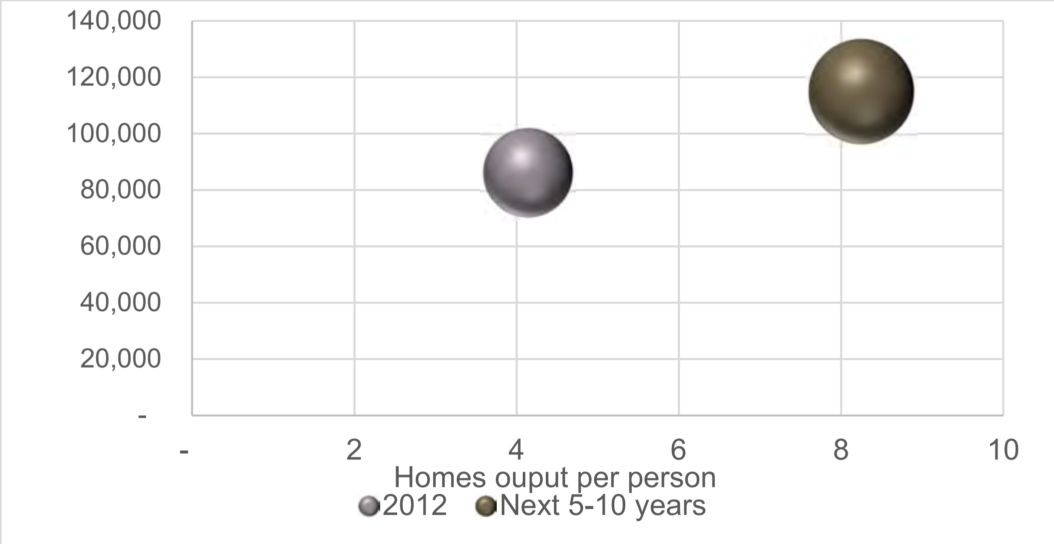


Figure 18. Scottish offsite sector productivity, secondary data calculations based on findings from (Smith *et al.*, 2013). 1 unit = 1 home = 1 house OR 1 apartment.

Scottish offsite sector distribution and gap analysis

The Scottish construction market differs from those in England and Wales in offsite timber systems utilisation. In Scotland open timber panel construction represented three-quarters of new built homes (The NHBC Foundation, 2016), which in turn represented 75% of Scottish construction (Smith *et al.*, 2013). Moreover, Smith *et al.* study identified the distribution of offsite systems as 81% panelised systems versus 19% volumetric systems. Open timber panels represented 44% of the offsite market turnover, followed by closed panel systems (37%). In contrast, volumetric construction with insulation, services and finishes represented 11%, the highest among the volumetric categories. The Scottish offsite market output was dominated by residential construction, and a few manufacturers specialised in non-residential construction.

Therefore, it could be said that the Scottish offsite sector was dominated by open and closed timber panel construction concentrated in home-building, whereas volumetric construction was less utilised and therefore could have opportunities for growth.

2.3.3 Offsite sector market summary

It is generally accepted that the value of the offsite sector in the UK represents approximately 7% of the output, however further studies are needed to update and break-down this figure. Although the statistics and scope of work differ between research studies, there is a shared pattern that connects them. The offsite sector is represented mostly by panelised methods of construction, which are in turn characterised mostly by open timber panel construction, concentrated in Scotland. There is a market gap for application of offsite timber systems across the UK. Volumetric systems represent a small proportion of the offsite construction market in the UK, predominantly represented by lightweight steel modules and pods for high-density residential construction in England. CLT and other laminated timber systems were not specifically reported in any of the reviewed offsite market literature.

Overall the following key offsite market issues were identified:

- Volumetric timber systems, panelised timber systems and other offsite timber systems are not specifically reported in official national statistics, and the available mixture of academic and industrial sources is fragmented.
- There was a UK market gap in the utilisation of volumetric systems. At the time of research volumetric construction was concentrated in the London area for multi-storey steel buildings. According to another UK-wide study, 60% of respondents had no intention to use volumetric systems (irrespective of their main material).
- There was a market gap in the volumetric systems utilisation in Scotland, where open timber panels dominated the market (44% of output) in 2012, whereas volumetric systems with high levels of factory completion were marginal (11%).
- The Scottish offsite sector had ambitions to increase their average output from 4.13 homes per employee in 2012, to 8.5 homes per employee by 2017 to 2022. However, these figures are now out of date and further research is needed to benchmark the hypothesised capacity increase in offsite manufacturing.
- To enable scientific investigation into the productivity of different offsite timber systems, it was necessary to review and identify suitable construction productivity measures

2.4 Productivity measurement in construction

The Organisation for Economic Co-operation and Development (OECD) published their *Manual* for productivity measurement in 2001, which outlined the most often used productivity measures as shown in **Table 4** (OECD, 2001). In the UK, the Office for National Statistics (ONS) utilises OECD guidance in combination with established productivity measure frameworks originating from Solow (Solow, 1957; OECD, 2001). Labour productivity is measured using several input-output metrics: total output, gross value added (GVA) and gross domestic product (GDP), further sub-divided into three measurement methodologies, income, production and expenditure; and labour inputs of workers, jobs, worked hours expressed as quality-adjusted labour input (QALI) and the volume index of capital services (VICS) (Office for National Statistics, 2016). However, not all input measures have equal accuracy, indeed the recommended hierarchy of labour units according to OECD and ONS is as follows: labour-hours (ideally adjusted for workers' skills via QALI, per worker (headline measure of productivity), and per job (the most detailed in terms of data) (Office for National Statistics, 2016). Therefore, with consideration for this recommendation, productivity measurement in this research has attempted where possible to collect and comparatively analysed labour-hour data, which accounts for differences in working patterns between individuals. In addition, benchmarking studies between manufacturing plants are recommended by ONS, which supports the need for this comparative offsite timber productivity doctoral study.

Table 4. Productivity measures (main only) (OECD, 2001)

	Type of input measure			
Type of output measure	**Labour**	**Capital**	**Capital and labour**	**Capital, labour and intermediate inputs**
Gross output	Labour productivity (based on gross output)	Capital productivity (based on gross output)	Capital-labour MFP (based on gross output)	KLEMS multifactor productivity
Value added Table	Labour productivity (based on value added)	Capital productivity (based on value added)	Capital-labour MFP (based on value added)	-
	Single factor productivity measures		***Multifactor productivity (MFP) measures***	

Based on the findings from the literature review on offsite timber systems, their productivity performance should consider multiple factors, and therefore the Multi-Factor Productivity (MFP) measures are the most applicable in this research thesis. The two dominant types of MFP measures are labour-capital value added, where increase in GVA is mapped to increases in labour and capital; and KLEMS total output productivity (KLEMS = Capital, Labour, Energy, Materials, Business services) (O'Mahony & Timmer, 2009; Koszerek *et al.*, 2007). A detailed research analysis of construction MFP confirmed the high productivity growth associated with information technology and that the lower construction productivity would suggest a slow adoption of technology in construction (Ruddock *et al.*, 2011).

There are further layers to productivity measurement in construction, they can vary from a high-level analysis of the entire industry, to very specific processes such as the installation of a floor cassette onsite as summarised in **Table 5** (Kenley, 2014). Kenley proposed that future research should improve each productivity level via an established methodology, such as Lean production or location-based management. This recommendation was taken up by this research, which included investigation of Lean in the manufacturing and construction of offsite timber systems.

Table 5. Construction productivity improvement methods (Kenley, 2014).

Level (reference)	Productivity measure
Industry (Nasir *et al.*, 2013) (Vilasini, Neitzert & Rotimi, 2014)	A comparison between construction productivity of different countries can be used for benchmarking.
Firm (Van der Vlist, Vrolijk & Dewulf, 2014)	Investment in information and communication technology can be used to increase the competitivity of a company in the market.
Project (Isaac & Navon, 2013)	Automated data collection and transformation of the data into efficiency estimation calculations.
Activity	By measurement of physiological indicators such as heart-rate a connection was discovered between strain and productivity.

2.4.1 Methods utilised in similar previous research studies

In architecture, often a *precedent* analysis is undertaken before the start of design work to learn from the past, and similarly in research it is recommended to review studies with similar goals, to analyse their methodologies interpret them in the context of this doctoral research (Gray, 2004). Productivity measurement and optimisation in construction has been the topic of several keystone research studies, which could be theoretically categorised as frameworks, evaluations, comparative and LCA-type studies (Sarker *et al.*, 2012).

Construction productivity frameworks

Previous research in the area of productivity frameworks proposal has been investigated in the area of business implementation using an operationalization methodology based on the construction of a phenomenon-based model (Saari, 2006). The proposed model facilitated evaluation of growth in productivity with consideration of quantity, quality, influence of input volume increase, distribution, surplus value, capital and labour with reference to the KLEMS methodology. The findings of the research set out the gap in knowledge of more in-depth multi-factor productivity analysis of growth in business with relative inputs representative of reality. This thesis interpolates this approach to the construction industry, specifically to advanced offsite timber systems.

Moreover, the Chartered Institute of Building (CIOB) has proposed a framework for evaluation of priorities for policy-makers in the area of productivity in construction, developed by a survey of MSPs and 481 industry participants (Green, 2016). The survey consisted of a single-page questionnaire with three ranking questions enquiring of priority, effectiveness and positive impact. The conclusions of the survey identified *people* as the top issue in construction productivity improvement policy-making, followed by *economy* and *innovation;* specific recommendations were made regarding the pressing need to develop novel business models and increase the efficiency of training in construction. These points could be reflective of the reluctance to investment in the construction industry and the established association between low skills development and low productivity (Chan, Puybaraud & Kaka, 2001; Farmer, 2016). However, the main finding of this study was the requirement for improved construction productivity measures, a wider evidence-base creation, both of which are targeted directly by this doctoral research (Green, 2016).

The CITB has moreover reviewed the measurement of productivity in construction utilising the perceptions of an expert panel of 18 representatives with biennial meetings with an aim to report debate labour trends in construction (CITB, 2015). This work represented the fifth work package outputs within a wider-encompassing research project, and investigated construction labour productivity influencers, data tendencies and conceptual commendations for further labour improvement. Important to this thesis, the findings touched on the most relevant and useful measures of productivity, including units of reporting, namely 'Gross Value Added per hour worked' (CITB, 2015). The research also considered output per hour worked however dismissed it due to its limited practical application in productivity analysis, typically restricted to official national statistics in the UK and the USA. Yet, output per hour worked could be more applicable to this doctoral research, due to the availability of output data for the offsite construction sector, and the easier measurement of products output in manufacturing survey.

Productivity and constructability evaluations

Construction productivity studies are most often concerned with high-level national or industry level measurement and reporting issues, including trends in industry performance and international construction productivity comparisons of monetary output (Best & Meikle, 2015). However, when examining the productivity of different construction systems, a lower in scope but higher in detail approach has typically been utilised to analyse construction systems' buildability characteristics. Two productivity-constructability studies were undertaken to evaluate the effect of offsite methods on concrete formwork and pouring processes (Jarkas, 2010; Jiang & Leicht, 2015). In these two cases, contrasting methodologies were applied, in the former a quantification of material utilisation efficiency measured in numbers of beams/panels per floor area; and in the latter, an algorithm-based automated rule checking method. Amongst these, the Jarkas approach is more applicable due to its relevance to evaluating the impact of several offsite systems.

Comparative construction productivity

The productivity growth differences between the USA and Canada have been investigated with emphasis on data sourcing and availability from trust-worthy national statistics in North America with reference to KLEMS with three strands, international construction productivity, comparisons between activity-level productivity, and growth change analysis (Nasir *et al.*, 2013). A similar comparative approach has been applied to an analysis of trends in productivity improvement programmes in the UK, Hong Kong and Singapore, however with emphasis on reconstructing historic trends with respective fluctuations in economic factors (Green, 2012). This study identified a need for future research to analyse specific productivity improvement targets set in each economic context, the role of the organisations responsible for delivering these changes in construction, and the overall performance according to each variable. This gap in knowledge supports the need for this research on the performance of offsite construction systems in the UK context.

Moreover, comparative offsite system studies may be conceptually connected to the identification of criteria for selection of one system over another with an aim to extract the upmost value from construction projects (Pan, Dainty & Gibb, 2012). The researchers' methodology consisted of a two-phased case study approach, where one case equalled one housebuilder company, underpinned by a literature review. The first phase of case study was based on only one housebuilder and was explorative in nature, in that the decision criteria for value-based selection of a construction system were developed during the case study through frequent interactions with the housebuilder to test and improve the criteria, with an element of action research techniques. The findings from the first phase were then verified with further five case studies through (five housebuilders), whose distribution of building types and systems of this study are shown in **Table 6**.

Table 6. Case studies utilised in building system decision-making research. Adapted from (Pan, Dainty & Gibb, 2012).

Case study	A	B	C	D	E	F	Total**
Building types							
Semidetached			✓	✓		✓	*3*
Terraced		✓	✓			✓	*3*
Low-rise apartment buildings	✓				✓	✓	*3*
Building types count per company	*1*	*1*	*2*	*1*	*1*	*3*	
Building systems							
Traditional brick and block	✓	✓	✓	✓	✓	✓	*6*
Thin-joint masonry				✓			*1*
Open timber panel*	✓	✓	✓	✓	✓	✓	*6*
Closed timber panel*			✓		✓		*2*
In situ reinforced concrete frame	✓						*1*
Precast concrete cross wall	✓						*1*
Steel frame with precast concrete floors	✓						*1*
Steel-framed modular					✓		*1*
Building system count per company	*5*	*2*	*3*	*3*	*4*	*2*	

* indicates building systems within the scope of this thesis
** indicates additional table fields created in this thesis

The survey emphasised on blockwork and open timber panel construction, and only one surveyed company utilised volumetric steel systems. The findings regarding weighed criteria for value-based selection of construction systems varied between companies but were summarised in eight key factors: cost, time, quality, health and safety, sustainability, process, procurement and regulatory. The authors recommended that all should be considered, however the main emphasis fell on cost and time, which can be directly linked to productivity of construction projects. These findings are relevant in the context of multi-factor productivity analysis for offsite timber systems because of the identification of significant factors, which would drive the selection of one build system over another. However, due to the emphasis on blockwork and open panel construction, the generalisation of the findings to engineered timber, enhanced closed timber panels and volumetric timber construction is questionable and this supports the need for this doctoral research.

A similar univariate ANOVA methodology was applied in the context of Auckland, New Zealand using a larger sample of 66 projects from existing national records, which increased the generalisability of the results (Shahzad, Mbachu & Domingo, 2015). The study included 33 low rise single family residential projects, 5 medium rise multi-family residential projects, 16 commercial, 7 educational and 5 public projects, whose distribution of offsite systems varied between components with panels (45%), modular (20%), whole house (5%) and hybrid (30%) solutions. The conclusions indicated that the largest advantage of offsite utilisation emerged from time reductions (approximately 34%), followed by cost reductions (approximately 19%) and marginal productivity improvements of 7% on average. The researchers moreover investigated the effect of building typologies on these three factors and identified housing construction as the typology with highest productivity improvement potential (11%). However, the researchers did not investigate the effect of systems with different offsite completion levels on construction project productivity. This gap in knowledge is directly targeted by this doctoral thesis.

Productivity in the context of sustainability and skills

Another approach for multi-factor measurement of productivity in construction could be adapted from sustainability studies with an environmental dimension (Forbes *et al.*, 2011). A comparative analysis of leading at the time BREEAM and Ecohomes schemes (Ecohomes is currently not in use) discovered that the sustainability evaluation frameworks covered in high level of detail environmental sustainability issues. In comparison, the scope of social sustainability factors was moderate, whereas economic factors were limited. To mitigate the knowledge gap in integrating environmental and economic sustainability, the authors proposed the utilisation of a ratio with Ecohomes scores based on price indexes, as shown in **Equation 3** (BCIS, 2008).

$$Ratio = \frac{\text{Ecohomes score (\%)}}{Cost\ per\ unit\ area\ (£/m\ sq.)} \qquad \textbf{Equation 3}$$

In addition, Life-Cycle Analyses (LCA) on offsite construction systems utilise analysis of multiple criteria to determine the overall Global Warming Potential (GWP) (Quale *et al.*, 2012; Kamali & Hewage, 2016). These studies investigated one case study building each, a residential building representative of the local geographic context. The aims and boundaries of LCA studies may be decided on a case by case basis, however the two referenced studies tended to cover the following main topics to arrive at carbon dioxide-equivalent results:

- materials quantities and energy utilised for their production

- materials and labour resources transportation
- water usage
- waste materials
- energy used in the construction
- energy used in the operational stage of the building life-cycle

Last but not least, precedent research methods for this thesis may be discovered in research studies in the area of skills demand, supply and development in construction, which has been proven to have an influence on productivity (Chan, Puybaraud & Kaka, 2001). With this in mind, the *Labour Forecasting Tool* has been developed on behalf of CITB to predict demand for skills on building sites, which could then be utilised to plan the resourcing of local labour (CITB, 2015). Interconnected to this association between productivity and labour, is the analysis of skills supply and demand within an entire council area in the UK (Forbes *et al.*, 2017a, 2017b). The methodology utilised in these studies was based on data collection from the following established databases: *Construction Skills Network, Glenigan Pipeline, National Infrastructure and Construction Pipeline (NICP), Local industry networks and The Labour Forecasting Tool*. These data were analysed firstly to predict the upcoming pipeline of construction work in the area, then associate the construction works with forecasts for demand per trade to complete the construction works, followed by a synthesis of trade skills supply in the geographic area. The analysis culminated in a gap analysis, which mapped the demand and supply utilising clustered bar charts, with consideration for mobility of labour resources, to draw conclusions on the trades whose training required the highest attention to support anticipated construction in the area.

However, the scope of these studies omitted the changes in labour resourcing as a consequence of offsite systems utilisation, which could provide opportunities for enhanced sequencing of labour through innovative location-based management techniques, and the multi-skilling of labour resources in the context of technological advances enabled by factory production of buildings (Arashpour *et al.*, 2015; Kenley, 2014). At the time of writing this thesis, a survey is being accrued out on behalf of the UK Government and CITB, to determine the estimated changes in skills with increased utilisation of Modern Methods of Construction (MMC) in housebuilding, with definitions provided for panelised and modular systems. However this study did not account for different levels of factory completion and different materials of the offsite systems, and was based on the perceptions of the survey participants (CITB & WLC Ltd, 2018). This doctoral research builds upon this work with a multi-factor productivity analysis of different offsite timber system using primary labour, product and process data collected from comparative construction projects

2.4.2 Work Breakdown Structure review

The Work Breakdown Structure (WBS) is known to form the foundation (or framework) for labour productivity calculations (PMI, 2017; Alton *et al.*, 2017). In quantity surveying for example, the WBS is closely interlinked to the cost categories for quantities and monetary value calculations (Sequeira & Lopes, 2015). The British Standard on construction planning defines the WBS as 'the hierarchical description of the work packages in the project plan' and it furthermore emphasises on the importance of including the responsible individual, equipment use, lead-in times and milestones (BSI, 2010). With regards to construction planning and control, the Chartered Institute of Building (CIOB) in the most recent edition of the Code of Practice for Project Management gives recommendations to ensure that the master programme for the development gives sufficient high-level information at the start of the project for all stakeholders, followed by releasing additional level of detail for the sub-stages, in accordance with the masterplan depending on progress (CIOB, 2014). This builds upon earlier recommendations by the CIOB on five levels of schedule reporting, ranging from executive managers to subcontractors (CIOB, 2011). The Handbook of Construction Planning and Scheduling adds that a Level 0 can be added should a portfolio of projects need to be presented to senior management, however no reference is made to comparisons between projects with a high level of detail (Baldwin & Bordoli, 2014).

Academic publications have investigated the use of WBSs in complex projects, and for cost estimation and control. The simplified WBS proposed by Sequeira & Lopes for project cost estimates prior to construction start, was found to increase the accuracy of cost calculations (Sequeira & Lopes, 2015). The authors furthermore propose simplified matrix spreadsheets, which can be used to connect the WBS to responsibility, duration and cost units. Polonski argues that the inclusion of summary task-level cost buffers is necessary in the reality of overrunning project costs and proposes a dynamic control for these buffers, as well as the introduction of a project-level cost buffer (Połoński, 2015). Jung and Woo proposed a flexible WBS with the aim to connect the schedule control and the cost control of construction projects. The main aim in the development of the flexible WBS was the reduction of data required for collection, as this was identified as the main barrier to synchronised progress and cost control (Jung & Woo, 2004).

All three of these publications, whilst contributing to the body of knowledge, discussed the application of a WBS within a single project and suggested that their approach was useful for contractors, who work on multiple projects constructed using similar construction techniques, for example in-situ concrete. Indeed, publications discuss the calculation of labour hours as part of the economic costs of a single project, which entails a detailed project-specific approach. In contrast, the comparison between projects which use different construction systems requires standardisation of the WBS and associated calculations. Therefore, to the best of the author's knowledge a WBS has not been previously developed for comparative productivity analysis of offsite timber systems. This research builds upon ideas presented by the aforementioned researchers, such as the simplification of labour hour spreadsheets, dynamic modelling and data collection reduction, however adds to the body of knowledge a WBS for cross-project comparison.

2.4.3 Productivity measurement summary

Overall, the literature review of productivity measurement in construction revealed a gap in knowledge on a (MFP) index for comparative analysis of offsite systems with consideration for differences for offsite completion percentage. This is the main knowledge gap targeted by this doctoral thesis.

The themes of the reviewed literature within the topic of productivity measurement in construction are summarised in **Table 7**. From the table it may be observed that although several of the studies covered one or more themes, none have provided in-depth multi-factor productivity measures for offsite system on a project level, according to variables relevant in today's economic context. Additionally, three key gaps in knowledge regarding productivity measurement in construction for offsite timber systems were identified:

- Collecting data on construction productivity was a common challenge, as the prevalent methods were manual and there was a gap in knowledge on their automation or streamlining.
- It was not known which BIM tools and techniques were the most applicable in connection with improvement of offsite timber systems construction productivity.
- To enable calculations of labour productivity across different projects and systems, a WBS needed to be rigorously devised, as there was no pre-existing purpose-built WBS for offsite timber construction

Table 7. MFP research knowledge gap analysis*

Reference	Industry-level prd measures	Multi-factor prd measures	Frameworks	Evaluation	Construct-ability	Comparative cnstr prd	Sustainability	Prd & Skills	Offsite
This thesis	✓	✓	✓	✓	✓	✓	✓	✓	✓
(OECD, 2001)	✓	✓							
(Office for National Statistics, 2016)	✓	✓		✓					
(O'Mahony & Timmer, 2009)		✓							
(Koszerek *et al.*, 2007)		✓							
(Jäger, 2017) (Jorgenson, 2017)		✓							
(Timmer, 2017) (ONS, 2018)		✓							
(Ruddock *et al.*, 2011)		✓							
(Saari, 2006)			✓						
(Green, 2016)			✓					✓	
(CITB, 2015)			✓				✓		
(Best & Meikle, 2015)	✓					✓			
(Jarkas, 2010)					✓	✓			
(Jiang & Leicht, 2015)					✓	✓			
(Shahzad, Mbachu & Domingo, 2015)			✓			✓			✓
(Nasir *et al.*, 2013)		✓				✓			
(Green, 2012)						✓			
(Vereen *et al.*, 2016)		✓				✓			
(Pan, Dainty & Gibb, 2012)			✓			✓			✓
(Forbes *et al.*, 2011)							✓		
(Quale *et al.*, 2012)							✓		✓
(Kamali & Hewage, 2016)									
(Forbes *et al.*, 2017a)								✓	
(Arashpour *et al.*, 2015)								✓	✓
(Kenley, 2014)				✓	✓				
(CITB & WLC Ltd, 2018)	✓			✓		✓			✓

** prd = productivity; cnstr = construction*

2.6 Limitation to existing knowledge

The following gaps in knowledge were identified and were utilised to build the methodology of this doctoral work, using the themes of the knowledge gaps to form a multi-phase research design, as described further in the next chapter:

- A lack of surveys on the perception and knowledge of built environment designers on advanced offsite timber systems, especially VTC
- A gap in knowledge on the international comparative productivity of volumetric and panelised offsite manufacturing processes, with productivity measurements which consider the differences in work completed in the factory
- There were no specific data collection and analysis tools proposed for comparative productivity measurement of offsite timber systems
- A gap in knowledge on the multi-factor construction productivity performance of offsite construction systems with different levels of work completed in the factory, including open panel, closed panel, CLT and volumetric

The above incremental steps lead to the over-arching limitation to knowledge, the lack of a single measure to evaluate the MFP performance of different offsite timber systems across different manufacturers and construction projects, according to variables relevant to today's construction industry challenges.

Chapter 3: Methodology

This thesis has used a mixed research methodology shown in **Figure 19** to interrogate the multi-factor productivity of offsite timber systems. The initial research phase included an extensive literature review regarding the UK economic context, the key attributes of offsite timber systems and the existing construction productivity measures. This identified a number of gaps in knowledge, which were investigated in subsequent research phases according to a devised framework of ten MFP variables. The first research mechanism was a survey among designer professionals to capture the market perceptions regarding the most advanced offsite timber system, namely volumetric within the current economic context. Secondly, the manufacturing processes of volumetric timber, closed timber panel and open timber panel systems were comparatively analysed in an international context, covering the UK, and Northern and Central Europe. With additional work, offsite perspectives from Canada, USA and New Zealand were added to contextualise the manufacturing research.

Following on from this, the construction processes of four offsite timber systems were investigated using case study methods. A scientifically significant volumetric timber construction project was identified as the starting point. It was the first large-scale development to achieve Section 7 Sustainability Gold accreditation (The Scottish Government, 2013). The author participated in a Construction Scotland Innovation Centre research project on this case study, and through snowball sampling within the interdisciplinary research team, a comparative standard-practice open timber panel residential development case study was identified in the outskirts of Glasgow. These comparative case studies served as a pilot study to develop a constructability and productivity analysis method. This was later used to analyse the full construction process in two comparative case studies, one of which was the tallest timber building in Scotland using CLT, and the benchmark was a closed timber panel project.

The resulting multi-phase results were summarised according to ten MFP variables in six subsequent phases focusing on multi-factor productivity analysis. Based on the collected data and its analysis, a proposal for a comparative multi-factor productivity index for offsite timber systems was developed.

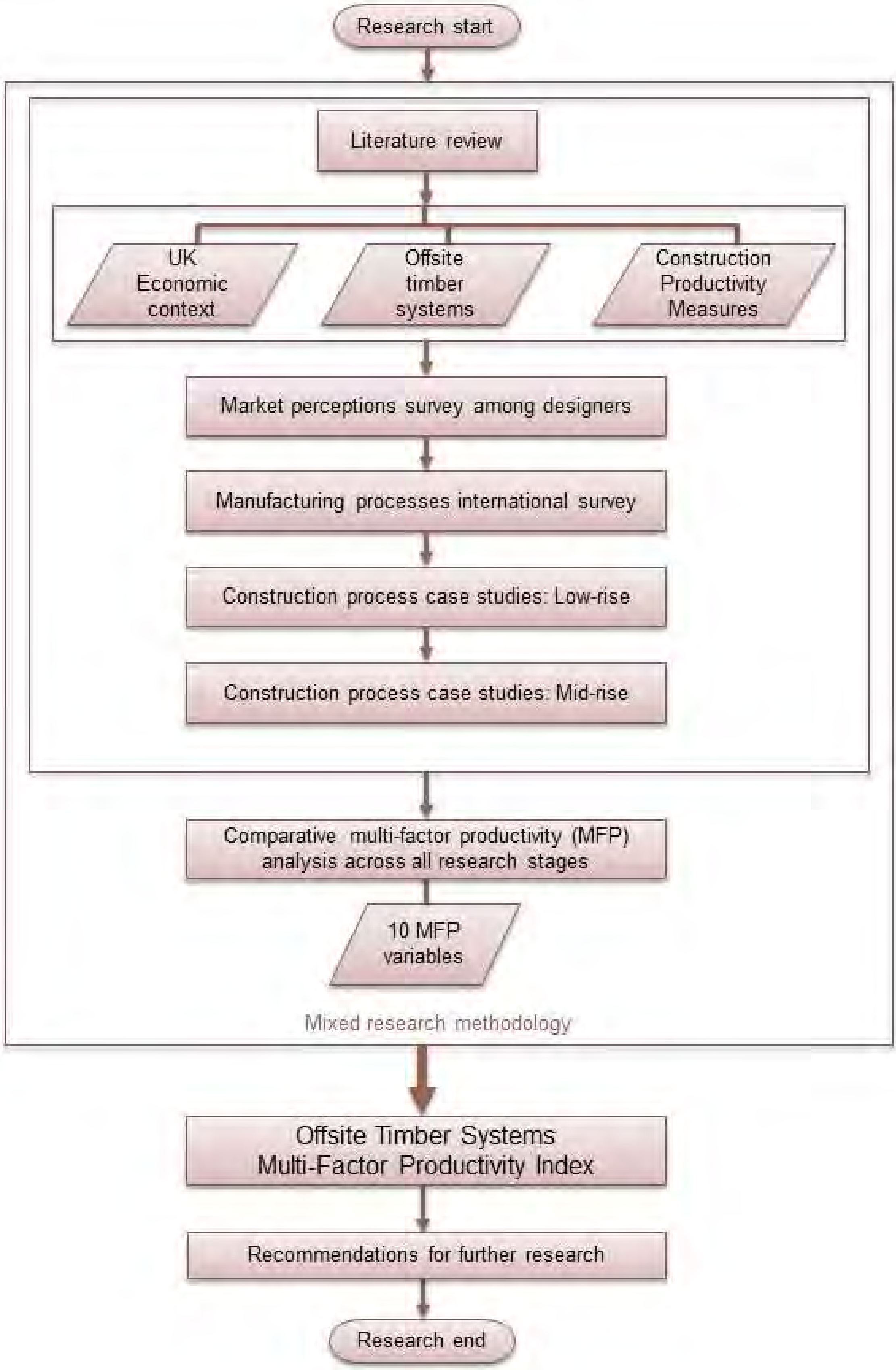


Figure 19. Research methodology.

Throughout these research stages, several methodologies were combined within an over-arching mixed methods research methodology. In the initial research stage regarding the market perceptions towards advanced offsite constructions systems, survey tools from the social sciences were implemented within a market research method (Mason, 1996; Bethlehem, 2009; Wedel & Kamakura, 2000). This approach was augmented with some investigation of management techniques in offsite timber manufacturing, including a quantitative labour-productivity comparison (Eiselt & Sandblom, 2010). In the construction case studies methods utilised in operations research were applied, which investigated the construction management aspects of the sampled case studies (Yin, 2014). Finally in the MFP analysis the fields of social research quality of life and econometric were combined to write the foundations to an offsite timber systems MFP index which may be utilised to comparatively analyse a large sample of case studies with further work (Land, Michalos & Sirgy, 2012; OECD, 2008). A gradual transition from 'softer' perceptions-based to 'harder' numeric-based positivist science fields was therefore achieved in this doctoral work, within an overall econometric development of a composite productivity index (OECD, 2008; Beran, Feng & Hebbel, 2015).

In this research the philosophical paradigm of critical realism was used, which is the most suitable for investigations whose aim is to improve the contemporary practice of the professions (Hooper, 2015). In line with the critical realism paradigm, this thesis holds the ontology (worldview) that the most optimised method for constructability of offsite timber systems exists in theory, however the applications in practice depend on external factors, which impose restrictions. Similarly, the epistemology (nature of knowledge) applied in this thesis could be located in the middle between positivism, associated with experiment-based quantitative research, and interpretivism, associated with the subjective interpretation of data in the social sciences (Hesse-Biber, 2010).

3.1 Research aim and objectives

The aim of this research was to comparatively analyse the MFP of offsite timber construction systems across designers' perceptions, manufacturing and construction, and through this process to set the foundations for an innovative offsite timber construction MFP index. This index may be utilised to collect data for a large geographic sample of a variety of building typologies to create a database. This data can be useful to help guide decision-makers who want to understand what the most optimum for their priorities offsite timber construction system could be.

To achieve this aim, the following objectives were set:

- Identify ten MFP variables for MFP analysis of offsite timber systems, as a theoretical framework.
- Create a snapshot in time of the perceived opportunities and challenges of VTC in the context of panelised timber systems, and the most effective offsite timber knowledge dissemination strategies.
- Comparatively analyse the differences and similarities between the products, project management, and production operations of offsite timber systems manufacturers in the UK and mainland Europe.
- Comparatively analyse two sets of construction case studies, one set low-rise and the other set mid-rise residential construction, regarding their MFP performance. The exploratory case studies should investigate use of BIM and Lean techniques to improve productivity, and provide data for an initial comparison of offsite timber systems MFP.
- Synergise the findings from the previous research stages into a unique and original comparative productivity analysis method

3.2 Research design

The mixed research methodology utilised in this thesis was designed according to the stages of construction projects, and in response to the research aim and objectives outlined above. The initial scope related to the designers' perception and knowledge, followed by a manufacturing stage and finally an onsite construction stage (Hesse-Biber, 2010). Combinations of qualitative and quantitative data collection and analysis were used in each research design stage (Creswell & Clark, 2007). Quantitative data was analysed using statistical methods to reveal trends and groups, and the qualitative methods were utilised to explore the reasons for the differences or similarities in quantitative results (Barbour, 2014).

Established analysis tools such as NVivo were used for coding of the qualitative survey responses, SPSS analysis for quantitative questionnaires analysis, and project management software for the construction case studies, as explained in more detail in the following section (Gray, 2004). Each stage was followed by validation and sensitivity analyses designed according to each research method. For example the quantitative questionnaire findings were validated using statistical approaches, whereas face to face interviews with industry experts were used for the validation of the constructability and productivity data and analysis (Murray-Smith, 2015; Gray, 2004). Furthermore, as the research progressed, the findings from all stages were reviewed and the research methods were streamlined to ensure the conceptual coherency of the research project (Given, 2008). The thus created triangulated mixed research approach therefore enabled for findings from one stage to inform the scope, aim and sampling of the following research stage.

3.3 Use of analytical software tools

To analyse the available scientific literature, Mendeley software was used for day-to-day management of collected literature, and a reading record was created for each read literature piece in MS Excel. Within this reading record descriptive data about each reviewed source were noted, along with its applicability in the development of the research question.

In the market survey NVivo was used to analyse qualitative interview transcripts, and IBM SPSS Statistics was used to analyse the quantitative on-line questionnaire data. Both of these tools were identified as industry-standard in research analysis (Bazeley, 2011; Goulding *et al.*, 2012; Johnsson & Meiling, 2009). Training sessions were attended at the University of Strathclyde to provide a robust foundation with for the data analysis. Within SPSS the data from the questionnaires was added in the form of two interconnected spreadsheets – one with data and one with variables. The thus created dataset was used for statistical descriptive analysis and a Pearson correlational analysis (selected due to sample size). Results were exported as charts from SPSS for visual analysis and understanding.

Within NVivo, each of the interviews were entered as a separate case in the form of a PDF with interview transcripts. Nodes were created for each of the interview questions. As the coding of the cases with nodes progressed, additional nodes were created with typical answers for each question. Some such additional nodes were general, for example ‘positive’, ‘neutral, and ‘negative’, and others were more specific such as ‘time on site’, ‘waste materials’, etc. From NVivo tools were used to export results as a variety of charts and reports, including bar charts, cluster trees and word frequency. These reports were referred to during the write-up of the market survey chapter.

To analyse the data from the manufacturing survey a combination of Excel and NVivo were utilised, for the quantitative and qualitative aspects of the research, respectively. In Excel a master spreadsheet was created with each of the survey questions in rows and each of the factory visits in columns. Data was entered in each field based on notes taken during the interviews and site tours. Separate spreadsheets were created for quantification of the offsite completion percentages, normalisation of production data to a single unit of measurement and labour productivity calculations. From these data, charts were also created in Excel to aid the comparison of productivity-related aspects. In addition, a report was created for each interview and factory tour with selected photographs, and was imported in NVivo as a separate PDF case for each manufacturer. This qualitative data was analysed in the same way as the market data described above, but with nodes adapted to the specific survey questions. Key quantified qualitative results such as the numbers and types of waste minimising strategies were exported as Excel spreadsheets for creation of charts to use in the thesis.

During the construction case studies, a combination of Excel and MS Project were utilised to quantify the labour-productivity and time on-site of the construction case studies. This was combined with qualitative interviews analysis for the five secondary qualitative variables. A BIM workflow for productivity analysis was also trialled using a combination of Revit and BIM 360 Field, but was dismissed due to its found challenging applicability in scientific labour productivity analysis. Within Excel a separate spreadsheet was set up for each of the ten variables listed in the following section. Each spreadsheet included data entry from site visits as rows, and columns with units of measurement for each variable (for example, start date, finish date, actual start, actual end, duration) and analysis columns with Lean wastes and tools, and BIM tools and principles. Additional spreadsheets were created to allocate individual codes for each site visit record, and for input in drop-down menus within the main spreadsheets, such as Lean wastes, construction stages, labour types and BIM tools.

However as the case study research scope was extended from the offsite system installation only, to the entire project, it was found that this Excel-based data entry and analysis system was too laborious. Therefore MS Project was identified as the industry-standard tool for quantitative construction time and labour analysis. A project file was created for each of the mid-rise case studies using a unique work-breakdown structure to list tasks in rows. Start and end dates were allocated to each task using data collected from site visits, and work resources were allocated to represent the labour utilised on each task. The calculation method for labour-hours from this data was validated with manual calculation for a case study completed in Excel. Using the MS Project reporting tools Gantt charts, bar charts and tables were exported for the case studies to enable a direct comparison in the thesis chapter.

3.4 MFP Variables

There were differences in the exact analysis variables throughout the research project, as the focus of the work gradually narrowed and expanded. Finally ten MFP variables were identified, according to which the overall analysis and index development were completed:

1 Time
2 Cost
3 Labour productivity
4 Logistics
5 Waste
6 BIM
7 Specification & installation
8 Energy-efficiency
9 Build quality
10 Health & Safety

These ten variables were refined during the course of the research to reflect the most critical issues connected to offsite timber construction productivity. The list grew gradually from six, to eight, twelve and finally to ten as the research unfolded and the most critical elements applicable across the design, manufacturing and construction stages were identified.

3.5 Sampling

The first stage of the research, the market perceptions survey, included a total of 69 UK built environment professionals, more than 60% of whom were architects, followed by engineers (13%) and the remaining percentages were approximately evenly split between manufacturers, developers and others, such as sustainability consultants or housing associations. When compared to the national population of approximately 49,000 registered architects in the UK on average in the survey period 2014-2016 (Statista, 2018), the survey captured a 0.14% of practicing architects, however in this qualitative study the aim was to achieve a variety of opinions and saturation of represented ideas (Gray, 2004).

The second stage, the international manufacturing survey with a focus on the UK and the EU, included 15 interviews among 10 offsite timber manufacturers in the main comparative analysis survey, with more than 23 completed UK and EU projects visited. In addition, the author participated in approximately 15 manufacturer's tours in Canada, Sweden and Scotland with representatives from the U.S.A and New Zealand. The interviews were conducted with representatives of various professions within the manufacturing companies, and the largest group were architects.

In the comparative construction case study stages four construction projects were selected overall. Two of these were identified within the authors' professional network for their scientific significance as first-of-a-kind offsite timber projects, the tallest timber building in Scotland, and the first large-scale residential development built to Section 7 Gold standard (The Scottish Government, 2013). Through snowball sampling among the clients, architects, and offsite timber manufacturers of these projects two benchmark conventional offsite timber construction projects were identified. This stage included additional approximately 15 built environment research participants.

Overall this doctoral research sample included:

- 114 research participants
- 15 offsite timber manufacturers' tours
- 23 completed offsite timber projects
- 4 during-construction offsite timber projects

3.6 Ethics

All research phases were carried out with ethical due-diligence, following best practice principles of anonymity of participants. Advance clear information was provided, outlining the intended data use and providing participants with an opportunity to review and amend their responses (Reason & Bradbury, 2008; Iltis, 2006). Compliance with non-disclosure research project agreements was also ensured regarding the construction case studies. Before the start of the multi-stage survey, ethical permission was sought and granted by the Department of Architecture at the University of Strathclyde. Signed and dated research participation sheets were collected and stored for all survey participants (in a separate location to the stored data). In addition, any research participants' special requests such as exclusion from all photographs, or the opportunity to review scientific publications drafts, were granted.

3.7 Chronological sequence

The information as presented in this thesis does not necessarily represent the chronological order of the work carried out. Indeed, the research was conducted broadly according to construction projects sequence, starting with an investigation of designers' perceptions, followed by manufacturing and subsequently construction processes. However, some aspects such as the literature review phase captured multiple research phases and content was added to the review as further gaps in knowledge were identified with each stage of the research. For example, the review of productivity measures was undertaken during the construction case studies, and was directed by the findings from the manufacturing processes analysis, which identified the importance and gap of an offsite timber system MFP analysis method.

3.8 Scientific limitations

The international research scope of the work was broad and included study visits across the UK, mainland Europe, Northern America and indirectly through discussions at conferences captured the offsite context from New Zealand. Although every effort has been made to ensure the sample was representative of systems typical for their respective economic contexts, the sampled companies could not be said to be completely representative of offsite timber products and processes across the globe.

Furthermore, due to the complex nature of qualitative and quantitative data collection throughout the research stages, in certain cases there were gaps in the data availability, and some assumptions were necessary. Therefore, the probability exists that these assumptions were not completely representative of the true values. However, this has been minimised through the utilisation of knowledge from scientific literature and from the collected interviews with built environment professionals.

Chapter 4: Market perceptions survey

4.1 Research design

4.1.1 Aim and objectives

The market perceptions survey aimed to answer the research question below:

How do specifiers (architects, engineers, quantity surveyors and manufacturers) perceive volumetric timber construction in the current UK economic context?

To answer the research question, the following objectives were set:

- Distribute questionnaire to participants with long term experience in the construction industry;
- Conduct face-to-face interviews with selected participants who have experience with or are interested in offsite timber systems; and
- Attend focus groups which discuss the enablers for offsite construction in the UK and conduct follow-up interviews with selected participants.

4.1.2 Method

Questionnaire

The questionnaire was divided into three main categories of 'Knowledge', 'Opportunities and Challenges', including the low carbon agenda and BIM, and 'The next 5-10 years'. The first question asked the participants to agree or disagree with a set of ethical statements on voluntary and anonymised participation. Excluding this, there were 12 closed ended questions and a final open-ended question, which gave participants the chance to express their opinion on the potential effect of VTC on the construction industry.

The wording of a question can influence the response of the participants (Groves *et al.*, 2009). In a study on the effect of positive, negative and bi-polar questions, it was found that the negatively phrased questions influenced the participants towards a positive response (Kamoen, 2013). However, the difference found between positive and bi-polar questions was not that significant. Therefore, to minimise the chances of influencing participants' answers, the majority of questions were formulated as using a bi-polar Likert scale and positive wording was used instead where a bi-polar option was not applicable. The wording of the questions was reviewed by fellow researchers in architecture and engineering, as well as members of the public prior to distribution to research participants.

The questionnaire was distributed using Qualtrics (Qualtrics LLC, 2016), an on-line in-browser software platform for composing and sending questionnaires. Qualtrics was selected over other options because of its superior properties such as unlimited time-span of the survey, unlimited responses and immediate statistical analysis features. The digital distribution of the survey allowed for rapid sharing and ease of completion for the participants. The user on-line interface was designed with a minimalist design to ensure the questionnaire was clear and intuitive to fill out. The first and last questionnaire responses were collected on 26/04/2015 and 04/04/2016 respectively.

A full example of the used questionnaire can be seen in **Appendix 4A - Market survey questionnaire**.

Interviews

Semi-structured interviews were conducted using pre-defined questions with the option to re-order the questions or make additional enquiries in reaction to the responses given by the participants. The interview questions followed a similar structure to the questionnaire, but were open-ended throughout to give participants the chance to express their opinions without any constraints. There were 15 questions organised in 4 groups of questions: ‘About the participant’, ‘Technical aspects and specification’, ‘Market opportunities and challenges’ and ‘The next 5-10 years’. The interviews started on 04/09/2015 and completed on 02/03/2016. The average interview duration was approximately 26 mins, with maximum and minimum of 28.5 and 21 mins, respectively.

The interviewee details and interview transcripts were be pseudo-anonymised, identified only through a number and digit code (Int01, Int02 etc.). An excel spreadsheet with a key to the identities and contact details of each interviewee was kept in a separate location to the interview transcripts. This was an ethical research conduct measure to prevent unwanted revealing of the interviewees’ identities.

A voice recorder was used with the consent of each participant. Notes were also taken during the interview to highlight important points. The interviews were transcribed selectively, with the assistance of the hand-written notes, to note succinct responses in order according to the designed questionnaire for streamlines cross-analysis. This approach has been recommended as best-practice transcription practice by (Bazeley, 2013). A full example of the used interview questionnaire can be seen in **Appendix 4B** - Interview .

Focus groups and follow-up interviews

The researcher was invited through Edinburgh Napier University to attend and assist during focus group discussions related to a research project funded by the Scottish enterprise. The aim of this external project was to identify enablers and barriers to the growth of offsite specification, manufacturing and construction in Scotland. The external research company had invited participants from diverse backgrounds and long-term experience in the construction industry. Two focus groups were attended in November 2016, one in Glasgow and one in Edinburgh with approximate duration of 2 hours and 30 minutes each. Face-to-face interviews were conducted with three workshop participants to elaborate on topics of interest, which were highlighted during the focus groups. Notes were taken during the focus groups. The face-to-face interviews were recorded and selectively transcribed.

Questions determination and validation

The questions utilised in the questionnaire and interviews were devised based upon previous similar studies such as the *Barriers and Opportunities for Offsite in the UK* and the *Perspectives of UK housebuilders on the use of offsite modern methods of construction* (Goodier & Gibb, 2005; Pan, Gibb & Dainty, 2007). Both sets of questions – for questionnaire and interviews were reviewed internally with the Architecture Department of University of Strathclyde for clarity and consistency. Two minor edits were made based on their feedback prior to use of the questions.

Due to the more qualitative and open-ended nature of the interview questions, it was considered necessary to undertake a more extensive questions validation process. A pilot set of 8 interviews were conducted using a 14-question template. An initial analysis was conducted on this sample and based on the findings one of the questions was removed and another one was re-worded to be more specific.

The focus groups were organised by an external consultancy and the author could not set the entire focus group questions, but selected key questions from the interviews were asked during these focus groups. In addition, in follow-up interviews with focus group participants, the same questions used during the main interviews described in the previous paragraph were utilised for consistency.

Results reporting and analysis

Full results and analysis of the questionnaire results may be found in **Appendices 4C and 4D**. Within the main body of the text, the reporting of the questionnaire and interview results was kept consistent through the use of a set of sub-headings: knowledge, time, cost, supply, demand, energy-efficiency, build quality and specification. To enable this, the questionnaire reporting was transformed to identify key findings within each sub-heading and in some instances may refer to several questions. Where the significance of the variables is referred to, the reader is advised to refer to the appendix for justification of these statements. Within Appendix 4C the number of responses to each question may be observed, and in Appendix 4D the full creation of categories and their analysis can be observed.

4.1.3 Sampling

The survey sought to gather responses from a variety of disciplines within the construction industry and from people with different offsite timber systems experience and knowledge. This contrasts the typical approach in quantitative research to reach a high number of responses, forming representative sample of the survey population (Gray, 2004). Instead in this survey saturation of information and high variety of responses were used as measures of sample completion (Barbour, 2014).

Non-random sampling of the target group was used, as random sampling was expected to lead to a low response rate. Participants were invited among colleagues in research institutions and practitioners who attended CPD sessions, trade shows and conferences on offsite timber construction. The drawback of this approach was that a smaller sample of the overall construction practitioner population was targeted. This limitation was targeted with the authors' participation in externally organised focused groups, part of a national research project on the offsite industry in the UK. Although the researcher had no powers over the sampling of focus group participants, the consultancy who organised the study utilised their data base of leaders in the construction industry, again using non-random sampling, to identify participants with wide-ranging national trends and micro-processes knowledge.

Overall 26 usable on-line questionnaire responses were collected, face-to-face interviews were conducted with 21 participants and 2 focus groups were attended, with 9 and 14 participants in each focus group, respectively. The total number of participants in this survey can therefore be confirmed as 69. Details of the participants' representative professions and sectors can be seen in **Table 8** below and their distribution is shown in **Figure 20**. Those participants whose occupation was 'Other' included "Sustainability Consultant", "Housing

Association", "NDPB" (non-departmental public body), "director", "carpenter" and "developer".

Table 8. Market survey sampling.

	Architect	Engineer	Manufacturer	Developer	Other
Questionnaire	13	7	2	0	4
Interviews	15	2	0	2	2
Sub-total	**27**	**9**	**2**	**2**	**6**
*Focus groups**			23		
Total			**69**		

* Exact data on each participant's profession was unavailable, however the majority were managers within offsite timber construction companies.

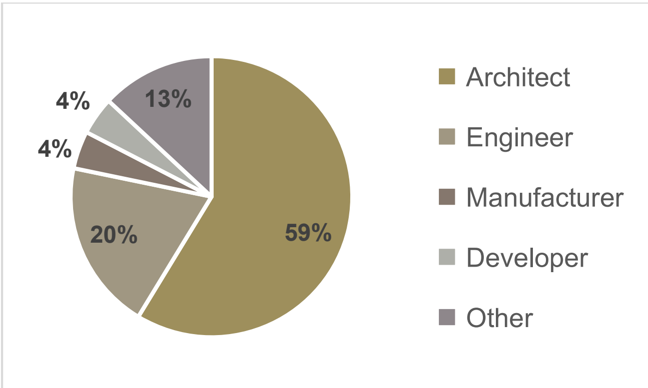


Figure 20. Total main market survey sampling distribution by profession (questionnaire and interviews).

4.1.4 Limitations

These results were limited by both the number of participants and their geographic locations. The results therefore cannot be directly generalised for the entire UK construction industry, as the sample cannot be said to be representative of all construction related professionals in the country. However, because of the variety of participants' professions, workplace organisations and previous experiences, their responses provide a snapshot in time of the main perceptions of construction professionals.

The investigation was limited practically by a time constraint of one calendar year, resource constraints connected with travel across the country and the crew size constraint of only one researcher. In addition, engaging effectively with construction professionals, who are an especially busy group of people, and convincing them to give some of their valuable time to this research instead of managing their construction projects was more challenging than anticipated.

4.2. Questionnaire results and discussion

4.2.1 Knowledge of offsite timber systems

The knowledge of the participants with offsite methods of construction was assessed via two separate questions to gauge their existing knowledge and experience. The first question was part of the introductory section of the questionnaire and enquired about the participants' general familiarity with VTC on a 5-point Likert scale. The second question was in the main section of the questionnaire and enquired of the participants' level of working knowledge and previous experience with seven offsite systems, from façade panels to 3D volumetric. In the comparison of responses shown in **Figure 21** a discrepancy can be seen between the firstly provided general familiarity (black line) and actual knowledge and experience with VTC (brown bar), however the data for all systems peaks at 'limited working knowledge'. In general, the participants had more knowledge and experience with 2D offsite systems than with 3D systems. Volumetric timber in particular was the lowest scoring system for knowledge and familiarity.

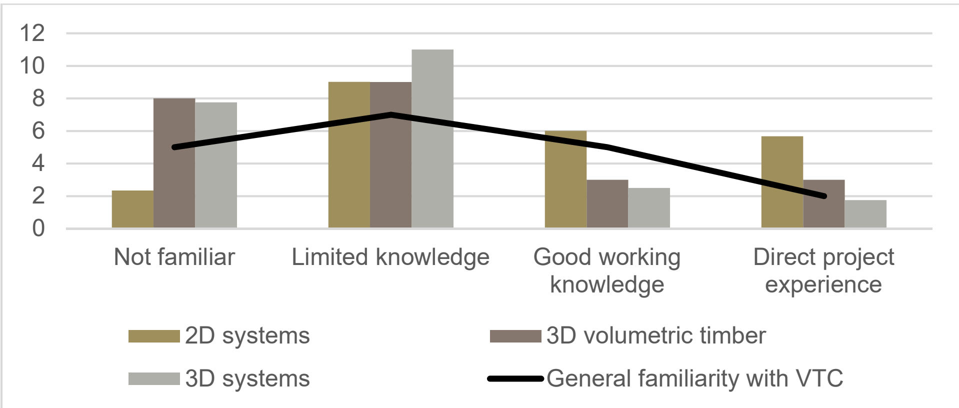


Figure 21. Participants' knowledge of offsite systems, combination of two questions with averaged values for 2D systems (façade panels, open panels, closed panels) and 3D systems (bathroom pods, kitchen pods, volumetric steel and volumetric timber) with called out familiarity with volumetric timber systems.

4.2.2 Time

Construction time reduction was the most highly ranked advantage of VTC compared to traditional construction. Construction time was identified as a 'strong advantage' by 10 participants, as an 'advantage' by 11 participants and as 'neutral' by 1 participant, and none of the participants perceived time as a disadvantage (see Figure 4C6). The perceptions of design time were less positive with a mean value of 3.14, situated closer to ‘neutral’ than ‘advantageous’. The overall mean score for design and construction time combined as one category was 3.8, closer to ‘advantageous’ (see Fig. 4D2.). These results are shown in **Figure 22**. Furthermore, when enquired about the efficiency of construction in the final qualitative question, four out of seventeen participants cited time savings as one of the main effects of VTC such as: *‘reduction of construction time’* and *‘reduced costs from off-site construction time’*. These two attributes could moreover be associated with productivity measures in construction such as the reduction in onsite installation time established in the literature review (Lawson, Ogden & Goodier, 2014).

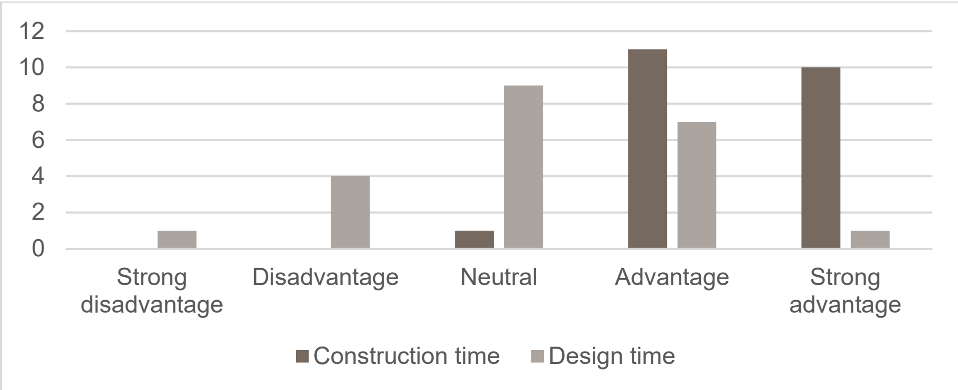


Figure 22. Perception of time as an advantage or disadvantage compared to traditional construction methods.

4.2.3 Cost

Overall the participants perceived that the cost of VTC was neutral in comparison with traditional building systems. Ten participants ranked cost as ‘neutral’, six ranked it disadvantageous and six ranked it as advantageous. The mean value of the variable was 3.05, which was marginally more than ‘neutral’.

However, cost was also perceived as a relevant barrier to VTC specification in the UK, and only two participants ranked cost as ‘neutral’ in this category, as shown in **Figure 23** below. Additionally, reduced cost was identified as a very relevant factor, which could increase the specification of VTC in the UK. Cost was also the most often cited factor in the final qualitative question. It was mentioned as either an advantage or an opportunity by six participants, two examples of which were:

‘3D VTC decreases build time and cost. Both are critical factors in today's marketing where housing supply does not meet demand. Build time and costs will decrease further with time as processes are streamlined.’

'3D VTC has great potential to provide consistent quality at attractive cost, using local timber but this will rely on an industry that is equipped to deliver and a suitable contractual arrangement.'

These data can be interpreted as a statement that cost for VTC is perceived as slightly higher than for traditional construction, which is currently a barrier to specification. However, should the cost be reduced below this line, VTC could be specified in more projects.

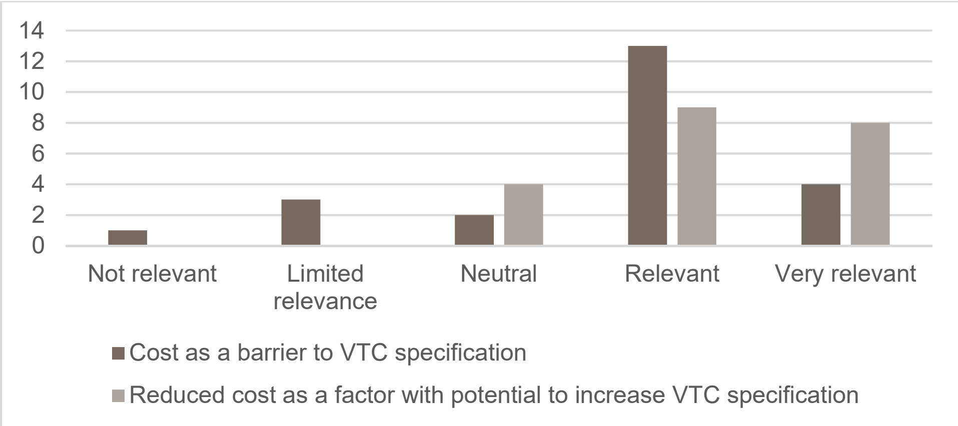


Figure 23. Perceived relevance of cost as a barrier and factor to increase VTC specification.

4.2.4 Supply

The lack of manufacturing facilities in the UK was the most highly ranked barrier to VTC specification with a mean of 4.27, between 'relevant' (9 responses) and 'very relevant' (10 responses). As a potential enabler, local manufacturing facilities had a similar mean of 4.24 with 10 'relevant' and 8 'very relevant' responses.

Furthermore, automated construction was identified as an applicable opportunity for VTC specification by 14 participants. This can be logically connected to the perception of 'skills availability' as advantageous by 9 participants although the mean of 3.18 for this variable was only marginally higher than 'neutral'.

Therefore, there is a need and potential to establish automated volumetric timber manufacturing facilities in the UK, which could help to alleviate the existing skills shortage in the construction industry. This was highlighted by the qualitative response cited below:

'It (VTC) should increase efficiency enormously but only where supporting and interlinked works move away from site install as well.'

4.2.5 Demand

Building types

Among the opportunities for VTC specification in the UK the demand for housing was ranked as the most relevant by the participants, as shown in **Figure 24**. Housing was also emphasised in the final qualitative question with references by 4 respondents, two examples of which are shown below. Furthermore, housing was perceived as the most suitable building type for VTC with a high mean value of 4.43 on the border between 'suitable' and 'very suitable'. Office buildings were ranked similarly highly suitable for VTC with a mean value of 4.1. School buildings were also identified relevant to VTC buildings in the UK, ranked as 'very suitable' by 6 participants.

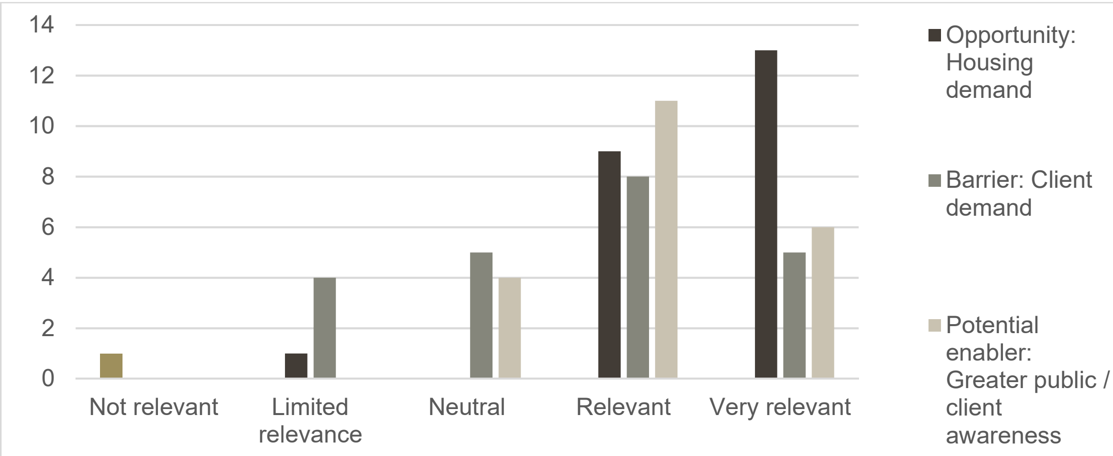


Figure 24. Perceptions regarding selected VTC demand factors.

'Shortage of housing'

'80%+ of Scottish housing is timber frame, which means efficiency in production can be very beneficial to the whole construction process.'

Clients

The influence of the clients in specifying VTC was highlighted by the 13 respondents, who ranked client demand as either a 'relevant' or 'very relevant' barrier to VTC. Increase in client awareness regarding volumetric timber systems was ranked as a highly relevant potential enabler with a mean value of 4.1, slightly higher than 'relevant'.

Building systems in the next 5-10 years

Structural closed panels received the highest ranking for relevance to the UK market in the next 5-10 years with a mean value of 3.29 and structural closed panels were the highest ranked building system for the UK market, with seven ‘very relevant’ scores. Three-dimensional volumetric timber systems were perceived as similarly important for the near future of construction in the UK, whereas volumetric steel and open panels were reported as less relevant, as summarised in **Figure 25** below.

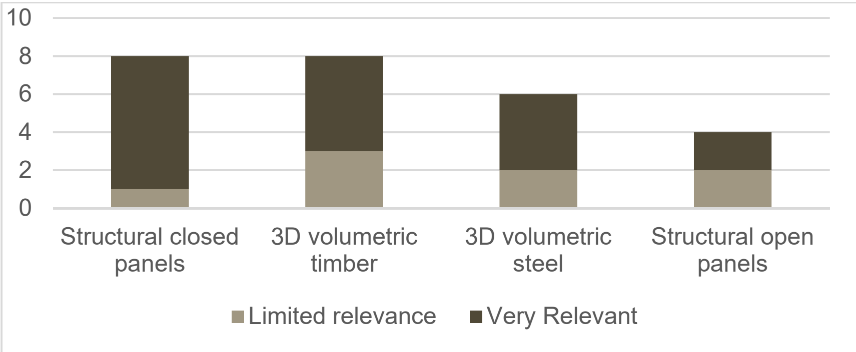


Figure 25. Perceived relevance of building systems in the UK growing market context of the next 5-10 years.

4.2.6 Energy efficiency and build quality

The energy efficiency of a building depends on build quality, such as correct fitting of insulation and application of seals at points where the building fabric is punctured. For this reason, these variables are grouped together. Build quality was the second highest ranked advantage of VTC compared to other construction methods, perceived as an ‘advantage’ by 12 participants and as a ‘strong advantage’ by 6 participants, equalling 18 advantageous ranks out of 22 responses as a mean of 4.05 located very closely to ‘advantage’. Furthermore, build quality assurance was one of the three highest ranked factors with potential to increase VTC specification. The low carbon agenda was also ranked as a relevant potential enabler for VTC in the UK, as shown in **Figure 26**. In the final qualitative question 4 participants referred to energy efficiency and build quality, examples of their statements are:

‘3D volumetric has the potential to deliver low cost, defect free housing.’

‘Improved quality control / not weather effected in the same way as traditional construction.’

‘The ability to create Passivhaus buildings as a common standard and bring their construction cost down to a more realistic level.’

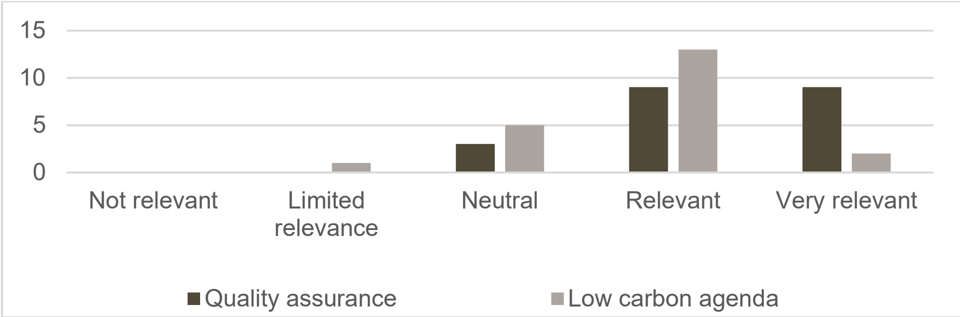


Figure 26. Perceptions of energy efficiency and build quality as potential enablers.

4.2.7 Specification

Design options

Design flexibility was ranked as the most disadvantageous VTC aspect, ranked mostly disadvantageous (9 out of 22) with a mean value of 2.82, between 'disadvantage' and 'neutral'. Design flexibility was furthermore identified as a relevant barrier to VTC specification, which if improved could potentially increase the use of VTC in the UK. The results are shown in **Figure 27** below. The mean values for design flexibility as a barrier and as a potential enabler were 3.68 and 3.95 respectively, located in the vicinity of 'relevant'.

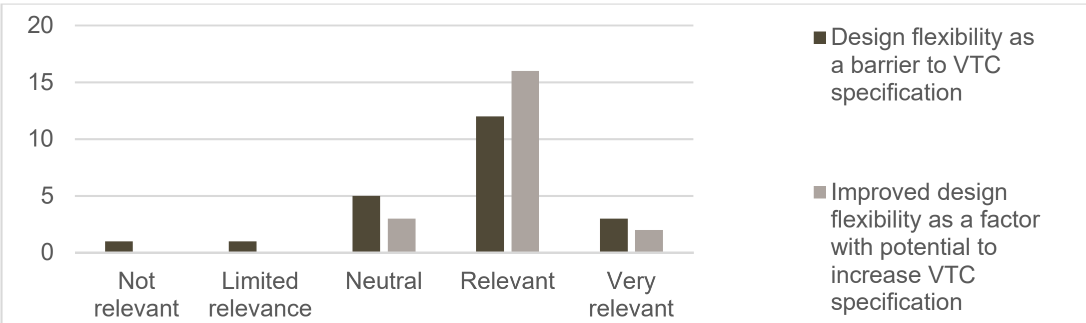


Figure 27. Design flexibility perceptions as a barrier (N responses=22) and as a potential enabler (N responses=21) to VTC specification in the UK.

Materials

The use of new engineered timber products was the penultimate perceived opportunity for VTC specification, with 13 'relevant' and 7 'very relevant' ratings. The recyclability of VTC was identified as the third highest rated advantage with 11 'advantage' and 3 'very relevant' responses. Therefore, regarding the material specification of VTC, it was generally perceived that VTC can be specified to enable material recycling and in combination with timber engineered products.

Building Information Management (BIM)

BIM utilisation was ranked as the third most relevant opportunity for VTC specification. However, application of BIM was also identified as the least relevant potential enabling factor for VTC specification, with less than half relevant ratings and the only enabler variable rated 'not relevant', as shown in **Figure 28**. Furthermore, cross-industry collaboration early in the design process, which is essential for BIM implementation, was rated selected as a barrier by 14 out of 22 participants, with a mean value 3.95 in close proximity to 'relevant'. This aligns collaboration as a more relevant barrier than cost according to the perceptions of the questionnaire participants.

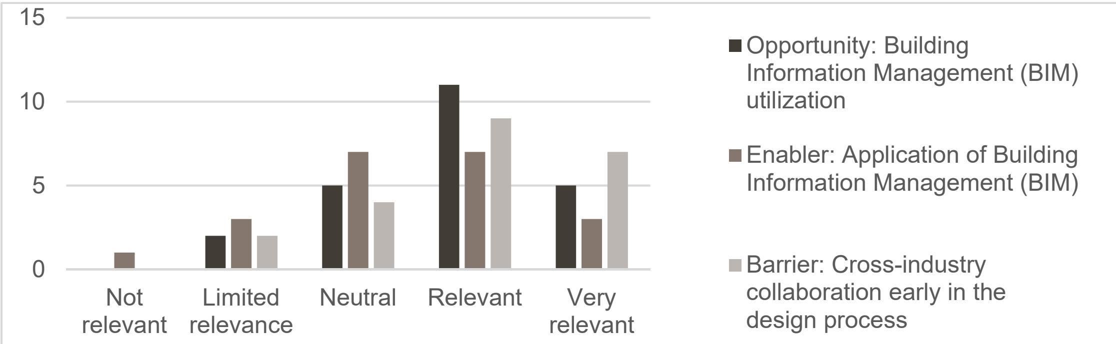


Figure 28. Perceptions of BIM variables.

Knowledge and skills

From the perceived barriers, professional working knowledge was ranked second most relevant, followed closely by the education and training of construction professionals, as shown in **Figure 29**. These two factors can be grouped into one barrier category of theoretical and practical knowledge. On the same topic, the provision of technical literature and guidance was ranked as a 'relevant' potential enabler by 7 participants and as 'very relevant' by 3 participants. In a later question the majority of respondents (12) selected their preferred knowledge transfer mechanism to be the 'provision of best practice recommendations and technical guidance' on the topic of VTC. This was followed by the provision of as built prototypes, which was selected by 6 participants. Therefore, existing knowledge and skills were identified as a barrier to VTC specification, which could be mitigated by the provision of technical literature and guidance reports.

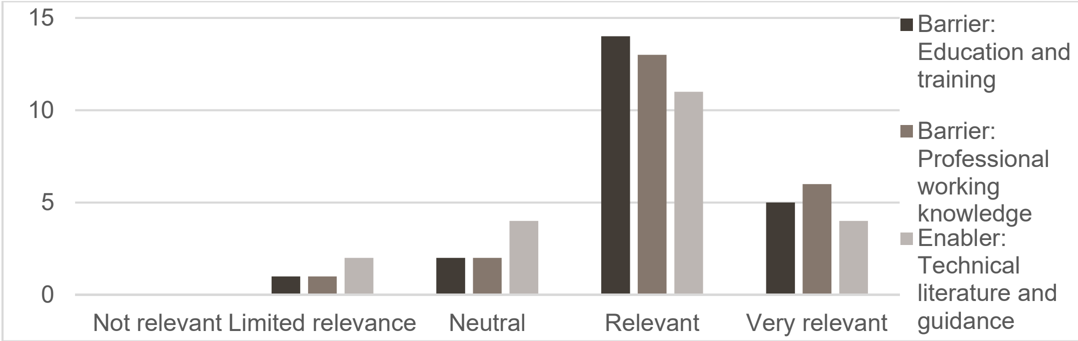


Figure 29. Perceptions regarding working knowledge.

4.2.8 Statistical analyses

Because of the small sample number of 26 responses statistical analyses cannot be trusted as the sole methods of data interpretation in this survey. With an exploratory purpose the 52 questionnaire variables were configured into 13 categories, the full descriptions of which can be seen in **Appendix 4D** along with the remainder statistical analyses. Descriptive statistics and bivariate correlational analyses were conducted, where the Pearson coefficient generated from SPSS indicated whether there was a positive or negative correlation, and the number indicated the correlation strength (Bethlehem, 2009). In case of a zero Person coefficient, this indicated there was no correlation between the variables. Thirteen categorical variables were utilised to identify interrelated categories. From this step five correlated categories were identified as the 'VTC perceptions summary group', shown in **Table 9**. The table shows that the categories with the strongest correlation were BIM, Design, Low carbon, Housing and Next 5-10 years all to the perceived quality of VTC. Respondents who perceived positively the quality of VTC, also tended to respond positively BIM questions, low carbon, housing and near future of VTC questions, but tended to respond negatively regarding design questions (with a similar magnitude). The difference in correlation type between quality and design may be explained with location of design-flexibility related questions within the barriers questions. These correlations were true for approximately half of the respondents in each of the pairs, or in other words the categories were moderately correlated. These findings suggested that quality, BIM, low-carbon, design flexibility, housing market and the near future should be included in questions in the following research stages, and indeed were utilised to guide the subsequent manufacturing processes survey creation. Attempts were also made to analyse the data using factor analysis and grouping according to the skewness of the variables, however because of the small sample size these generated less meaningful results (Krzanowski & Marriott, 1994).

Table 9. Correlational analysis results by category.

VTC perceptions summary group		BIM category	Design category	Low carbon category	Housing category	3D systems in 5-10 years
VTC quality perception (advantage/disadvantage)	Correlation Coefficient	.434*	-.467*	.456*	.516*	.512*
	Sig. (2-tailed)	.049	.033	.038	.017	.025
	N	21	21	21	21	19

4.3. Interview results and discussion

4.3.1 Knowledge about VTC

Only approximately 1/3 of the interviewees were familiar with the meaning of the term 'volumetric timber construction'. Their definitions were considered as correct if they represented the basic idea of a module containing a volume of spaces with finishes and services prefabricated in a factory. Two examples of definitions considered correct are listed below.

'Process of using off-site 3D volume modules, which can either stand alone or are components stitched together on site to form a larger volume.' and

'… it is construction of a complete 3D box. It is different from modular panels or SIPs, as it is constructed off-site to a much greater extent.'

As shown in **Figure 30**, approximately half of the interviewees assumed that VTC is a form of panel construction, predominantly making associations with engineered timber products such as CLT and Glulam. Ten participants provided a panel-based definition of VTC. One participant suggested a connection to recycled timber products and two interviewees could not make any assumptions on the meaning of the term.

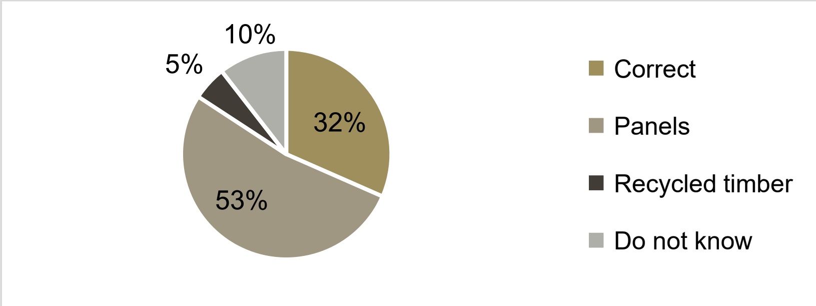


Figure 30. Interview participants' definitions of VTC.

Previous experience

The interviewees had a large diversity of previous experiences, as shown in **Figure 31**. More than half of the respondents' previous experience examples were from a type of off-site timber panel construction. Six of the respondents' examples were connected to volumetric construction. There were three mentions of sustainability-related experience, which were either in sustainable materials or the Passivhaus standard. Three participants only had experience in conventional construction, marked as not relevant.

Open panels were the type of timber panel previous experience with the highest number of six previous experience examples. Similarly, five examples were given of closed panel previous experience. These two methods of construction were mentioned by design and public organisation representatives. Among designers there were also two examples given of experience with engineered timber products and one example of a timber portal frame building method.

Only one interviewee had direct experience with VTC and that was in a foreign country more than two decades previously. Both design and public organisation representatives had considered volumetric timber construction either for projects or as part of research into construction methods. This was the type of VTC experience with the highest number of examples among the interviewees. One interviewee reflected in retrospect that one of their projects could have potentially been designed and constructed using VTC.

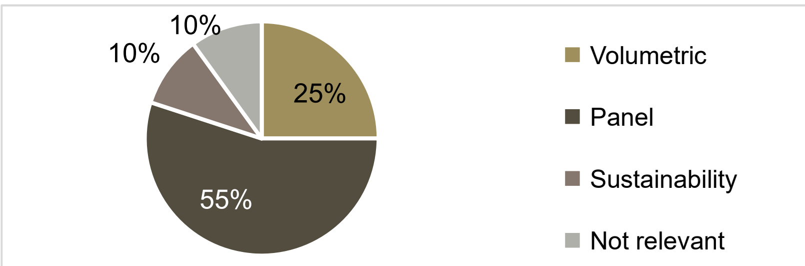


Figure 31. Types of participants' previous experiences.

4.3.2 Time

Overall 18 interviewees thought that VTC would be quicker than conventional construction, or 88% as shown in **Figure 32**. Half of these interviewees highlighted that time on site would be minimised and potentially reduced to only 'a couple of days'. The other half emphasised on the opportunity for quicker project process overall, including a front-loaded design process which would reduce the time spent on defects remediation. One interviewee could not provide an answer, one said there would be no difference and one response was negative, that the time to manufacture a volumetric timber building would be a challenge for implementation.

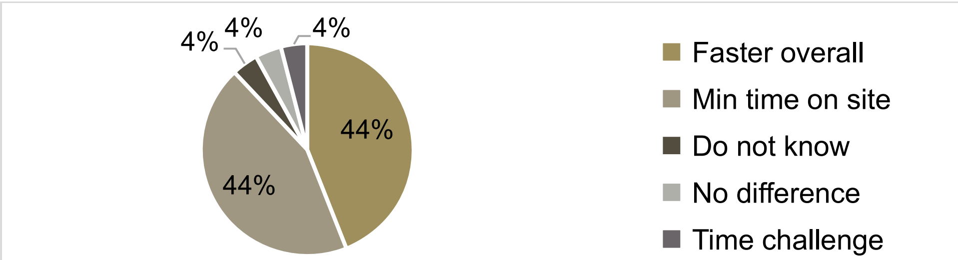


Figure 32. Perceptions of VTC project times vs conventional construction.

4.3.3 Cost

The views on cost were more diverse. Overall, nearly half of the participants expressed a negative view that VTC would be more expensive than established methods of construction, as shown in **Figure 33**. Several comparisons were made between open timber panels and VTC. Approximately 1/3 stated that VTC would be more cost-efficient, but many participants put conditions on this such as replicability of the modules in the design and the experience of the manufacturer. Four interviewees postulated that VTC would be cost-neutral, especially if the balance between the high costs of manufacturing equipment and the reduced project management costs were considered.

Interviewees also perceived cost as a major challenge, which could hinder the application of VTC, shown in **Figure 34**. Comparisons were made between the expensive equipment needed to make timber modules and the simpler to manufacture and established on the market timber open panels. Views were expressed that to succeed, VTC would have to be either cost-neutral or less costly than conventional construction, as the decision on what construction to use is most often based on cost.

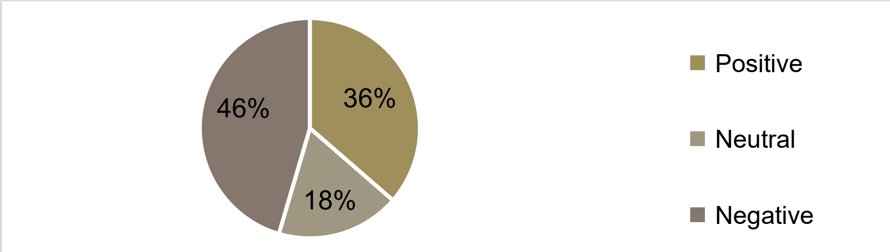


Figure 33. Perceptions of the cost of VTC compared to conventional construction.

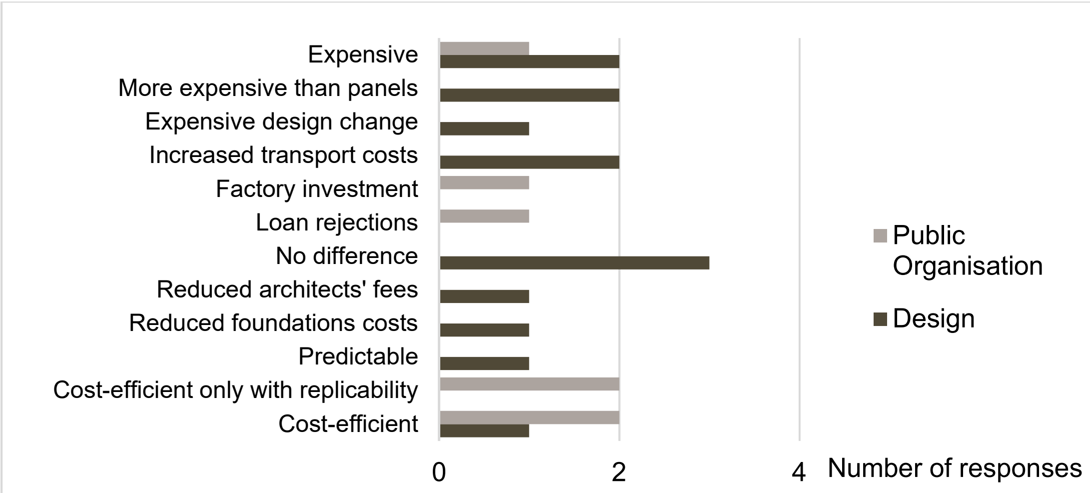


Figure 34. Perceptions of the cost of VTC compared to conventional construction in more detail and divided into professional groups.

4.3.4 Supply

Procurement

Regarding procurement, there were a wide variety of opinions expressed. The option with the largest number of agreeable answers was the potential to have partnership procurement between the key stakeholders. Three design and two public organisation representatives expressed this view. Four interviewees stated that a traditional tender and bid procurement route would be suitable for VTC. Three participants emphasised that the manufacturer's role would be key in the procurement strategy, especially the communication between the design, manufacturing and construction teams. One design professional perceived the procurement route as a challenge to implementing VTC in the UK.

Challenges

According to the interviewees, transportation was a key supply challenge, indeed it was one of the most significant barriers to implementation among others such as culture and cost shown in **Figure 35**, where variables located above the red line are typically identified as significant. The diagram was extracted from a barriers analysis and only the supply-related challenges are discussed here (cost and culture are discussed in more detail in separate sections as applicable). Within the cost perceptions the prohibitively high upfront investment for VTC factory establishment was often identified as a barrier to growth. Furthermore, several participants stated that the manufacturing facilities in the UK were insufficient to implement VTC, located prior to the grey line in the diagrams (indicating moderate significance). Transportation was explicitly highlighted as a leading perceived technical challenge by the survey participants, who made statements such as:

'… one of the disadvantages of volumetric compared to panels, that you are essentially transporting air within the module.' and

'But you are limited in volume to the size of a truck. This is where you lose out to the panel system, because if you can flat pack a panel on a truck then you can get lengths as long as the truck and then you could use these to make rooms.'

The supply of local timber was considered insignificant by the survey participants, as may be observed in its location after the grey dashed line in the diagram. Transportation was therefore the most significant supply-related aspect to be interrogated in subsequent research stages.

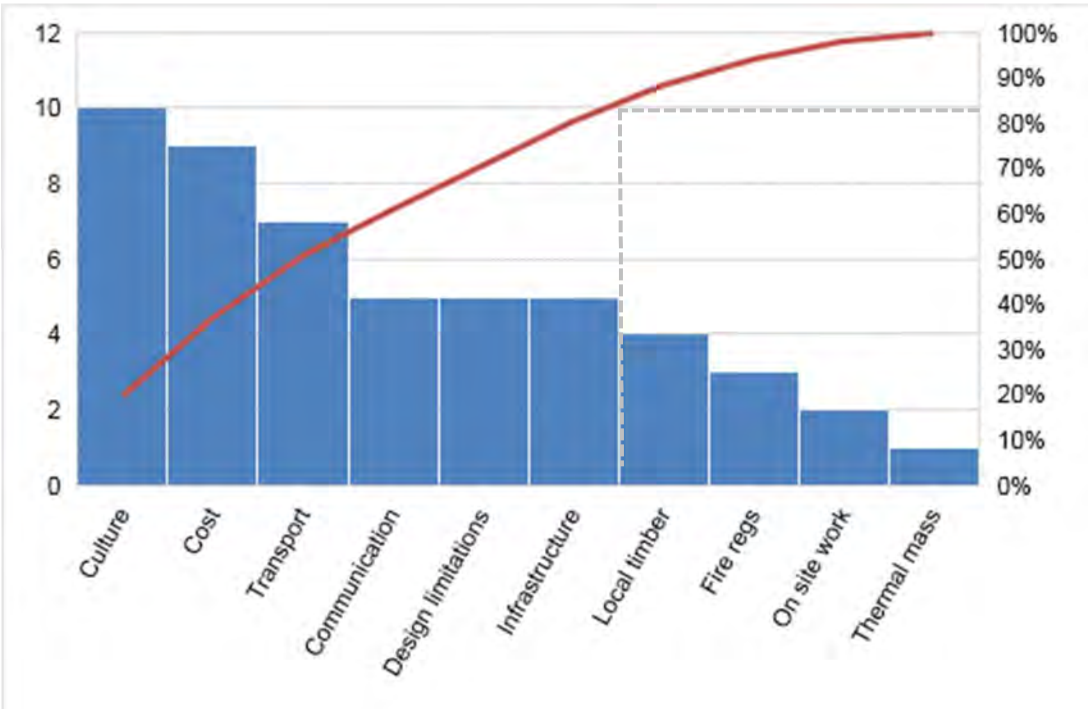


Figure 35. Pareto diagram of perceived barriers to VTC implementation, where the red line is used to determine the most important factors by drawing a perpendicular dashed line.

4.3.5 Demand

Building types

There was an overall opinion that VTC would be most suitable for housing, shown in **Figure 36**. Two main reasons were given in support of this argument, the current need for more high quality affordable housing in the UK and the suitability of the room sizes typical of houses and apartments for modular construction. Education buildings were also perceived as suitable building types, especially smaller primary schools, but not larger buildings such as colleges. Both hotels and 'any building with an already cellular layout' had strong positive support for VTC suitability. There were contrasting comments from different participants on the suitability of healthcare buildings, offices and sites in remote locations. There was a trend among participants to regard any types of buildings of larger scale or larger height as unsuitable for VTC.

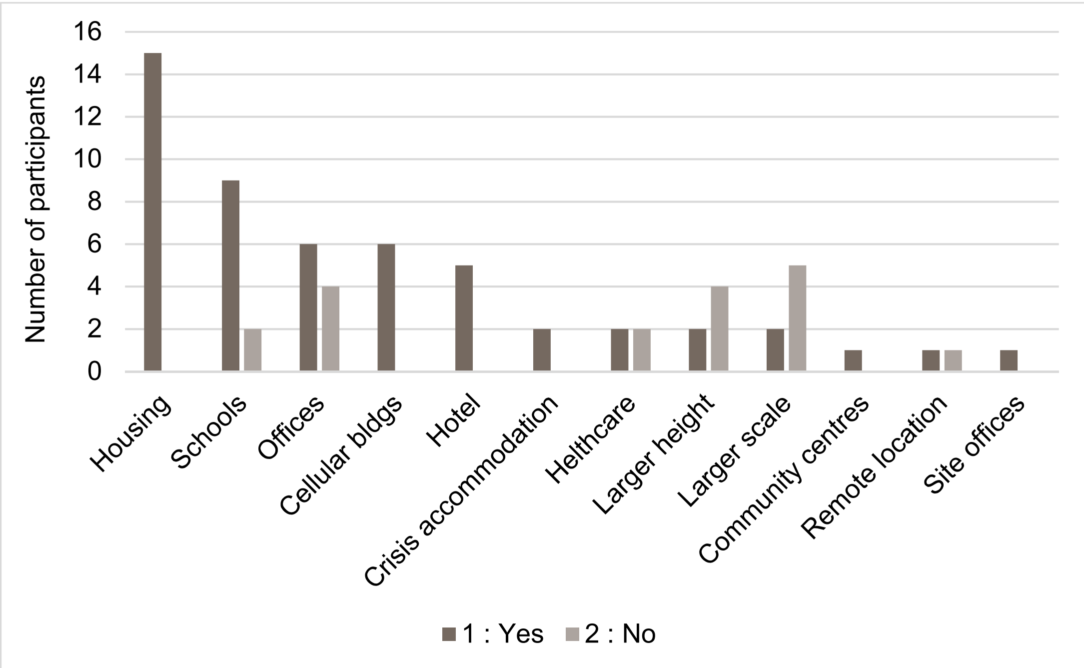


Figure 36. Perceived suitability of building types for VTC.

Client-led demand

Overall nine interviewees made connections between VTC implementation and the decision-making authority of the client. Three of these interviewees emphasised that clients would need to be provided with convincing data to the advantages VTC could offer for them, such as time reductions. The lack of flexibility in design was one of the main perceived barriers to convincing clients to implement VTC, because clients tended to change their brief criteria during the design process and because they might not want their buildings to be 'boxy'. Additional potential barriers were a perceived risk by clients to implement innovative building methods and previous negative experiences with timber frame construction.

Two designers stated that VTC might appeal to clients who were more demanding of the use of natural responsibly-sourced materials, and to whom the organic warm feel of a timber interior appeals. This was countered by the observation of another two designers that owners neither understood nor were interested in 'what is behind the plasterboard', To be able to comprehend the advantages of VTC, they needed knowledge in the basic principles of construction.

Culture

The main perceived challenge for VTC was culture, mostly associated with:

- designers, who may not be aware of VTC and associate it with 'buildings that look like boxes',
- clients who would have a stigma about modular construction from post-war construction and
- contractors, who would prefer to build using established methods they have experience with.

Competitor offsite systems

There was a frequent connection made between VTC and panel construction in the responses of interviewees. The comparison was made by 14 participants, 8 of whom expressed the view that VTC would be at a disadvantage compared to panel construction. The main reasons for this were design flexibility, transportation restrictions, costs and status as an established method of construction. In contrast, 2 interviewees stated that VTC would be advantageous because of improved build quality due to less exposure on site and de-constructability opportunities. In addition, 5 interviewees made neutral associations between VTC and panel construction, grouping them in the category of off-site timber construction methods. The themes of association were the reliability of costs, the opportunity for innovation through automated production and the need to convince clients and contractors to implement the system while it is still unfamiliar.

An association was also made by 5 interviewees between VTC and temporary steel modules. Four of them made a connection to temporary school modules used across for 10-15 years instead of the intended 1-2. The association was dominantly negative, that the construction sector and the public would consequently have a bad opinion of all types of modular construction. One participant added that this could be an opportunity for VTC, to provide higher quality permanent school modules. Another person suggested that the structure of steel modules could be applied in VTC, such that four very stiff corners were made and there was freedom to make openings in the walls as they were not supporting elements.

4.3.6 Energy efficiency

Changes in regulations

Overall 75% or 15 of the interviewees expressed the opinion that the regulations on the operational energy of buildings will become more stringent in the next 5-10 years. This was expressed by using words such as 'energy', 'carbon', 'insulation' and 'air tightness' in order from most to less frequently mentioned. Most participants were aware that the frequent changes in the building regulations were part of Scotland's strategy to reduce the energy consumption in buildings, as may be seen in **Figure 37**. Some commented that these requirements were becoming unrealistic, as they required not only sensible 'passive design' but also active on-site energy production which may not be feasible in all cases. A few comments were also made that the local differences in requirements may change, leading to a levelling of building regulations across England, Wales and Scotland.

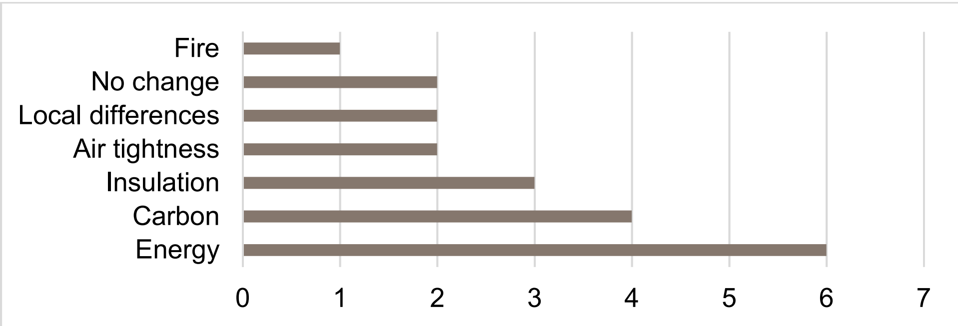


Figure 37. Perceived changes in the building regulations in the UK in the next 5-10 years.

The influence of regulations on VTC

There was a predominant view that VTC will be favourable method of construction with the increasingly stringent regulations regarding the energy performance and the environmental impact of buildings. A selection of quotes are presented below. Only two participants expressed the opinion that VTC would be less favourable with the stricter regulations on Health & Safety, because of the large and potentially hazardous equipment needed during construction. This was countered by one participant's statement that VTC would simplify and reduce the risks during construction. Only one participant saw no potential influence of the changes in the building regulations on VTC.

'The low carbon agenda is now a great challenge to the country and this would be a good selling point for the products.'

'There is a natural match between off-site construction and higher construction standards.'

'The recent changes in Part L of the building regulations would be advantageous for off-site construction. It is interesting that the regulations have changed very quickly over the past few years and have caused many people many headaches. But the industry has not responded to these changes with a proposal of a radically new system of building. This is what is needed.'

4.3.7 Build quality

The most frequently cited advantage of VTC was the improved energy efficiency of buildings, because they could be built and tested in the factory. Ten participants expressed this view. Other significant perceived advantages were the controlled quality and improved design and construction process. All three of these are connected to the main opportunity to improve the efficiency of construction. Improved health and safety, waste minimisation and minimisation of disruptions on site were also mentioned as advantages of VTC.

4.3.8 Specification

Design flexibility

There were 22 comments on the perceived flexibility of volumetric timber to meet different client design requirements. These were approximately evenly distributed between 4 types of perceptions, shown in **Figure 38**. The 7-person majority perceived that the design of volumetric timber would be restricted. This was associated with module size limits due to transportation regulations, a strict restriction to design only rectangular modules a concern that standardisation would diminish creativity and lead to projects with identical layouts.

Six interviewees perceived the flexibility of VTC to be suitable for clients' design requirements. The majority of these comments were made by representatives of public organisations. Two designers expressed the balanced view that VTC would be flexible, but certain design limitations would have to be considered from the beginning of the project.

Furthermore, the interviewees feared that because of the small tolerances in VTC and the need to send all specifications early in the project, the communication between the client, designer and manufacturer would have to be more efficient than what was achievable and expensive changes would have to be made after construction has started.

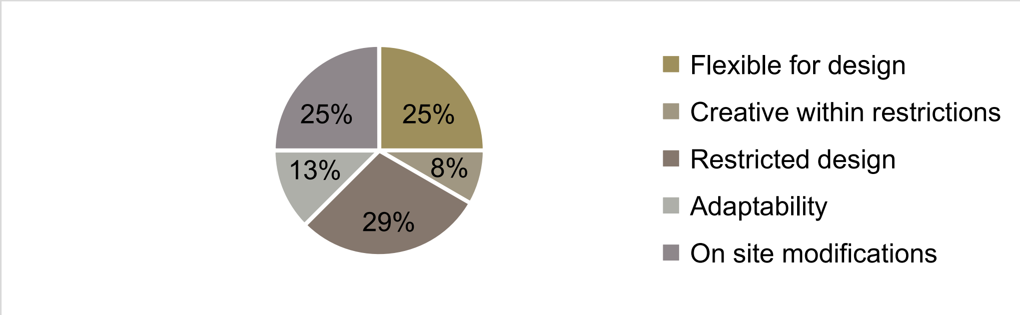


Figure 38. Perceptions of VTC design flexibility.

Different project management strategies

There were 8 different main topics discussed by interviewees when asked about the potential changes that VTC would imply to their project management strategies. These are summarised in **Figure 39** below. The topic that had the highest number of 7 mentions was the need to change the project time-line to a front-loaded design process, which would result in a longer design phase before construction but would also remove the need to correct mistakes or make adjustments after construction has started. Another topic with a high number of 6 associations was the need to work in partnership with efficient communication between designers, engineers, manufacturers and contractors. The third most discussed topic was the need for much more detailed technical design and a clear understanding of how the modules will be assembled in the factory and then on site.

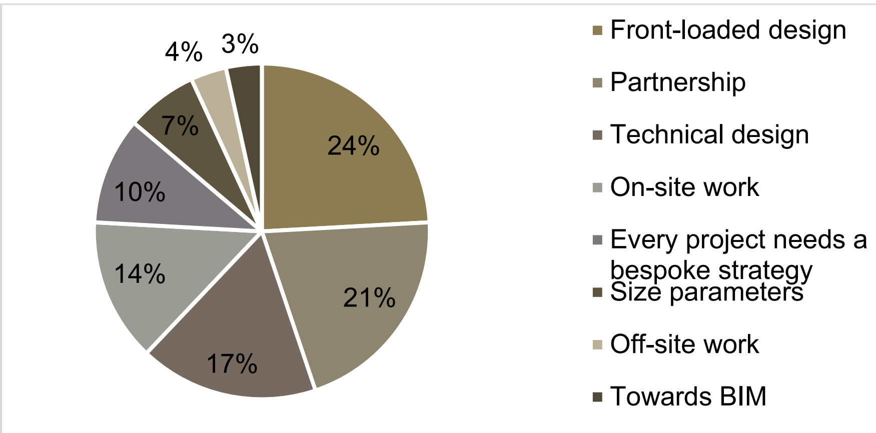


Figure 39. Perceived project management strategy changes needed for VTC.

Compliance with regulations

The dominant view among interviewees was that VTC could comply with regulations. This was expressed by 13 interviewees, shown in **Figure 40**. These respondents mentioned fire regulations, the new low energy construction standards, planning approval, the RIBA plan of work, the timber Eurocode 5 and hygiene standards for healthcare buildings. It was noted that the fire regulation solutions would have to be very carefully detailed and approved through a fire test. Two participants stated that timber would not be able to comply with the fire regulations, especially if there was a requirement for non-combustible materials. One participant said that planning approval would not be granted to VTC buildings, because VTC was an innovative method of construction.

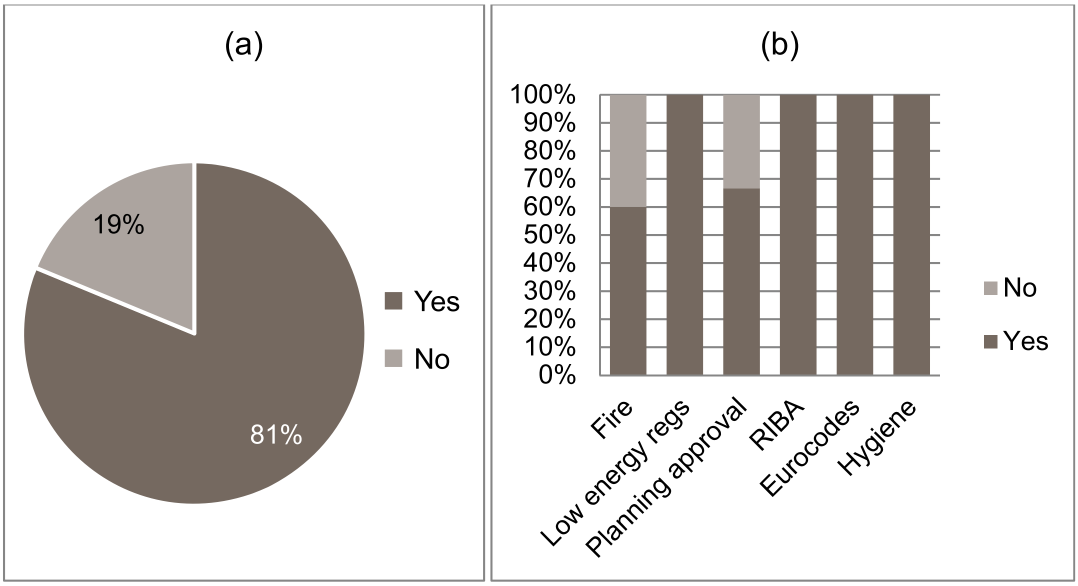


Figure 40. Perceived compliance of VTC with building regulations by (a) type and (b) theme.

Drivers to specify volumetric timber

When asked about the factor that might convince them to specify volumetric timber, participants stressed on the importance of having a team of skilled manufacturer and contractor. Cost, time and improved quality were also emphasised as factors which would convince both designers and clients.

Participants provided responses on both opportunities that VTC could bring to the construction industry in the UK and the advantages they perceived VTC had as a building system. The most significant perceived opportunity was increased efficiency of construction in terms of time and cost. This argument was supported by the replicability of modules in volumetric timber buildings, which could reduce costs from custom designs, reduce time in construction and provide more opportunities to design the details of the modules.

From the Pareto diagram shown in **Figure 41** below it can be seen that other significant perceived opportunities were increased trading times, especially for hotels and schools, and the opportunity to specify more natural and sustainable materials (American Society for Quality, 2016). Others perceived a more particular opportunity to use local timber. Participants also highlighted that VTC could be solution for sites where access was difficult such as dense city centre locations. The concept of establishing temporary factories near rural site locations was also discussed as a potential opportunity. The remaining topics shown in the diagram below were less significant.

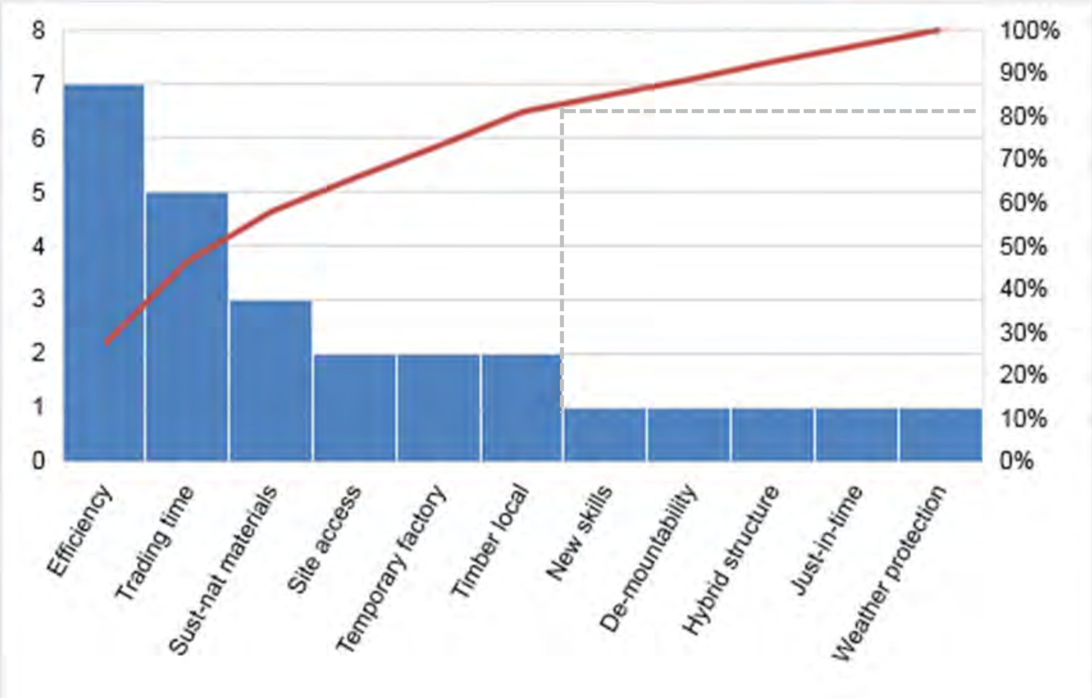


Figure 41. Pareto diagram (American Society for Quality, 2016) of perceived opportunities presented by VTC, where the red line is used to determine the most important factors by drawing a perpendicular dashed line.

Knowledge mechanisms

All participants who commented on this topic expressed the view that architects and engineers in the UK were not educated in VTC. The majority of them elaborated that designers were constantly learning new building and specification methods depending on the different projects they worked on and advances in technology. Although designers might not have received education in VTC nor specified it before, they do have the tools and methods to learn how to do it quickly. Some also mentioned that in recent years modular projects have been designed by university students.

BIM

Overall, the views expressed about the importance of BIM in the next 5-10 years were positive, as may be seen in **Figure 42**. Eleven interviewees stated that BIM will become mainstream with the new regulations on Level 2 BIM on public projects and as the technology develops to be able to deliver the promises of increased efficiency in design and construction. An additional 4 interviewees proposed that BIM should be driven by the clients, not the design and construction teams. An example was one participant who explained that they had received training in BIM and were ready to start a BIM-based project, but they had not had the opportunity given to them by a client yet.

At the other end of the spectrum, approximately 1/3 of the interviewees replied in a negative way. The most frequently given explanation for this was that the use of computers and increased collaboration have appeared as themes in construction before, but have not been applied in practice, and this phenomenon was being repeated but with a new marketing strategy.

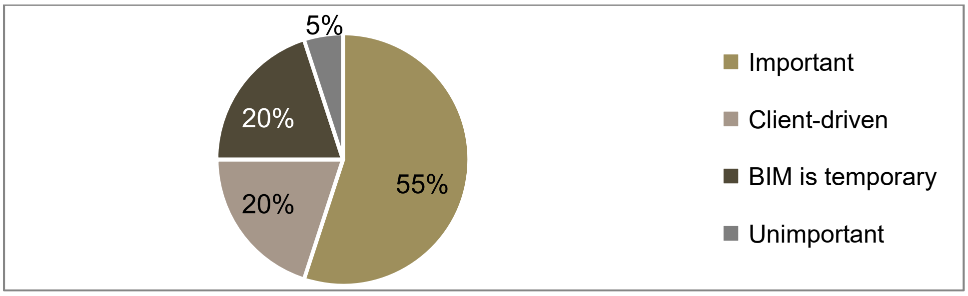


Figure 42. Perceived importance of BIM in the next 5-10 years.

Following on from the previous question, the participants were asked if they perceived any connections between BIM and VTC in the scenarios they had just described. As shown in **Figure 43**, overall 15 interviewees replied positively, of whom 10 perceived some connection and 5 stated that the use of BIM for VTC would be imperative. An example of such a statement and its justification is:

'The use of VTC in combination with BIM is inherent, you would have to use BIM for VTC. The ability to construct the building virtually and manage components will be needed for VTC.'

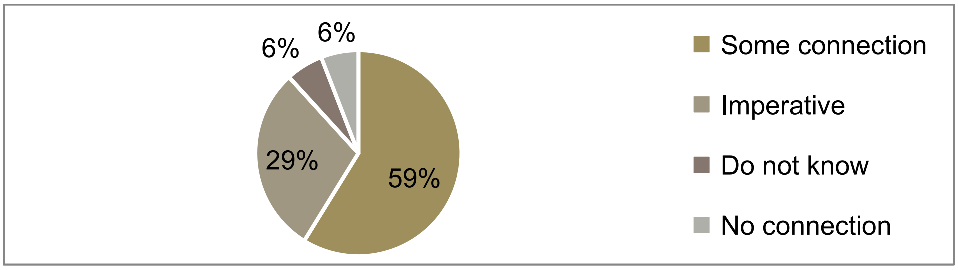


Figure 43. Perceived connection between BIM and VTC by type.

The connection between BIM and VTC for virtual component building and management was mentioned by the largest number of participants, 7 overall two of whom saw that BIM would be necessary, as seen in **Figure 44**. The themes of collaboration and clash detection received more imperative types associations than partial connections. In other words, participants felt that there would be a need for improved collaboration and clash detection methods in VTC projects and that BIM would be the only way to execute these.

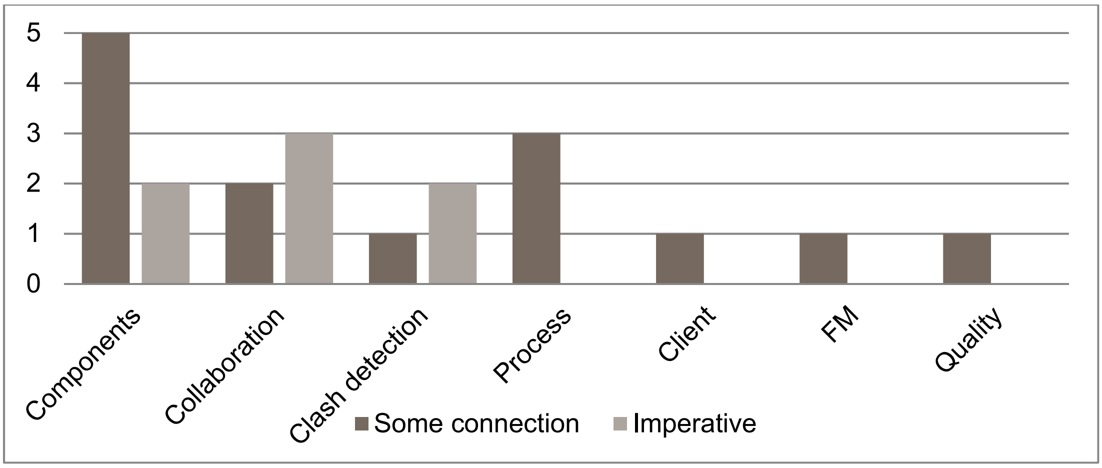


Figure 44. Perceived connection between BIM and VTC by theme.

BIM levels

Seven interviewees gave examples of how they applied BIM to Level 2. This was most often connected to the government regulations as mentioned previously. In general, each discipline would model their own part of the building design, upload it to a shared drive and the model would be co-ordinated and examined at regular meetings. One participant made the distinction that this was different from the fully collaborative Level 3 BIM approach where all designers and engineers work simultaneously from a single model. The examples of Level 2 application included component management, clash detection and cost estimating.

BIM software

Nine of the participants made comments on the software they used for BIM. Four of them mentioned that they use Autodesk Revit for complete project documentation. One participant mentioned that they use SketchUp for concept designs, because of its ease of modelling. Navisworks and Ecotect were associated by one participant each with negative trial experiences. Navisworks overestimated the number of clashes and caused unnecessary work to resolve them, while Ecotect was more complicated than necessary as a method for the simple results it produced. One person expressed the view that the software was not yet developed enough for the needs of the construction industry. One participant also mentioned that they export material schedules for the quantity surveyors, who import them into a cost estimating software package called CostX.

4.4. Focus groups results

The results from the externally organised focus groups confirmed several of the findings from the main market survey of this doctoral work.

4.4.1 Market drivers for offsite

The main priority of the construction market at the time was reported to be accommodation, including several typologies, care homes, single family housing, apartment blocks and student accommodation. In each of these differences in priorities for selection of successful bidders were identified such as low cost in public sector housing. This was combined with importance given to place-making, or the creation of entire communities including schools, healthcare and childcare amenities. In contrast, when student accommodation is concerned cost was secondary, and time was the main criteria for success. Rapid onsite programmes and higher certainty of handover in time for the start of university term, were some of the main drivers for offsite systems utilisation, and volumetric construction was identified as the most suitable system to meet these criteria, yet was limited to installation of bathroom pods.

4.4.2 Offsite sector capacity

The focus groups participants highlighted the lack of manufacturing capacity in the UK. This was speculated to be the result of an uncertain financial context combined with an acute skills shortage. Skilled designers with project experience in different offsite systems and an understanding of DfMA principles were difficult to find on the job market in the UK. This confirmed the findings from the main survey regarding the lack of knowledge among designers about VTC specification. In addition, where market demand was sufficient to justify investment in an offsite manufacturing facility, the same demand often fluctuated from year to year and from month to month, which in turn often resulted in factories operating on less than optimum capacity. Secure pipe-lines of projects associated with the Government goals to construct more housing could mitigate some of these capacity challenges.

4.4.3 Offsite sector challenges

Developers', contractors' and clients' were reported to have a misconception regarding the cost of volumetric construction, in that it would definitely be lower in cost than other forms of building. This often resulted in volumetric construction being rejected as the projects continued, due to the realisation that volumetric could instead save time onsite however required a new approach to construction, with high utilisation of manufacturing. The second most critical reported barrier to increased volumetric utilisation regarded the design flexibility in terms of being able to express different aesthetic languages through design, and having multiple design variations in a project. The focus group participants tended to agree that architects on projects often misunderstood the creative limitations for volumetric construction and produced designs which required extensive re-work.

4.5. Market perceptions survey summary

The survey results demonstrated that there was a gap amongst construction professionals of lack of theoretical and practical knowledge regarding VTC. This finding supported the need for this research and its timeliness. There was an overall positive attitude towards VTC and belief that it could improve the multi-factor productivity of construction in the UK in terms of construction time, build quality and energy performance. The main opportunities which were associated with VTC were the demand for housing and compliance with the increasingly stringent operational energy building regulations. However, these could not be exploited due to the current lack of sufficient manufacturing facilities, the prevalent culture in construction to oppose innovation and the perceived lack of design flexibility. The power to select the construction system of a project was often re-directed to the clients, who would have to be convinced that VTC did not represent a financial risk.

These results supported the initial assumptions made in this research and added new themes for exploration. The competition between VTC and offsite panel construction was revealed as an important consideration for the potential application of VTC in the UK. This was utilised as a guiding principle in the following research stages, which compared VTC to panelised timber systems. Furthermore, the full potential of BIM to optimise the building design and process of buildings was not grasped by the participants, who were mostly concerned with fulfilling the Level 2 regulations only on publicly-procured projects. Therefore, the use of BIM principles and tools was investigated in the following two research phases, namely on manufacturing and construction processes' and their multi-factor productivity comparison.

These findings are significant and novel in that they provide an overview of industry perceptions particularly on VTC in the current economic context. Albeit the overview is limited to the specific participants, their comments could be said to represent the general views of their colleagues, with the exclusion of very technologically advanced and late adopter professionals.

Chapter 5: Manufacturing survey

5.1 Research design

5.1.1 Aim and objectives

This study investigated the differences and commonalities in the products, project management, and production operations of offsite timber systems manufacturers in the UK, where timber panel systems are dominant, as well as Central and Northern Europe, where volumetric systems are dominant. The following research questions were defined and a survey was designed accordingly and used to collect responses from a range of stakeholders:

1) How do offsite timber products resemble and vary from each other between different systems, companies and economic contexts?
2) What are the similarities and differences between factory establishment, design, manufacturing and project management strategies implemented by the different manufacturers?
3) How do the companies vary in production and productivity metrics?
4) How could these performance differences be explained and benchmarked?
5) Can generalized observations be extracted from the findings?

5.1.2 Methodology

Previous studies, which have analysed the offsite sector and its productivity in different economic contexts, have in general employed quantitative research methods, which have collected secondary project-level data from databases, or have implemented closed-ended questions within structured telephone (or face-to-face short duration) interviews (Shahzad, Mbachu & Domingo, 2015; Smith *et al.*, 2013). However, qualitative in-depth explorations of offsite systems implementation have also been applied to extract generalizable findings about the implementation of offsite systems in the EU economic context (Nadim & Goulding, 2011). Indeed, qualitative research methods have been recommended for exploratory surveys, whose aim is to identify a wide-range of interconnected topics relevant to the research theme (De Vaus, 2005; Mason, 1996; Taylor, Bogdan & Devault, 2016).

A multi-factor in-depth qualitative survey method was therefore applied in this research study to explore the products and processes of volumetric (and panelised) timber manufacturers using semi-structured interviews (Reason, 1994). This study explored different approaches to the management of offsite timber systems in the UK, as well as in Central and Northern Europe. The discussion topics for the interviews contained 36 questions overall, grouped in six general topics: 1) Manufacturing line stages, 2) Building elements, 3) Modules / Panels, 4) Process, 5) Projects and 6) Volumetric timber in the next 5 years. A complete list may be found in **Appendix 5A** - Questions for interviews with factory tours of volumetric/panelised timber manufacturers. In addition, non-scheduled exploratory questions were asked where the company had a specific expertise area (Reason, 1994).

5.1.3 Sampling

The aim of this qualitative study was to investigate a wide range of companies and thus enable an overview of different production and management strategies (Kuzel, 1992). Three market-leading offsite timber panel manufacturers were selected in the UK, three offsite volumetric timber manufacturers were further selected in the UK and four volumetric timber manufacturers were selected in central and northern Europe. This sampling strategy was informed by previous research findings that timber panels were mainstream methods of construction in the UK, whereas the volumetric timber market was more mature in mainland Europe than in the UK (Taylor, 2010; Venables & Courtney, 2004; Meiling, Fredrik Backlund & Johnsson, 2015)

The sampling strategy aimed to collect data from manufacturers operating in different economic contexts, who were representative of technological or process innovation in construction. For example, one of the surveyed companies had manufactured the modules for (at the time) the tallest timber building in the world, whereas others participated in the production of the Ikea-based BoKlok system (Fern, 2014; Bjertnæs & Malo, 2014). As a starting point, available literature on volumetric timber and panelised timber manufacturers was collected and synthesised (Modularize, 2015). From the created database, twelve offsite timber manufacturers were contacted across the UK and mainland Europe via e-mail and follow-up telephone conversations to arrange face-to-face interviews. Ten of these manufacturers were finally selected as full surveys, to be included in the analysis and reporting of results of this thesis. Fifteen interviewees were selected as representative of a variety of occupations, including architects, production managers and directors as shown in **Figure 45**.

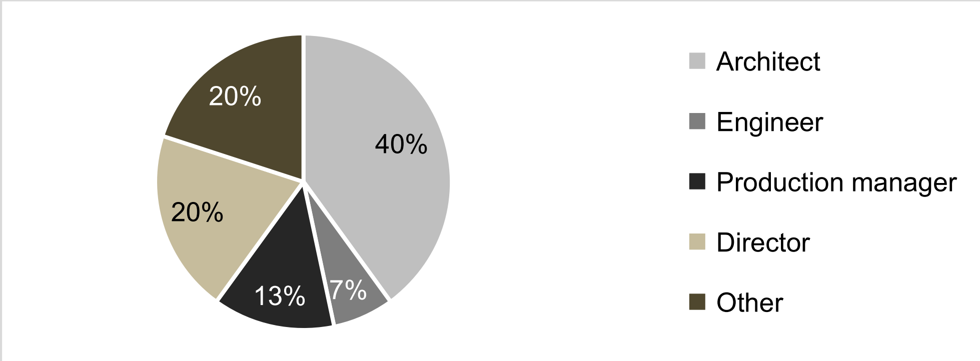


Figure 45. Total survey sampling by profession.

The ten manufacturers varied between family-run and international businesses, recently and long-established companies and those with either a single or several manufacturing facilities. They represented five countries in Europe. Between one and five company representatives were interviewed per manufacturer subject to staff availability. Technical drawings and specifications of exemplar projects sent by the company representatives were used as additional data sources. The sampling strategy of this survey therefore covered a wide variety of business models and stakeholders from offsite timber manufacturing companies in Europe.

The research was also informed by offsite construction research visits in Canada and Sweden, in 2016 and 2017, respectively. These have allowed to capture an international perspective of the offsite timber construction industry.

5.1.4 Data collection and analysis methods

The data collection for the main comparative survey of panelised and volumetric timber manufacturing strategies, was conducted between August 2015 and May 2016. This was followed by an analysis stage concluded in November 2016.The interviews with UK offsite companies were recorded with prior consent and were transcribed with the aid of hand-written notes to emphasise important points. The EU participants did not consent to interview recordings and therefore hand-written notes were the data sources, where to ensure accuracy the notes were written during and within 24 to 48 hours of the interviews with factory tours. Photographs were taken with permission using a DSLR camera with time and date metadata for each photograph.

Overall 15 interviews were transcribed and more than 2,300 photographs were taken to supplement the interview data. The length of the interviews was between 3 and 8 hours and the longer duration interviews took place in over two days. Some interviews were preceded by a presentation by the company representative on their strategy and projects and some were followed by building visits. All interviews included a factory tour, and one factory tour also included a house relocation observation. Between one and five company representatives were interviewed per manufacturer subject to staff availability and the company representatives included staff from sales, production management, architecture, construction and directors. Technical drawings and specifications of exemplar projects sent by the company representatives were used as additional data sources. Through a systematic semi-structured interview approach the risk of potentially gathering inconsistent or incomplete information was mitigated.

As per qualitative best practice recommendations, the interviews were explored at this stage through coding of repeated themes and cases in the software package NVivo (Bazeley, 2013). For each of the manufacturers a report was produced organised according to the semi-structured questions list, and supplemented with selected images from the factory tours. This allowed for comparison of response instances within NVivo, which enabled analysis of variables such as automation, lean manufacture, design for disassembly and other quantifiable qualitative survey explorations. In addition, the results were exported to a concise Excel spreadsheet, where each of the survey question responses was transformed into a row. Ultimately 230 rows of data were organised in seven themes to create a data-base for the survey analysis (Hesse-Biber, 2010). This allowed for identification of patterns in survey responses and categorisation of reported opportunities and challenges according to five themes: production, market, design, BIM and carbon. Moreover, the production outputs were reported using different units and their transformation to a normalised comparative unit of measurement was only possible through quantitative secondary manipulations of the data. Therefore, the three formed data sources were used to triangulate the findings, by combination of extracts of results from the NVivo analysis with the qualitative nature of the responses from the comparative spreadsheet to draw insightful and meaningful conclusions (Creswell & Clark, 2007).

This rigorous data collection, analysis and conclusions approach has been developed based on previous research studies in industrialised construction (Hairstans & Smith, 2017; Succar, 2009; Nadim & Goulding, 2011). For example, Hairstans and Smith applied a method of semi-structured interviews and thematic analysis with a feedback loop to triangulate the data. Whereas Nadim and Goulding interviewed 54 stakeholders from four countries (Germany, The Netherlands, Sweden and the UK) using open-ended questions with emphasis on the variety of responses in an exploratory research study.

5.1.5 Limitations

The qualitative multi-factor in-depth nature of this study represents a compromise between breadth and depth of research investigation. This study has aimed to explore the variety of production and project strategies from a carefully selected sample of offsite manufacturers. This is in contrast to a quantitative survey in which breadth would be favoured over depth and the aim would be to collect responses on limited topics from a high sample size. Therefore, the conclusions drawn from this study may not applicable to offsite systems in general because of the high variety of manufacturing systems on the international market, however through data analysis triangulation and detailed benchmarks against previous studies, the validity of the conclusions is increased.

One of the companies was removed from the comparative analysis because their factory was being established at the time of the research and was not operational yet, leading to gaps in the collected data. Furthermore, another company announced bankruptcy hours prior to the scheduled interview which understandably therefore didn’t take place. These examples shine light on the practical limitations of conducting fieldwork in the dynamic economic context of offsite timber construction.

The productivity analysis element was present in the survey, however it became a dominant research topic only in the data analysis stage, therefore with hindsight the survey questions could have been revised to include more detailed information on the manufacturers’ output with pre-specified units of measurement. It is anticipated however that if specific units had been requested from the interviewees, they may not have responded to the output units used by the manufacturer.

A further limitation of this study is the investigation of the manufacturing process in isolation from the perceptions of clients, main contractors, policy makers and other construction stakeholder groups. Therefore, although the results from this research study will be of relevance to architects, engineers, housing associations, local authorities and developers to name a few, the analysis of their role in offsite timber projects was outside the scope of this study. In addition, although cost factors are important in business models, this survey avoided collection of sensitive cost data and therefore items such as investment in R&D, new equipment, training, software, etc. were excluded from the scope of the research.

5.2 Project management and productivity

5.2.1 Timber products

Product types

Three UK companies manufactured open or closed panel systems. The open panel systems comprised a prefabricated frame with a board on one side and the closed panel systems further included insulation, board on both sides and service cavity battens. All six volumetric companies produced modules, but two of them also offered panels to their clients if transportation or design requirements made a full volumetric solution unsuitable. For example open plan or double height spaces in the building were provided as panels and the other spaces were provided as modules.

The most common construction method was the traditional timber stud frame at 600mm centres, examples of which are shown in **Figure 46**. All manufacturers included a timber stud frame in their products, even if it was limited to the internal serviced partitions. Two volumetric manufacturers (UKV2 and EUV2) used Cross Laminated Timber as their main structural component and UKP2 and UKV3 used Structurally Insulated Panels (SIPs) to construct the walls of their modules. These companies added value to the engineered timber products in their factory by fitting stud frames for services and insulation. The floors and ceilings of the modules and the floor and roof cassettes of the panel manufacturers were constructed using either timber I-joists, web joists or CLT. The product types per company are compared in **Table 10**.


Figure 46. Examples of timber stud systems – closed panels (left) and volumetric (right).

Table 10. Factory comparison based on product type and timber system.

Type	UKP 1	UKP 2	UKP 3	UKV 1	UKV 2	UKV 3	EUV 1	EUV 2	EUV 3	EUV 4
Panel	✓	✓	✓				✓			✓
Volumetric				✓	✓	✓	✓	✓	✓	✓
Stud	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
CLT					✓			✓		
SIP		✓				✓				

Size, weight and transport

In general, panel and volumetric systems had similar size dimensions, as summarised in **Table 11**. Both the panel and volumetric systems had heights of approximately 3 metres. The volumetric systems however differed from the panels in that they had greater length dimensions and included a specified width dimensions.

Amongst the panel manufacturers, the size of the panel production equipment seemed to have the greatest influence on the standard panel sizes, as the companies explained that transport did not impose limits. UKP2 noted that closed panel systems transport more air that open panel systems and therefore less construction area can be transported in one truck load. UKP3 explained that they produced oversized panels on benches instead of assembly lines and that in this case the transport regulations and trailer sizes did impose limits.

The most significant factor which determined the module sizes was road legislation, in particular the distinction between permitted standard and oversized loads. Two UK volumetric manufacturers (UKV1 and UKV2) designed their modules within the standard load size limits (which do not require a police escort), whilst UKV3 designed either standard load or oversized modules, depending on the client’s specification. UKV1 transported two modules per truck load, aligned lengthwise. UKV2 had designed projects for unconventional air transport, which imposed even stricter size and load limitations to the modules. In addition, UKV2 did design, manufacture and transport oversized module elements as panels, such as roofs with an overhang. Two EU volumetric companies (EUV3 and EUV4) designed their modules for both road and water transport and sent them in batches of 30-60 depending on the ship size. The companies rented entire ships, but because of harsh weather conditions at sea the modules were at a higher risk of damage or loss than during road transport.

Table 11. Factory comparison based on maximum product size and average weight.

Dimension	UKP 1	UKP 2	UKP 3	UKV 1	UKV 2	UKV 3	EUV 1	EUV 2	EUV 3	EUV 4
Length (m)	10	10	4.8	5.6	16	10	13	12	14.5	15
Width (m)	n/a	n/a	n/a	3.6	4	5	4.5	4.95	5.3	4.2
Height (m)	3.2	3.2	2.9	3	4	3	3.65	3.5	3.8	3.8
Weight (t)	0.35	3.2	0.35	5	15-20	12	8	16	24	10

* The specified dimensions are for standard manufacturing line only and larger products can be assembled manually.

Offsite completion

As confirmed by the previously mentioned literature describing offsite methods of construction, the timber panel manufacturers had a lower level of offsite completion compared to the volumetric manufacturers. The different levels of completion in the factory between the different manufacturers was calculated utilising a simple binary system, where 0 indicated that the component was not included in the factory process, 1 indicated that the component was included, and 0.5 indicated that the component could be included or excluded according to client preferences. In accordance with the reviewed literature, and the maximum level of completion reported by the companies, the maximum number of components observed among the factories (11) was equalled to 90% component completion in the factory. To implement this Equation 4 was used, where the sum of component numbers c_1 to c_{13} was multiplied by 0.9 to arrive at an offsite completion percentage estimate. The results are shown in **Table 12**.

Equation 4

$$Offsite\ completion\ \% = \sum_{n=1}^{13} c_n * 0.9$$

Table 12. Factory product comparison based on offsite work activities.

Component	Number	UK P1	UK P2	UK P3	UK V1	UK V2	UK V3	EU V1	EU V2	EU V3	EU V4
Structure	c_1	1	1	1	1	1	1	1	1	1	1
Insulation	c_2	1	1	1	1	1	1	1	1	1	1
Airtight mbr	c_3	1	1	1		1	1	1	1	1	1
Int finishes	c_4	0	0	0	1	1	1	1	1	1	1
Cladding	c_5	0.5	0	0	1	1	1	1	1	1	1
Windows	c_6	1	0	0.5	1	1	1	1	1	1	1
Doors	c_7	1	0	0	1	1	1	1	1	1	1
MEP	c_8	0	0	0	1	1	1	1	1	1	1
Fittings	c_9	0	0	0	1	1	1	1	1	1	1
Furniture	c_{10}	0	0	0	1	1	1	1	1	1	1
Staircase	c_{11}	0	0	0			1	1	1	1	1
Roof	c_{12}	0	0	0		1					
Porch	c_{13}	0	0	0	1						
Sum		5.5	3	3.5	10	11	11	11	11	11	11
Offsite completion % estimate		45%	25%	29%	82%	90%	90%	90%	90%	90%	90%

mbr. = membrane; int. finishes = internal finishes (skirting, painting, flooring, tiling, etc.); MEP = Mechanical, electrical and plumbing systems, including heating and HVAC; max = maximum

UKP1 offered the highest level of offsite completion amongst the panel manufacturers, as their products could include insulation, windows, doors, cladding and triangular openings with guide strings for services installation onsite. However, UKP2 and UKP3 stated that their highest selling products were open timber panels, which have a low level of offsite completion and include only the structural frame and OSB sheet on one side. A comparison between three examples of offsite construction systems is shown in **Figure 47**, which demonstrates that the construction details of the panel and volumetric products were similar in principle, but had some differences in material specification.

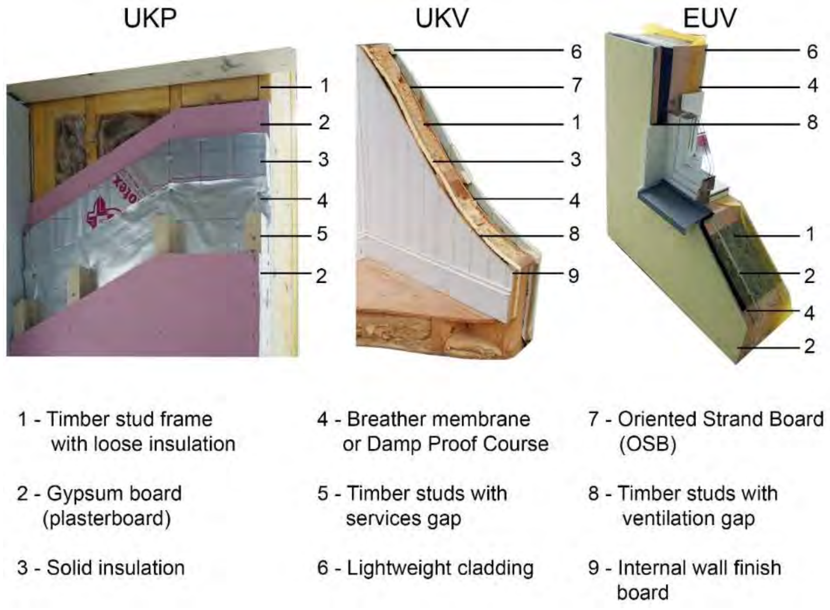


Figure 47. Construction detail examples.

The volumetric timber products included the structure, insulation, air tightness membranes, internal finishes, cladding, windows, doors, MEP, fittings, built-in furniture, staircases, roofs and outdoor entrance areas. There were several exceptions to this observation. Some volumetric manufacturers' projects did not require staircases due to design reasons – the buildings were single-storey. UKV2 had delivered multi-storey projects where the external staircases were delivered by a sub-contractor. Likewise, most volumetric manufacturers did not construct the building roof, this was the responsibility of the main contractor. The exceptions were UKV1 and UKV2, who delivered the roof of the building either as part of the module or constructed on-site using traditional methods. Finally, the porches were included solely in the products of UKV1, whose house types echoed traditional homes. Furthermore, UKV3 could include IT and other specialist equipment in their commercial modules, which enabled quick 'plug and play' installation on site. Overall, the volumetric timber manufacturers stated that they constructed approximately 90% of the building in the factories and UKV2 had intentions to increase this up to 98%.

Of note is that the offsite manufacturers were often flexible with the level of prefabrication to suit each specific client and project requirements. Four volumetric manufacturers aimed to construct as much in the factory as possible and offered only complete products. This was supported by statements of improved build quality in the factory.

Onsite activities

All systems manufacturers reported that they required the main contractor to build the foundations to smaller tolerances than in traditional on-site masonry, timber or in-situ concrete construction. The onsite activities for all observed systems are summarised in

Table 13. The panel systems required a higher number of activities done on site, whilst the on-site activities of the volumetric systems were fewer in number and therefore required fewer trades onsite.

For the lighter weight panel systems, a smaller capacity crane was required for loading and installation on site. Whilst the volumetric systems required cranes with capacity over 10 tonnes, the open timber panels could be installed by hand with a specified maximum weight of 100 kg for 2 people to carry. Amongst the volumetric systems, UKV1 had the most compact and lightest modules, whilst EUV3 produced the largest and heaviest modules. The additional weight was mainly due to concrete floors in the bathroom areas.

Table 13. Factory product comparison based on on-site work activities.

Dimension	UKP1	UKP2	UKP3	UKV1	UKV2	UKV3	EUV1	EUV2	EUV3	EUV4
Foundation*	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
MEP services	✓	✓	✓							
Connection to mains	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Air tightness seal	✓	✓	✓		✓		✓			
Plasterboard	✓/x	✓	✓				✓			
Wall paint and tiles	✓	✓	✓				✓			
Flooring	✓	✓	✓	✓/x		✓/x	✓/x			
MEP fixtures	✓	✓	✓							
Windows	✓/x	✓	✓/x							
Doors		✓	✓					✓/x		
Scaffold*	✓	✓	✓	✓/x		✓/x		✓	✓	✓
Cladding								✓	✓/x	
Roof*	✓	✓	✓	✓/x	✓/x	✓	✓	✓	✓	✓
Insulation between elements	✓/x	✓/x	✓/x				✓			
Crane required	✓/x	✓/x	✓/x	✓	✓	✓	✓	✓	✓	✓

* Actions executed by the main contractor, who can also be the client.

5.2.2 Design, procurement and markets

Contractual role

Nine out of the ten companies reported that their roles were that of a sub-contractor, delivering and often constructing the offsite timber system only, as may be seen in **Table 14** Amongst the panel manufacturers, UKP1 and UKP3 sometimes constructed projects in collaboration with their sister companies, who were traditional masonry onsite contractors. The smaller companies, UKV1 and UKV2, had more responsibilities per project, which included the project design from concept to final production drawings. In addition, UKV1 were responsible for the entire project, apart from the ground-works masonry and services routing. The main contractor role of UKV3 was different, in that they were responsible for the offsite system, however preferred to be a main contractor in projects to give them the same authority and the onsite builder company. Amongst the EUV companies the only outlier was EUV4, who acquired land and speculatively developed housing projects for private sale, in addition to providing modules for external companies and projects,

Table 14. Factory comparison based on contractual role.

Dimension	UKP 1	UKP 2	UKP 3	UKV 1	UKV 2	UKV 3	EUV 1	EUV 2	EUV 3	EUV 4
Designer				✓	✓					
Sub-contractor	✓	✓	✓	✓	✓		✓	✓	✓	✓
Main contractor *	✓/×		✓/×	✓		✓				
Developer									✓	

*main contractor role may be sister-company

Markets

At the time of interview, all manufacturers were producing residential projects. There was a pattern of house production in the UK and apartment production in Europe. The projects observed in the factories during the interviews varied between high-end bespoke and low-specification refugee shelters. In addition, UKP1 were producing a nursery and intended to continue their growth in the education sector alongside residential construction.

In general, all companies perceived that the residential market, especially apartment blocks, had the largest growth potential for their products. A variety of residential building types were perceived as suitable for offsite timber construction, as summarised **Table 15**. Nine out of the ten surveyed companies manufactured offsite systems for apartment buildings, eight for private housing and seven for affordable housing.

Table 15. Factory comparison - building types manufactured by the factories.

Building type	**UKP 1**	**UKP 2**	**UKP 3**	**UKV 1**	**UKV 2**	**UKV 3**	**EUV 1**	**EUV 2**	**EUV 3**	**EUV 4**
Apartments	✓	✓	✓		✓	✓	✓	✓	✓	✓
Houses	✓	✓	✓	✓	✓	✓	✓	X	X	✓
Affordable housing	✓	✓	✓	✓	✓		✓		✓	
Student residences	✓	✓	✓				✓		✓	✓
Retirement homes	✓	✓			✓		✓	✓	✓	✓
Emergency housing							✓			✓
Schools	✓	✓	✓		✓	X	✓	✓	✓	✓
Nurseries	✓	✓							✓	✓
Healthcare*	✓		✓		✓			✓		✓
Offices	✓	✓					✓			
Recreation		✓			✓	✓				✓
Rooftop extensions		✓					✓	✓	✓	
Remote locations		✓			✓		✓			
Commercial *		✓				✓				

*Projects with relatively small footprints for their sector.

In the UK the main targeted markets for offsite timber construction were private sale houses, private sale apartments and affordable housing. In mainland Europe multi-storey apartment buildings, student accommodation and retirement homes were seen as the residential building types with the largest opportunity for growth. Two EU manufacturers explained that the single-family house market was over-saturated in their countries and therefore was not a prosperous option for volumetric timber construction. EUV4 added that volumetric timber manufacturing was viable only if it was produced in countries with lower GDPs and salary rates and exported to countries with higher GDPs and salary rates, therefore adding value to their product through export to foreign markets. Examples of affordable and high-end housing built using off-site timber systems are shown in **Table 16**.

Among the non-residential building types, the education market was perceived as the most viable opportunity for offsite timber construction. Eight companied manufactured schools and this was followed by the healthcare which were manufactured by five companies. Recreation buildings (hotel, hospitality), nurseries and extensions were manufactured by 4 companies each. Examples of non-residential volumetric buildings are shown in **Table 17**.

Table 16. Examples of different types of off-site timber housing projects.

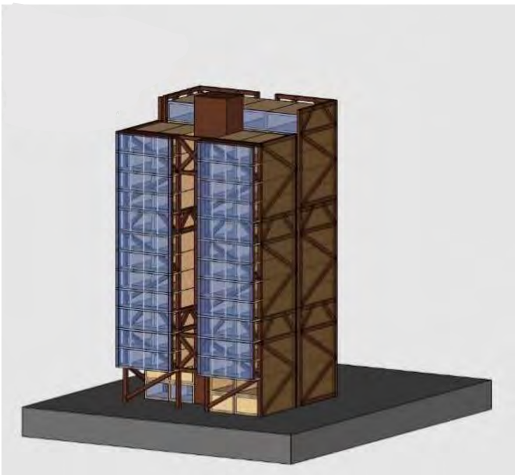
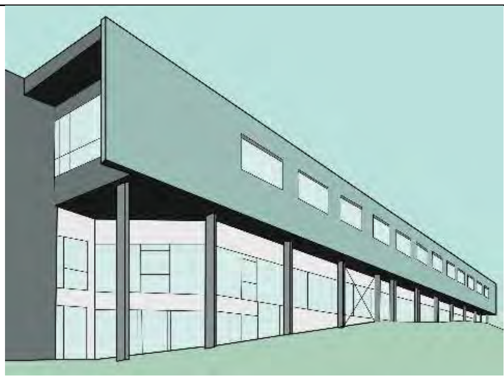
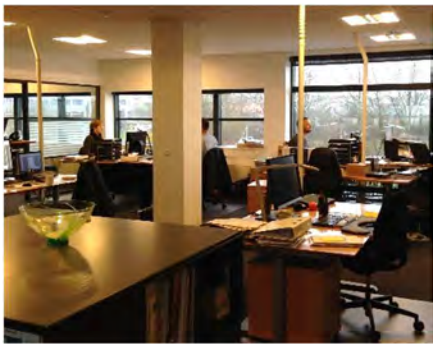
	Affordable	High-end
UK Houses		
EU Low-rise apartments		
EU High- and Mid-rise apartments		

Table 17. Examples of non-residential volumetric timber buildings by EU companies.

	Exterior	Interior
Education		
Healthcare		
Office		
Leisure		

In addition, two building types were perceived as especially suitable for volumetric construction, projects in remote locations and rooftop extensions to existing buildings. The addition of levels to existing buildings was mainly practiced by the European companies and one of them had constructed a rooftop extension to a building in the UK. The UKP and EUV companies manufactured a similarly high variety of non-residential projects, whereas only UKV2 manufactured 4 non-residential projects.

Overall, apartments, houses and schools were the building types, constructed by the largest number of surveyed manufacturers. In contrast, commercial projects and emergency housing were constructed by two companies each. UKP2 and EUV1 constructed the largest variety of building types, twelve and ten, respectively, and UKP1 and EUV4 manufactured nine building types. UKV1 and UKV3 constructed the smallest variety of building types; two and four respectively. On average, the companies constructed seven building types per manufacturer.

Cost-efficiency and repetitive design elements

The panel manufacturers shared the view that the level of repetition within one building did not influence the cost-efficiency of their products, however the project design and specification time could be reduced by having repetitive buildings within a project. Thus repetition, for example of house types within a development, would have little effect on the manufacturing time and cost efficiency. Furthermore, because the panel companies ordered and stocked large quantities of typical materials, they stated the panels were more cost-efficient than conventional construction where materials are purchased per project.

The UK volumetric manufacturers had contrasting opinions and expressed a need for repetitive elements in their projects. UKV1 considered that their product was only cost-efficient for houses with up to five modules, which were set house types ranging in size from studio to two-bedroom set house types. UKV2 emphasised that the project had to resemble one of their previous projects, so that the design and manufacturing processes were familiar to the staff. UKV3 stated that repetitive modules were essential to making volumetric timber cost-efficient. Variations could be done on the facades or elements such as balconies being added, but the module structure and layout had to have a significant level of repetition. In support of this standpoint, UKV3 explained that they were producing a bespoke volumetric timber project at the time of visit, but this had caused issues in the factory line layout because of delays.

The European volumetric manufacturers stated that the cost-efficiency of projects was subjective according to the clients. Their projects were mainly multi-storey apartment buildings with approximately 150 modules, but they also accepted contracts for 1-module projects. UKV4 emphasised that although the apartments were all identical in footprint, the owners purchased them in advance and requested modifications such as bespoke kitchen furniture, windows relocation or different finishes in the interior.

Building regulations and building height

All companies did emphasise that offsite timber construction can comply with the building regulations as with any other method of construction, and that the details simply had to be engineered to meet compliance.

However, building regulations on timber construction affected the companies' market scopes. The UK companies were limited to build timber buildings up to 6 levels. However, only UKP3 had built buildings up to 5 levels, UKP1 up to 4 levels and UKV3 had constructed a 3-level project. The remaining UK companies had built only single or two-level buildings. In Europe the majority of projects were similar in height, 5 levels on average. EUV2 and EUV3 had constructed taller buildings, over 8 levels. EUV2 achieved the structural stability using CLT, whilst EUV3 used an additional structural frame for projects over 5 levels. EUV4 noted that a four-floor apartment building was ideal for their system in terms of achieving a balance between design time, repetition, manufacturing and construction.

The reasons for height restrictions differed between countries and between companies within one and the same country. The UK panel manufacturers stated that the limit was imposed by building regulations for timber construction. The European volumetric timber manufacturers stated that fire and acoustic regulations in the countries where the projects were to be constructed had the largest impact on building height restrictions. In some cases, fire tests could be commissioned to independent research centres to prove that a certain construction type met the burning time and non-combustion requirements for tall buildings. The UKV1 and UKV3 project height restrictions were due to structural testing and engineering of their building systems. UKV2 and EUV2 stated that they could construct taller buildings because of the structural properties of CLT, but UKV2 had not had commissions for tall buildings and EUV2 could not meet the acoustic and fire regulations for taller buildings with their current system.

Energy-efficiency

The buildings' operational energy was carefully considered by all companies and could be delivered per project specification. The typical U-values for some of the standard offsite timber systems are summarised in **Table 18**. The table shows that the EU companies constructed to stricter energy-efficiency standards compared to the UK. Five companies (UKP1, UKP2, UKP3, UKV3 and EUV3) referred to the Passivhaus standard as a measure of their ability to achieve high energy efficiency. UKP1 had a matrix with different options for achieving different standards. UKP2 and UKP3 had developed standard details for different thermal performance. Three manufacturers (UKV2, EUV1 and EUV2) stated they could build up to any specified thermal conductivity and air tightness specification. Three companies had standard energy performance values for their homes and standard solutions, UKP3, UKV1 and EUV4. However, in addition to their standard systems the majority of manufacturers stated that they could construct to higher energy efficiency standards, as specified by the clients.

Table 18. Factory type comparison based on energy efficiency metrics.

Metric	Component	Unit	UKP	UKV	EUV
U-value	Wall	W/m^2K	0.44 - 0.1	0.15	0.18 – 0.12
U-value	Roof	W/m^2K	0.15 – 0.08	0.16	0.13 – 0.1
U-value	Floor	W/m^2K	0.14 – 0.09	0.15	0.17 – 0.1
Air flow	Building	l/h @ 50 Pa	1.5	0.7	0.5 - 1.0

One timber stud volumetric manufacturer (UKV1) and the two CLT volumetric manufacturers (UKV2 and EUV2) took precautious measures against achieving too low air flow values. UKV1 had made a design and specification decision to maintain a higher air flow rate of 2.6 l/s @ 50 Pa and thus create a breathable timber building. EUV2 made a similar remark:

'However, the air tightness should not be too low, because the wooden house should breathe; the apartments should not feel like closed bottles.'

When asked about embodied energy calculations, in general the UK companies responded that they conducted SAP calculations as required by Section 6 of the Building Standards in Scotland and Part L of the Building Regulations in England and Wales. However, the SAP calculations do not include embodied energy or embodied carbon calculations. Only UKV2 stated that they were indeed interested in embodied carbon, however the interviewed engineer investigated embodied carbon in his personal time but calculated only key components. The European companies did not calculate the embodied energy of their buildings. In fact, EUV4 considered the question was rather amusing and explained humorously that they had been asked to calculate the earthquake resistance of their structures more often than carbon calculations or Life Cycle Assessments (LCA).

Design for Disassembly

Overall, none of the companies had considered the adaptability of their buildings to the occupants needs such as changes in building size, repurpose, refurbishment or relocation of the modules. The reason for this was said to be the lack of Design for Disassembly requirements in the project specification issued by the clients. UKP1, UKP2 and EUV1 shared the opinion that the majority of the connectors in their products were mechanical (screws, ties, clips), therefore that disassembly was theoretically possible, but noted that they had not been designed for disassembly was technically impossible. UKP3 expressed a similar opinion and added that the insulation and services would make disassembly and re-use of materials unrealistic. EUV2, EUV3 and EUV4 stated that refurbishment and repurpose of the modules was not feasible because of practical considerations such as planning, disruptions to neighbours, knowledge of load transfer and services installed in the building.

UKV1, UKV2 and UKV3 provided more positive responses, that adaptations to the buildings will be possible because of standardised connections, compacts services cores and internal non-loadbearing walls. In fact, at the time of visit UKV1 relocated their first house, which was used as a show home. UKV3 had manufactured modules for tradeshow events, disassembled them at the end of the event, transported them back to the factory and refurbished them into a bungalow house.

5.2.3 Factory management

Factory establishment

Five companies (UKP1, UKP2, UKV2, UKV3 and EUV3) had purchased industrial buildings and re-purposed them for offsite timber manufacturing. Four manufacturers had purpose-built their factories and equipped them with a mixture of 'off-the shelf' and custom-designed offsite timber machines according to their manufacturing process. These companies were UKP3, EUV1, EUV3 and EUV4, indicating that this was more common practice among the surveyed European companies. One company, UKV1, used a temporary metal-framed building, which could be dismantled in three days if the workshop had to be relocated.

Three companies (UKP1, UKV1 and UKV3) had started as conventional construction companies and the offsite timber manufacturing was a new system for them, a way to diversify their product and market ranges. EUV2 was established in a similar manner, but as part of a larger group of timber product companies. EUV4 branched out as a new separate endeavour by employees of a neighbouring offsite timber panel manufacturer. Three manufacturers (UKV2, EUV1 and EUV3) had started their companies specifically for volumetric timber manufacturing and had progressively grown over the years, which included re-locations to larger facilities. EUV1 had been in operation for 29 years and had established a daughter company for specialised modules and had expanded the internal departments. EUV3 had been in operation for 20 years and in this time had developed into a holding of five companies, one of which was dedicated to manufacturing.

The perspective of a company establishing a volumetric timber factory

In addition to the main 10 companies included in this survey, two representatives from a UK sustainable construction company, who were establishing a volumetric production plant were interviewed. These interviews were conducted on the day the purchase documents for the land were sold. The entire process of setting up the factory took them approximately four years; two of which were preparatory. They had to secure funding through grants and loans, design the factory layout and purchase the land. To maximise the opportunities for profit, this company wanted to provide as much flexibility as possible for their clients and planned to continue their onsite construction alongside the volumetric enterprise. This was also to bring diversity into the architectural technician’s work, who would continue to design closed panel, I-joist, and portal frame projects alongside the new volumetric system.

The main motivation factors behind the addition of volumetric systems to their portfolio were quality control and reduced time on site. Another driver was the potential to reduce the risks of construction and improve the working environment of the workers, especially protection against cold wet weather. They also mentioned the advantage of materials being stored indoors, without putting timber through constant wet-dry cycles (which can cause twisting and bowing). Material waste could also be controlled better, to optimise the use of standard material sizes and segregate waste for recycling. The company did anticipate that there would be some challenges in cost estimates for the different timber systems, accounting for labour utilisation in addition to material utilisation. Therefore, clients might be inclined to choose a panel system because of the lower price for the panels compared with modules which include more building components.

Design management

All manufacturers employed in-house technicians who were responsible for production drawings. UKP1, UKP2, EUV1, EUV4 had design and specification capacities of 12, 18, 16 and 12 people respectively, compared to 5 designers at UKV3. These teams included a mixture of architects, engineers and timber frame technicians. Only UKV1 produced all design work internally. UKV2 had worked with external architects but mostly developed projects using their internal two architectural designers, two engineers and one design and specification intern.

The UK panel manufacturers were conventionally sent drawings by external architects. For process efficiency, the manufacturers recommended early involvement in the design process, to provide guidance on the buildability and limitations of their system. Unfortunately, often 'frozen' designs were sent to the manufacturer and their internal teams were responsible for transforming the project into panels with DfMA properties specific to their assembly lines. For example, UKP3 had had to re-design buildings specified as brick and block construction. The three panel manufacturers stated that the process should be more streamlined and that the design and manufacturing process should be more collaborative.

The situation was similar in UKV3, EUV1 and EUV4, in that the manufacturer was involved after tender stage and re-worked designs by external architects to be representative of the limiting conditions of their volumetric timber systems. EUV2 and EUV3 differed from this model in that their engineers worked collaboratively with the external architects from the early stages of the project. Despite these efforts, design re-work and exchanges of revised drawings were frequent and sometimes delayed the project progress.

The perceptions of three architects transitioning to volumetric design.

Furthermore, interviews were conducted with three architects from EUV4, who had recently transitioned from working on traditional build concrete projects to volumetric timber projects. According to them the greatest challenge when learning how to design and specify VTC was the technical aspect. Although the company had standard details, these could not be re-used but had to be adapted for every project. Manufacturing processes, transportation restrictions, acoustics and fire regulations were highlighted as important learning curves. The architects emphasised on the greater speed of volumetric timber design and construction, which meant that they had to both develop solutions quickly and be adaptable to different projects.

Production management

Eight manufacturers structured the production management as hierarchical levels of line staff, supervised by team leaders per manufacturing line, who reported to production managers, who worked alongside procurement, technical and other managers, all of whom were managed by the factory manager. This hierarchical system shown in **Figure 48** was enhanced by UKV2, UKV3 and EUV2 by outsourcing plumbing and electrical trades as and when required. EUV2 outsourced decoration personnel as well and had 50% permanent production staff and 50% outsourced production staff. This strategy was adopted to increase the flexibility of work distribution and the extra staff were employed in in full only at times when the production was behind schedule.

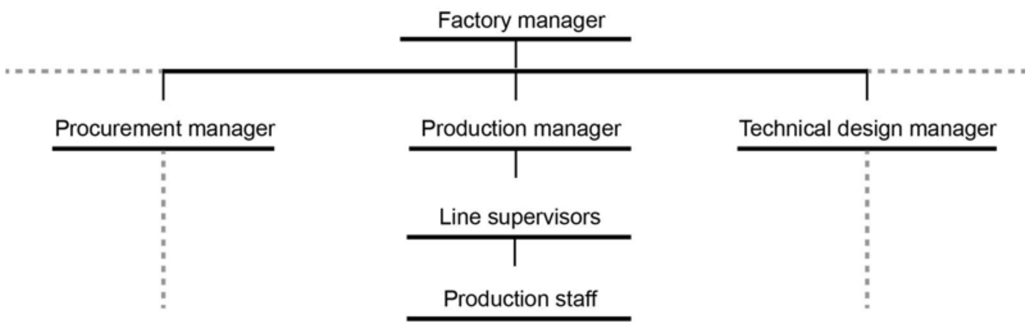


Figure 48. Generalized factory management hierarchical system.

The exceptions to this arrangement were UKV1 and UKV2, who did not use assembly lines and therefore had a less hierarchical system manufacturing staff. Both companies employed college students or apprentices who were receiving training in volumetric timber manufacturing whilst finishing their qualifications. Similarly, EUV1 employed 50% skilled workers and 50% unskilled workers, who were gaining technical skills. Examples of manual and automated processes and typical factory production environments are shown in **Figure 49**.

Figure 49. Examples of automated (UKP) and manual working environments (UKV, EUV).

Nine companies worked 8-hour days, which started between 07:00 and 09:00 and ended between 15:30 and 17:30. EUV3 explained that working longer hours or two shifts would lead to bottlenecks in the process, mainly because of the concrete floor curing time. In contrast, the UKP3 production teams worked in two shifts, from 06:00 to 16:30 and from 16:30 to 04:30; in total 22 hours and 30 minutes per day. The number of permanent production line staff varied between approximately 12 (UKV1) to 220 (EUV4) with a mean value of 40 people employed by UKP3 and UKV3.

UKV3, EUV2 and EUV3 emphasised on lean process improvement in their production management strategies. UKV3 had developed a meticulous materials handling system, in which every component from tools and nails to timber beams was tracked in a computer system, in addition to special 'kits' of materials pre-assembled for tasks at specific manufacturing stations. EUV2 aimed to halve the time needed to produce their modules through reduction of 'muda' (waste) similar to that applied in other manufacturing industries. EUV3 had developed a production system which maximised the efficiency of the space in their factory via continuous flow and ready availability of tools and materials in proximity to working stations. UKP1, UKV2 and EUV1 had also implemented similar lean principles, however these were less emphasised during the interviews. UKP1 had streamlined their factory processes and used barcoding to track materials and components along the manufacturing line. EUV1 had significantly reduced their materials stock, and only stored small standard components such as nails, timber and a few materials needed for the current project. UKV2 were optimising the design, procurement and manufacturing processes as a whole.

Property sale price

The level of automation, the size of the factory, the factory layout, the location of the factory, the location of the projects and the number of labour-hours all have an effect on the module price. For example, in mainland Europe there was a trend of exporting modules to countries with higher GDPs; this was most noticeably reflected in the final sale prices of EU4, as may be observed in **Table 19**. The final property prices for the home buyers, however, were set by the developers and were mainly dictated by geographic location and the local market. The home owners were indeed said to be unaware of the building technology in their properties, but put emphasis on the interior design elements. The internal surface materials and kitchen and bathroom appliance specifications determined the price difference between affordable and high-end housing. For example, in the leisure sector, high quality doors, windows and finishes were specified for hotel rooms, whilst in the affordable homes sector, the leading criteria were energy-efficiency and durability.

Interestingly, there was no direct connection between the level of automation in the factories and the property prices. The factories that had invested in automated production equipment did not inflate the module prices to recoup their investment. Instead they benefited from increased productivity rates; provided that the companies had the capacity to supply a high module output and also provided there was sufficient demand for large, repetitive modular projects such as apartment blocks. A major reported challenge to increased offsite application in the UK currently voiced however was the perception that VT modules were more expensive than traditional methods of construction because of the requirement for increased automation (Homes for Scotland, 2015). This research interestingly demonstrated that the final property prices were determined by the local market rather than by automation. This aligns with the conclusions of (Krug & Miles, 2013).

Table 19. Factory comparison according to average property sale price.

Property sale price average	**UKP 1**	**UKP 2**	**UKP 3**	**UKV 1**	**UKV 2**	**UKV 3**	**EUV 1**	**EUV 2**	**EUV 3**	**EUV 4**
1000s GBP/m²	1.9	0.3*	1.7	1.4	2.0	1.3	0.9	2.4	1.2	3.4

*excludes land and construction costs

Opportunities and challenges in the next 5 years

All companies stated that in the next 5 years they will focus on improving their existing products and expanding their shares in the residential market. Among the different companies there were different nuances to this general aim. The panel manufacturers, as well as EUV3 and EUV4 emphasised on increasing the productivity and profitability within their companies through systems optimisation. EUV1 and EUV2 intended to expand their markets in the multi-family residential areas as clients became more convinced of the volumetric timber construction advantages. In particular, EUV2 intended to construct more and increasingly taller apartment buildings in their country. In addition, UKV2 aspired to create a holistic product and project management strategy, which reduces the need for trouble-shooting and increases their efficiency through rigorous planning. UKV3 intended to expand their work in the affordable homes sector upon completion of their first large such project. UKV1 gave the most detailed account of their plan for development in the next 5 years, which included promotion of mortgage availability for their customers, compliance confirmation of their products as a dwelling according to English and Scottish building regulations and compliance confirmation with insurance companies. Finally, these would lead to a business up-scale to a new permanent building and a production of 50 houses per annum.

The main opportunity for offsite construction in the UK was said to be the housing crisis, which offsite could alleviate with increased productivity in the construction industry. UKV3 saw potential in expanding their manufacturing facility with a second branch nearer to their future projects. EUV3 considered that projects with reduced site space availability or reduced programmes, along with raising health and safety concerns, would prove to be the largest opportunities for volumetric timber construction. EUV4 saw opportunities in the migrant crisis in Europe as well as the potential to export products outside of Europe.

On the other hand, the main challenge noted both in the UK and in Europe was the culture of the construction industry, in other words the established processes and methods. The brick and block building techniques were highlighted by UKP3 and EUV1 as the main cultural aspect that has persisted in some parts of their countries. UKV3 explained that the conventional design and build procurement routes were in favour of on-site construction, because the main contractors had incentives to outsource offsite construction. UKV2 and EUV2 stated that their main challenges for the near future were their company processes, especially the seamless integration of design, engineering, procurement and production. UKV1 also perceived an in-house barrier, cash flow management and its dependence on market demand. Similarly, EUV3 noted that the unpredictability of the market can have a large impact on their future production. Moreover, EUV4's representative highlighted that there was increasing competition among volumetric timber companies and that the constantly changing regulations caused the company to change their specifications and processes, therefore reducing their efficiency.

5.3 Factory operation processes

In addition to the product, market and management strategies of the companies, their manufacturing strategies are key to high productivity. These are termed operations management and determine the methodology of product creation with the highest efficiency. Although the companies produced similar products, either panel or volumetric timber systems, there were different operations management strategies adopted by each company.

5.3.1 Manufacturing strategies

Overall, the panel and volumetric manufacturers shared many practices, especially in panel assembly and timber stud panel manufacturing. Essentially, the panel manufacturers produced similar products in a similar way to the volumetric manufacturers, however without a module assembly line, as shown in the **Figure 50**.

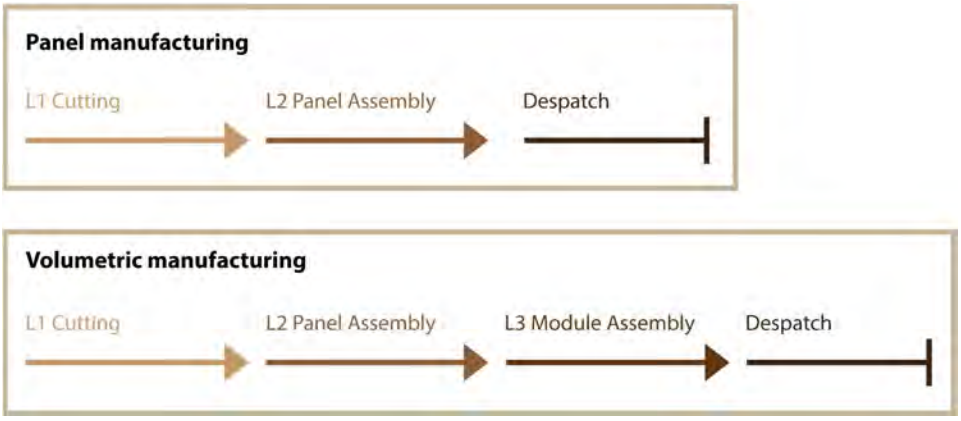


Figure 50. Generalized panel and volumetric manufacturing lines.

Number of manufacturing lines

Although the manufacturing sequence followed the generalized manufacturing lines above, each company varied in the actual number of their manufacturing lines and sequence. As shown in **Figure 51**, the panel manufacturers had the highest number of manufacturing lines, despite producing a lesser percentage of the building offsite than the volumetric manufacturers. The EUV manufacturers utilised 4 manufacturing lines on average, similar to the generalized sequence described in the section above. In contrast, the UKV manufacturers had mostly one manufacturing line; that is, they produced the modules in one location within their factory and the workers, tools and materials were moved to the modules. Among the UKV manufacturers, only UKV3 had established sequenced manufacturing lines, in which the modules moved from one station to the other, with workers, tools and materials situated at each station as required. The difference in these arrangements is illustrated in **Figure 52**.

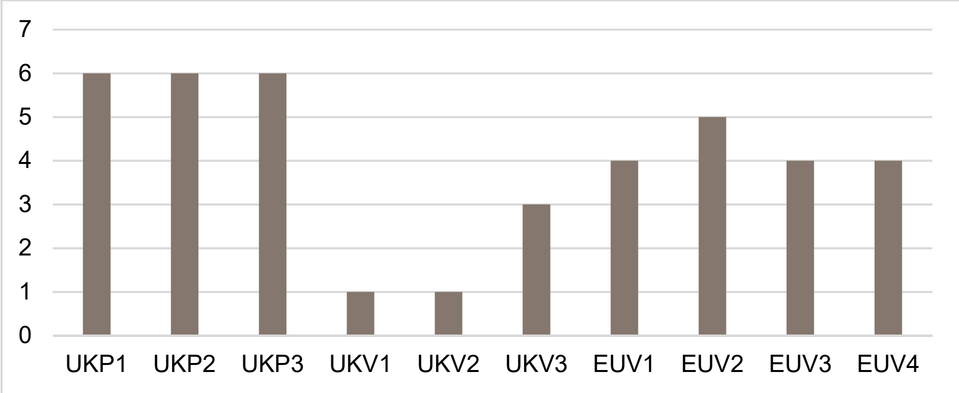


Figure 51. Number of manufacturing lines per company.

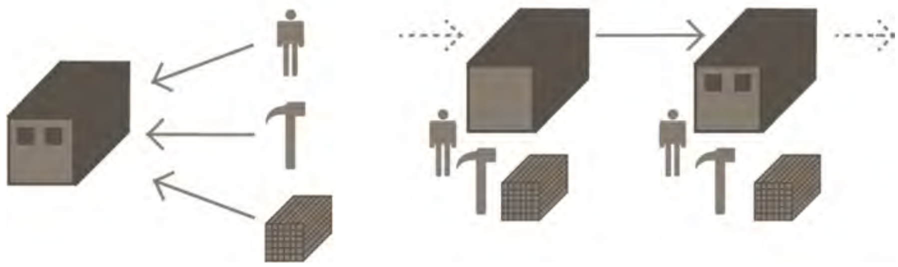


Figure 52. Manufacturing types: static production (left) and dynamic production (right).

Manufacturing operations flow

Similarities between panelised and volumetric manufacturing

The main similarities between the panel and volumetric manufacturers were in the operations flow of the panel assembly lines. The generalized workflow is shown in **Figure 53**, where the computer symbols indicating automation and hammer symbols indicating manual tools.

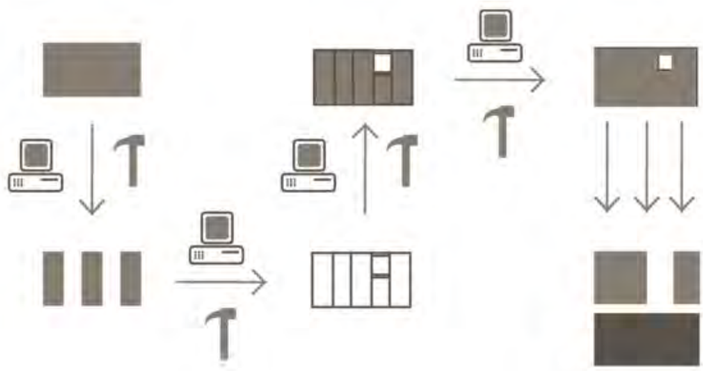


Figure 53. Generalized panel manufacturing flow, indicating a high potential for automation.

The process starts with handling of the delivered materials, such as timber, timber sheets and plasterboard. Usually, manual saws are used first to ensure the materials are within the acceptable tolerances, e.g. 5mm. Afterwards, using either a manual or automatic 5-direction saw, the materials are cut to size for component assembly. If a manual process is used, the panel frames are then assembled on benches; or on frame assembly machines if automated. The panels are then sheeted using a manual or automated nailing bridge and insulation is fitted between the timber studs. The panels are then rotated, conventionally using a mechanised butterfly table and a sheet is nailed to the other side of the panel. Depending on the specification, windows, service battens and a protective membrane can then be fitted onto the panel. At this point the closed panel is shrink-wrapped in protective polyethylene and is ready for despatch. These different tools are shown in **Table 20**.

Table 20. Main tools used during the panel manufacturing stages.

Manufacturing stage	**Manual tool**	**Automated or mechanised tool**
Cutting	Band saw	CNC saw
Frame assembly	Bench with nail gun	Framing station
Sheet nailing	Bench with nail gun	Nailing bridge
Insulation fitting	Manual cutting and fitting	Air blowing
Panel rotation	Rotation by 2 people	Butterfly table
Windows and battens	Lifting by 1-2 people	Vacuum machine
Packaging	Sheeting and string connection	Polyethylene heat shrinking
Despatch	Lifting by 1-2 people	Butterfly table and rails

From this stage onwards, similarities were observed between the volumetric manufacturers, summarised in **Figure 54**. The panels were assembled to form a box using cranes in the factory, after which generally the services were routed and the cladding was installed. Plumber, electricians, decorators, tilers, joiners then continued their work on specific stations, with each module progressing from station to station. At the end of the process, the complete module was shrink wrapped in protective polyethylene and prepared for despatch, stored in the factory yard. Examples of each of these stages are included in **Table 21**.

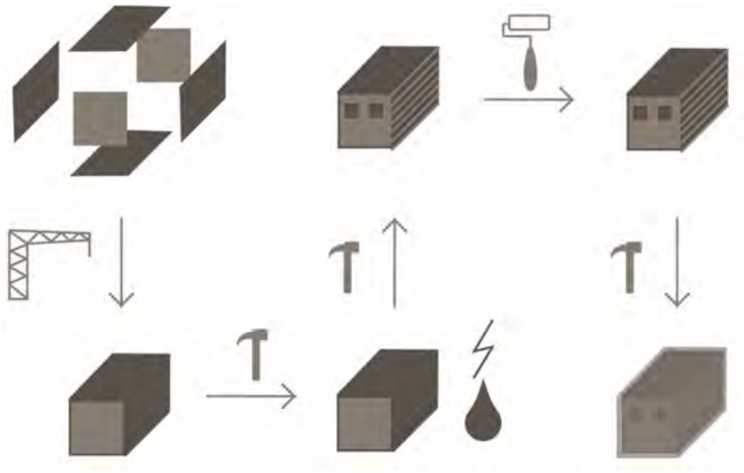


Figure 54. Generalized volumetric manufacturing flow, indicating mostly manual tasks.

Table 21. Main tools used during the volumetric module manufacturing stages.

Manufacturing stage	Manual tool	Automated or mechanised tool
Module assembly	Nail gun	Crane
Services routing	Drill	CNC saw
Cladding and windows	Lifting by 1-2 people	Vacuum machine
Finishes	Paint rollers, tiling	None
Fittings	Drills, nail guns	None
Cleaning	Broom	None
Packaging	Sheets connected with string	Polyethylene heat shrink wrapping
Despatch	None	Crane

Differences between panelised and volumetric manufacturing

Despite these similarities, there were many differences in the manufacturing process flow, which distinguished one company from another. Overall, the panel manufacturers tended to have single line manufacturing strategies, opposed to some of the volumetric manufacturers, who had multiple lines for module assembly. Furthermore, the panel manufacturers tended to have a flow, in which the lines started at the end of the previous line, creating a zig-zag type flow within the factory layout. In contrast, the EU volumetric manufacturers tended to have linear layouts, in which zones of the factory were dedicated to certain tasks. One panel and one volumetric manufacturer had separate connected buildings for separate stages of the production lines, whereas most companies manufactured in a single open space. These results demonstrate the variety of manufacturing strategies for offsite timber systems.

5.3.2 Automated production

As shown in **Figure 56**, the opportunities for automation were observed mainly in the first stages of manufacturing, in materials handling and cutting through to doors and windows installation.

Automation was mostly used in the frame assembly stage, which was automated using a framing station as shown in **Figure 55**. A Computer Automated Manufacturing (CAM) file was generated by the drawing office at the manufacturer's company and sent to the framing station. From this file, the machine displayed information to the operator on the plan of the panel frame and the elements needed to assemble it. The operator then positioned the elements as instructed by the screen and as the assembly progressed, the machine squared, stapled and nailed the frame elements together.

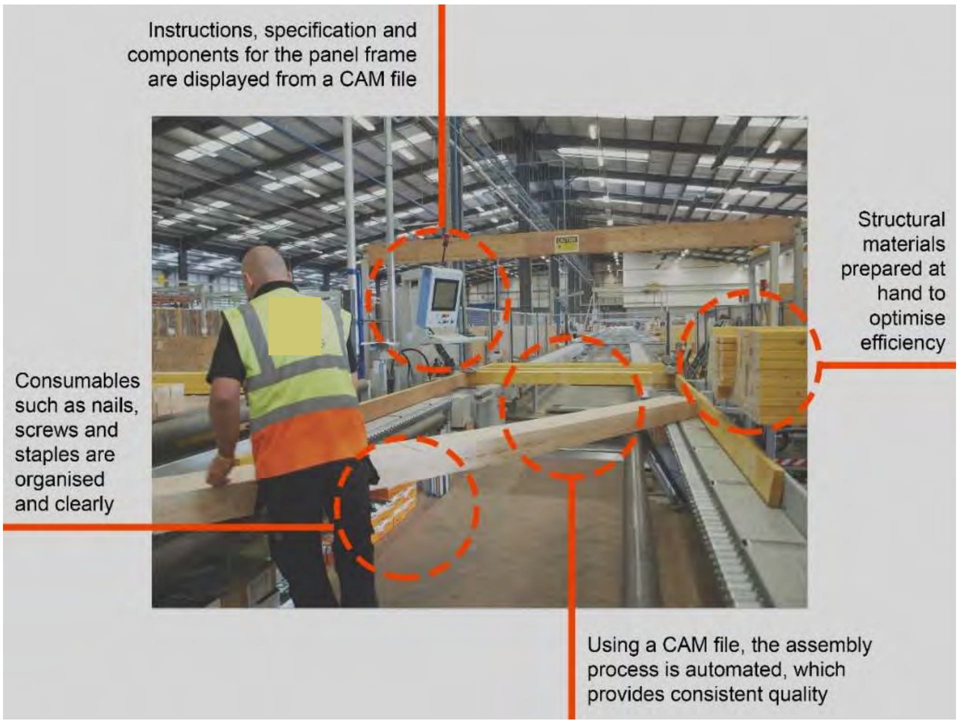


Figure 55. Framing station (semi-automated production) with annotated highlights.

Other forms of automation applied in the factories were nailing bridges and CNC saws which also operated using CAM files, as shown in **Figure 57** and **Figure 58**, respectively. After framing, the panels were rolled to the nailing bridge, where sheet material (e.g. plasterboard, OSB) is automatically squared, stapled and nailed to the frame. The CNC saws could cut either timber board materials in 5 directions to create both intricate and accurate shapes.

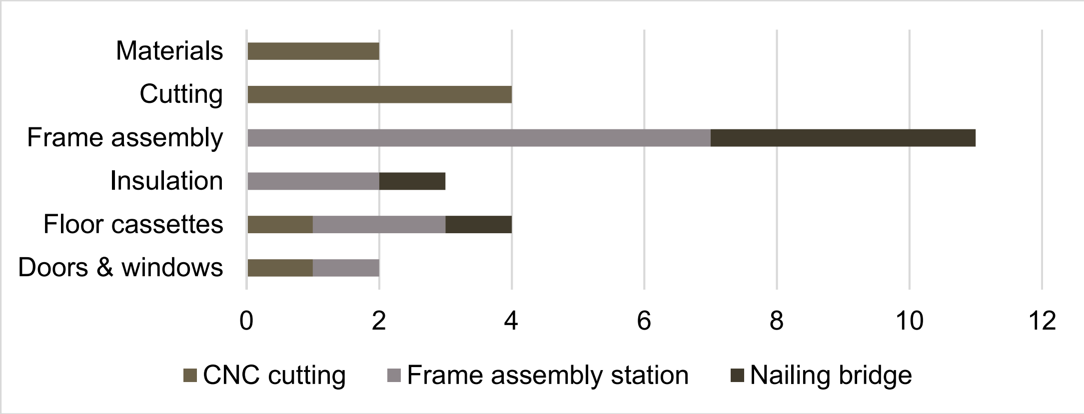


Figure 56. Automation use per manufacturing line.

Figure 57. Nailing bridge example with 2 nail guns, which move along support beams on 3 axis and automatically nail the OSB sheet to the timber frame in seconds.

Figure 58. Example of a CNC saw, which cuts intricate shapes accurately and quickly and reduces the risks of working with sharp cutting tools.

5.3.3 Mechanised production

In addition to automation, mechanised production tools also reduce the risks in construction, mainly by removing the need for heavy lifting. Butterfly tables, cranes and vacuum machines are all examples of mechanisation and their observations are recorded in **Figure 59**. These tools were used in 10 manufacturing lines among the studied companies, among which the most mechanisation examples were observed in the frame assembly stage. The mechanised assembly tool with the highest number of observations were cranes, which were used to lift and transport components and panels between manufacturing lines, an example is shown in **Figure 60**. Butterfly tables are more complex tools, in that they flip panels, as shown in **Figure 61**. Vacuum lifting machines, which are used to position doors and windows precisely in their frames without heavy lifting, were only observed in two instances, in the frame assembly and in the windows and doors assembly stages.

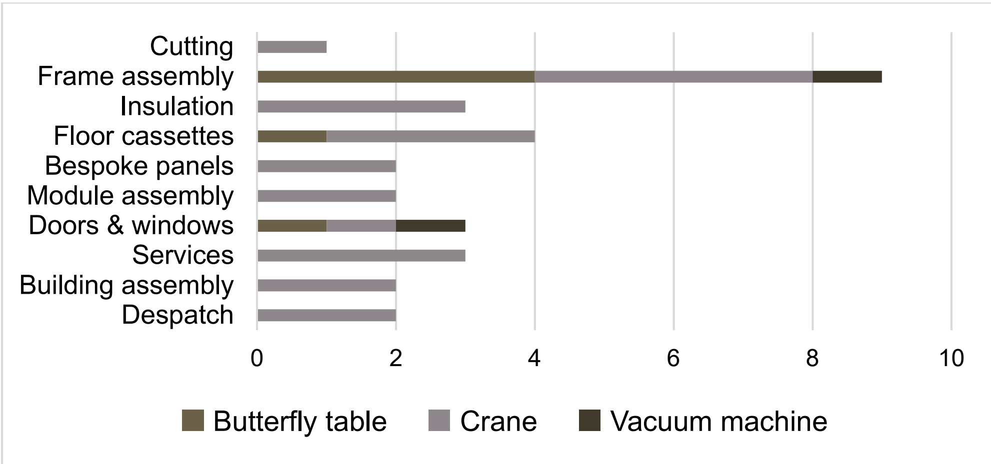


Figure 59. Mechanisation per manufacturing line.

Figure 60. Example of an indoor crane, attached to a floor cassette and a vacuum machine.

Figure 61. Example of a butterfly table, which rotates the panel from horizontal to vertical on one steel frame 'wing', the timber panel is then transferred onto the opposite wing and rotated back to horizontal position, 180° flipped from its starting position.

5.3.4 Manual production

Manual production methods can also be called traditional building methods. In manual production hand-held tools and manually operated saws are used. This type of production was observed in the largest number (namely 13) of manufacturing stages. The use of manual tools was the smallest in the first stages of production, materials cutting and panels assembly. In contrast, the module assembly stages were mostly manual, with 6 to 8 observations per manufacturing stage. The results are summarised in **Figure 62** and examples of manual assembly activities are shown in **Figure 63**.

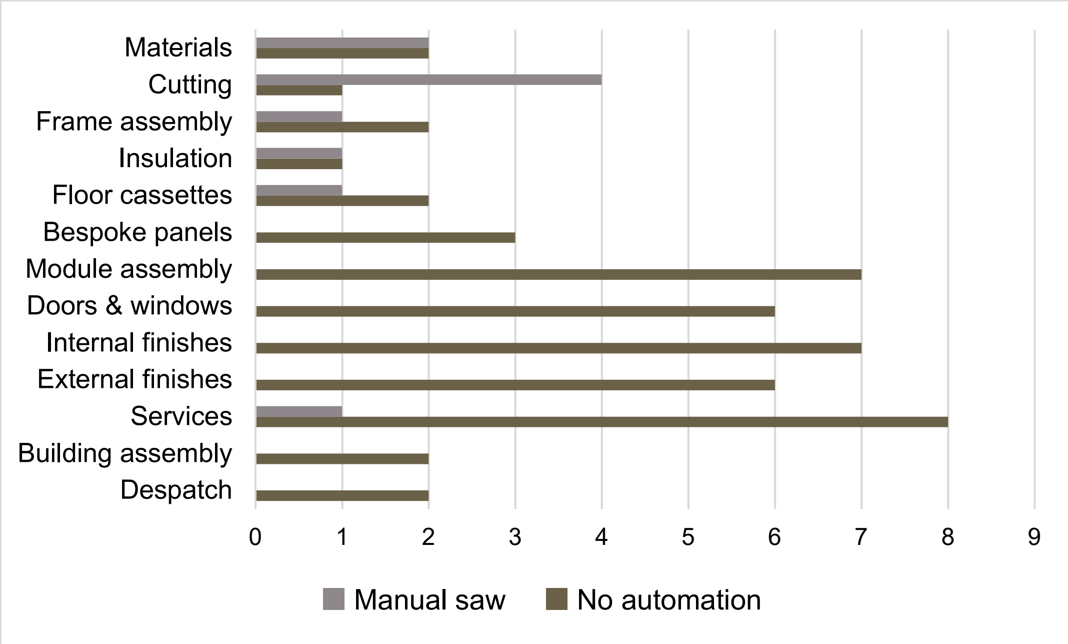


Figure 62.Manufacturing stages without use of automation nor mechanisation.


Figure 63. Examples of manual production activities, bespoke panels assembly with a manual nail gun and installation of insulation.

5.3.5 Waste control

Space, time and inventory waste

The most widely used space saving strategy was the use of rail storage for completed panels, which were observed in seven manufacturing stages amongst the surveyed manufacturers, as shown in **Figure 64**. Two modular manufacturers used the vertical panel storage stage for paint drying, which removed the paint drying stage from the module assembly stages. Examples of panel rail storage are shown in **Figure 65**. Just-in-time delivery was another widely-used technique, used not only in the module despatch stage but also in the materials preparation stages. One manufacturer employed kits of components per manufacturing line station. The kits were assembled just-in-time when required and removed the need for operatives to look for components during their work. A further method of space and time waste reduction observed was the control of inventory. This was applied mostly for non-timber components. One manufacturer demonstrated that they only used a warehouse for timber storage and two small utility rooms for other components. Economies of scale when ordering timber materials and their constant use in the production rendered attempts to reduce timber stock impractical.

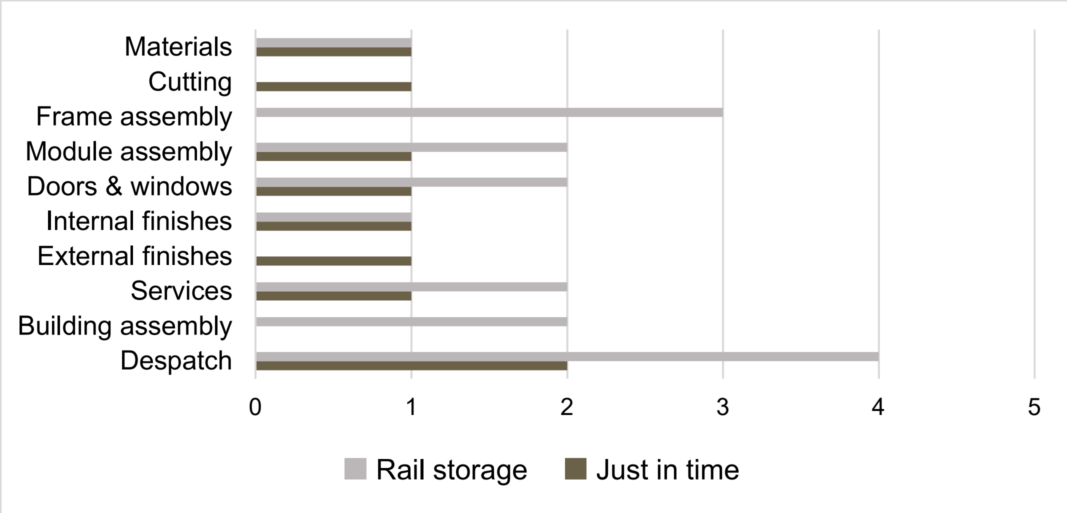


Figure 64. Space saving strategies per manufacturing stage.

Figure 65. Examples of rail storage and inventory control examples.

Reduce, re-use and recycle

All companies surveyed applied waste management strategies, the observations of their main strategies per manufacturing stage are shown in **Figure 66**. The two most common strategies were product labels and recycling bins. The product labels ensured that every component in the factory had a trackable number, sometimes accompanied by a scannable barcode linked either to a materials inventory or to manufacturing instructions. This drastically reduced the chances of wrongly installing components. Three types of recycling bins were commonly used, one for timber, one for plasterboard and one for general refuse, as shown in **Figure 67**. The materials control and the clean environment maintenance ensured that waste was located in the correct bin.

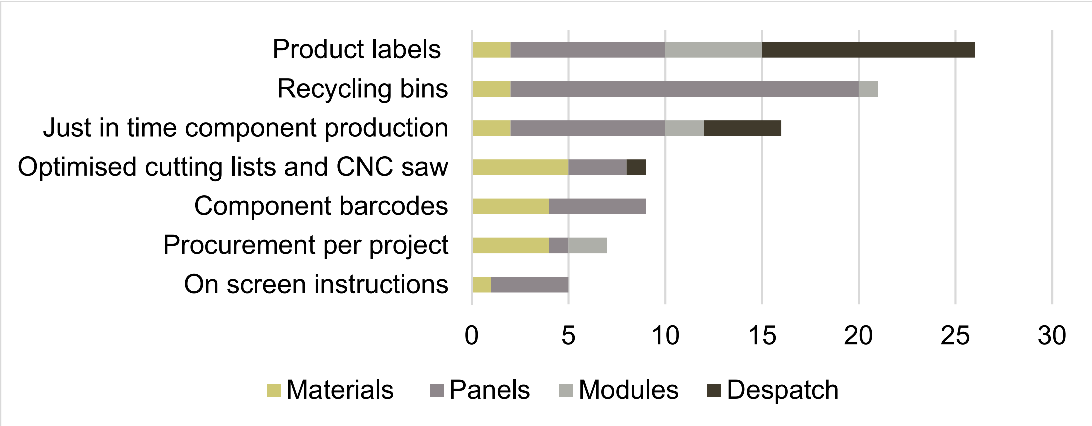


Figure 66. Waste reduction strategies observations per manufacturing stage.

Figure 67. Example of material type segregation for recycling.

Materials in the factories could be procured according to the production schedules, which removed the need for a 'safety margin' order in the material quantities. Such deliveries were scheduled just-in-time. Others observed waste minimisation strategies included re-use of timber offcuts and re-use of packaging. Solid laminated timber offcuts were used by one UKV manufacturer to produce hand-crafted furniture in their modules, whilst others made use of offcuts as separators or protective sheets. Only one manufacturer, a UKP type, re-used their panel despatch system elements and re-cycled their plastic packaging when returned from site.

Overall, the largest variety of waste reduction strategies were observed in the materials handling and cutting stage (16), whereas the fewest types of waste reduction strategies were observed in the despatch stage (7). The panels and modules production stages had similar varieties of waste reduction strategies, 11 and 13 respectively, as shown in **Figure 68**.

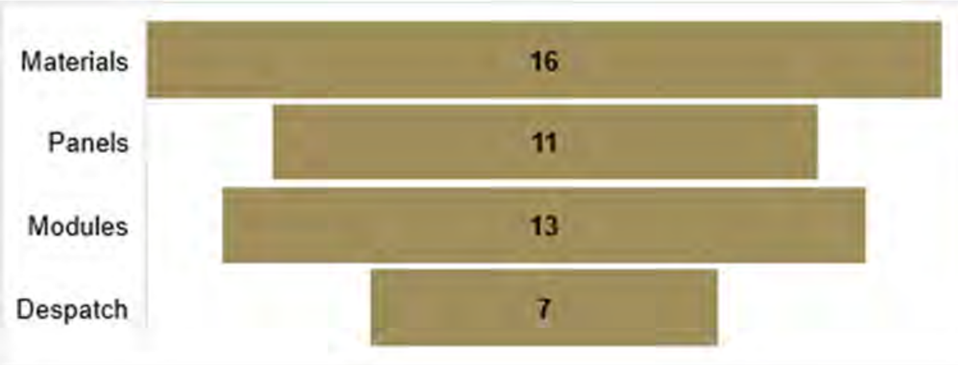


Figure 68. Variety of waste reduction strategies observed per main manufacturing stage.

5.3.6 Quality control

In all surveyed manufacturers the final products were quality checked prior to despatch. One manufacturer conducted this using an excel spreadsheet on a tablet. Furthermore, five manufacturers reported that they used quality control checks at each manufacturing stage. All quality requirements had to be satisfactorily complete before the product could continue to the following stage. Amongst these, the four EUV manufacturers used a set of identification documents attached to each product, panel or module, which were filled out and added to as the product progressed through the manufacturing process. EUV1 reported that in addition to these measures they conducted random quality checks throughout the process, to ensure that the manufacturing and inspections had been conducted correctly. The quality checks at each stage and prior to despatch included items such as the correct positioning of each element, specification of the build-up, connections, equipment installation and protective coverings.

Two manufacturers reported that they used external certification such as ISO standards to ensure the quality of their products, however it can be speculated that more manufacturers complied with these standards. EUV2 and EUV4 provided building warranties to their customers, with durations starting from 1 year, which covered not only the structural but the internal features, fixtures and services.

5.3.7 Building Information Management (BIM)

BIM levels and dimensions

Overall, nine out of the ten surveyed companies had applied BIM up to at least Level 1, as defined by the BIM Industry Working Group (BIWG, 2011). That is, they used 3D models with component information attached to the visual representation of the model elements, such as dimensions, cost, availability, sequence of manufacturing. UKV2 and UKV3 had applied BIM up to Level 2, information exchange through .ifc models, however this was mostly done internally between project members within their company. UKV2 had developed a system of software information exchanges, which made communication between the different disciplines more efficient. This made the work of the architect, the engineer, the quantity surveyor and the procurement manager streamlined and faster. One UKV2 representative summarised their BIM strategy in the following way:

> *BIM is a system that is made of different applications for different outputs. You could have rates (times), carbon consumption, price, etc.; and for each type you need to have a suitable application. For time, you will need to have a programme that can analyse that, and transfer BIM information to it. The main principle is having the right software, giving it the right information, and then knowing how to organise the output.*

Within the main BIM Levels, the surveyed companies also reported on their application of BIM Dimensions (3D components, 4D time, 5D cost, 6D facilities management and 7D energy analysis). At the time of interview, 7 companies were using 3D components with attached information for modelling of their projects. Only UKV2 applied BIM for production time estimation, 4D and 5D cost estimation and procurement. However, UKP2 and EUV2 speculated that 4D and 5D BIM could be useful for their companies, such as for time on site estimation, on site information availability and productivity estimation of the factory processes. Similarly, UKV2 were the only company who had applied BIM for 6D facilities management and 7D energy analysis. 6D was executed by providing as-built information to the client including the specification and maintenance requirements of the installed components. For 7D BIM application, the structural engineer of the company worked on reducing the carbon footprints of the buildings in terms of embodied and in-use energy.

Regarding other BIM levels, UKV1 had applied BIM only up to Level 0. In other words, they designed their houses in AutoCAD only, however because of the simplified dwelling designs and small-scale production this was the most suitable drawing production method for their company. Amongst the surveyed companies, none had applied BIM to a fully collaborative Level 3, however one UKV2 and one EUV2 manufacturers were optimistic that this would happen, whereas UKP2 and UKV4 were sceptical about BIM as a sustainable process of work for the near future.

Software

The most widely used software among the surveyed manufacturers was AutoCAD, reported by 5 volumetric manufacturers. The second most used software tools were HSB CAD and Revit, each of which was reported by 3 manufacturers. The use of Revit was mostly associated with internal tests of BIM workflows and in only one company this was the established software platform for architectural design. One manufacturer had conducted tests with HSB CAD for BIM collaboration through .ifc model exchange. Furthermore, two UKV companies used SketchUp, however for different purposes, one for conceptual architectural design and the other for BIM workflow tests including attached component data and automated schedules generation.

Other engineering software solutions (CAD Works and Solid Works) were reported by one company each. Inventory management systems (ODOO, Simplex, and Vertex) were also used by one company each.

5.4 European and UK manufacturing analysis and discussion

5.4.1 Offsite completion percentage

Offsite completion benchmark

According to the literature, offsite timber systems may be categorised as sub-assemblies, panelised, pods and volumetric solutions, however the descriptions of offsite methods of construction contains a plethora of classification options (Kamar, Hamid & Azman, 2011; Azman *et al.*, 2010). For example, the Buildoffsite *Glossary of Terms* distinguishes between ‘Component subassembly’, ‘Non-volumetric preassembly’, ‘Volumetric preassembly’ and ‘Complete buildings’, whereas the *Building Offsite An Introduction* differentiates between 4 sub-categories of 2D elements with applications for walls, floors and roofs, and 3D modules (Hairstans, 2015; Gibb & Pendlebury, 2013). Further differences in offsite systems classifications are shown in **Figure 69** (Gibb & Isack, 2003; Oliveira *et al.*, 2017; Smith, 2011; Hairstans, 2015).

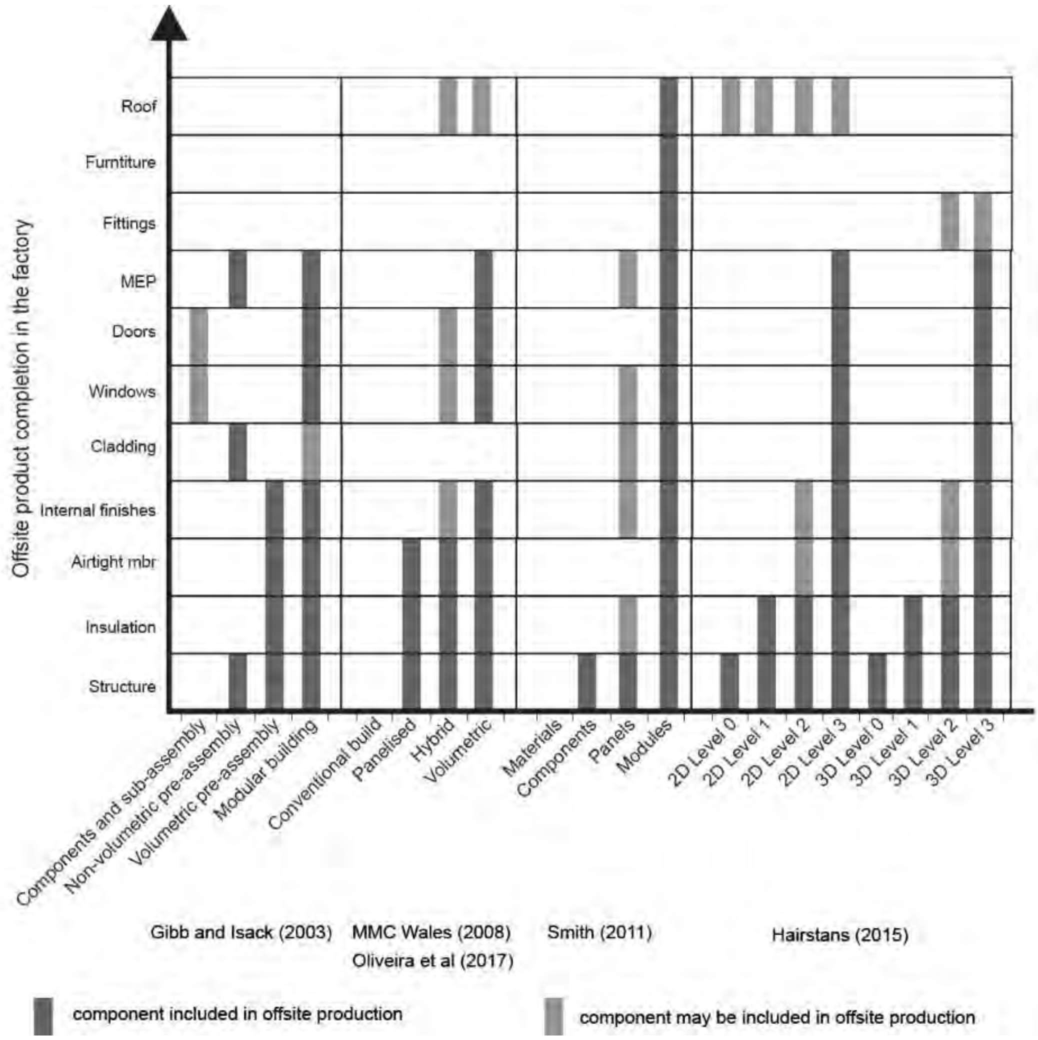


Figure 69. Offsite systems classification comparative review according to building elements completion in the factory (Gibb & Isack, 2003; Oliveira *et al.*, 2017; Smith, 2011; Hairstans, 2015; MMC Wales, 2008).

A common theme among the offsite categorisation systems is that they are founded on differences in the extent of building product completion in the factory, or in other words the balance between onsite and offsite work. To communicate this basis for differentiation, estimated percentages of offsite completion are often used, which increase incrementally with the increasing value added in the factory during the offsite systems production. However, discrepancies exist in the literature regarding the factory completion percentages of each offsite level. Specifically in the reporting of volumetric solutions level of offsite completion, the estimates vary between 70% and more than 95%, whereas panelised solutions tend to be grouped and attributed approximately 25% of offsite completion without regards for incorporation of insulation, sheeting, windows, etc. (Lawson, Ogden & Goodier, 2014; Smith, 2011). The level of offsite product completion in the factory may be co-related to strategies applied by offsite manufacturers to adapt to fluctuations in the market, and the corresponding design and production decisions made in the context of increasing competitiveness across market segments (Jonsson & Rudberg, 2014).

Offsite completion analysis and discussion

The starting point of the data analysis was the calculation of percentages for onsite and offsite activities of the studied offsite timber systems. The data from **Table 13** was used to propose a quantification of the offsite completion levels amongst the surveyed companies, where a value of 1 was attributed to elements, which were included in the offsite products, and a value of 0.5 was attributed to elements, which may or may not be included in the factory production process. Previous studies did not present methodologies for estimation of offsite level percentages and although this method has some limitations, it has been utilised in this instance to enable inclusion of offsite percentage differences in the productivity calculations in following sections.

This approach produced the following results, shown in **Figure 70**, which highlight that the offsite completion levels of the investigated systems tended to be within more moderate ranges compared to the higher percentages of offsite completion often attributed to volumetric timber construction in the literature (Smith, 2011). These results also demonstrate that the levels of offsite completion between systems sharing an offsite classification could be said to vary significantly; according to this research, by up to 15%. On average, the UKP companies utilised 25% offsite completion, the UKV companies 70% and the EUV companies 65%. This is generally in line with the estimates of Lawson and colleagues (Lawson, Ogden & Goodier, 2014). The differences between reported and calculated offsite completion percentages are shown in **Table 22**.

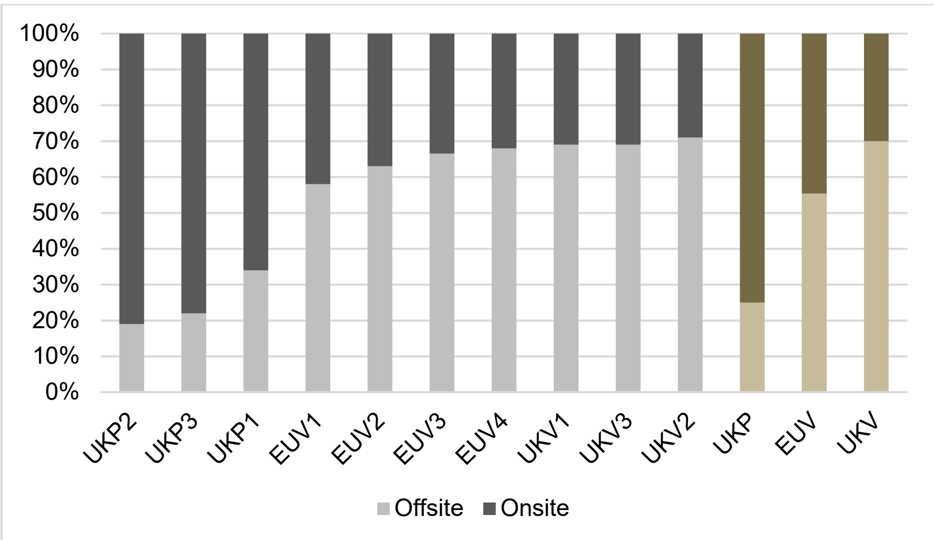


Figure 70. Offsite and onsite building completion percentage calculated values.

Table 22. Reported (OC1) versus calculated (OC2) offsite completion percentage per manufacturer.

	UK P1	UK P2	UK P3	UK V1	UK V2	UK V3	EU V1	EU V2	EU V3	EU V4	UK P	UK V	EU V
OC 1	45%	25%	29%	82%	90%	90%	90%	90%	90%	90%	33%	87%	90%
OC 2	19%	22%	34%	58%	63%	67%	68%	69%	69%	71%	25%	63%	69%

It must be noted however that the above approach is limited by the exclusion of labour-hours and GVA per task. Such an investigation could be the object of further work, whose data could be analysed to provide rankings for the different elements included in the offsite process. For example, it is anticipated that the roof of a two-bedroom house would require higher labour and materials input and would result in higher added value compared to the provision of a patio in the offsite completion of the system.

5.4.2 Production and productivity

The production output of each company was reported in different units shown in **Table 23**, which is reflective of findings from previous research that construction productivity measurement is inconsistent (CITB, 2015). Some examples of the reporting of the production output by interviewees are: ‘In the open panel assembly line each station takes approximately 2.5 minutes per panel. They produce approximately 50 floor cassettes per day.’ and ‘5-6 days to manufacture a module from start to finish; each panel/module progresses to the next station each day’. Therefore, although in an ideal world a unified international offsite production metric system would have been utilised across all manufacturers, due to the practicalities of the different companies using different units of measurement for their production, it was necessary to transform these units to a single unit of measurement to the best of the author’s knowledge. In the case of the 1-bedroom living unit for example, eight wall panels were utilised and if they were to be produced with approximately 2.5 minutes per panel, that would equal 20 minutes. Considering an average 8-hour working day on average the wall panels for 24 living-unit equivalents would be produced per working day. The two floor cassettes would equal 4% of the typical daily production of 50 cassettes per working day, and the floor cassettes for 25 living unit equivalents would be produced per working day. Therefore, the manufacturer would have capacity to produce on average 24.5 1-bedroom living unit equivalents per day, or approximately 122 1-bedroom living unit equivalents per working week.

Table 23. Reported units of production output per company.

Unit	UKP 1	UKP 2	UKP 3	UKV 1	UKV 2	UKV 3	EUV 1	EUV 2	EUV 3	EUV 4
Buildings per year					✓		✓		✓	
Buildings per hour			✓						✓	
Modules per year							✓	✓		✓
Panels per year										✓
Panels linear meters per day	✓									
Panels area per week		✓								
Panels Number of per shift			✓							
Minutes per open panel			✓							
Minutes per closed panel			✓							
Week per module				✓	✓	✓		✓	✓	✓
Modules per week						✓		✓	✓	✓
Modules per day							✓		✓	
Total output measurement unit types reported per manufacturer	**1**	**1**	**4**	**1**	**2**	**2**	**3**	**3**	**5**	**4**

Pilot: 1-bedroom living unit with reported offsite percentage estimates

Initially a pilot study was conducted by using a simple one-bedroom apartment living unit with dimensions as listed in **Table 24** and shown in **Figure 71**.

To illustrate the units conversion for the calculation, the more complex of the examples above, will be explained (time per open timber panel reported). Firstly, the working hours per week were extracted from the production management results regarding shift patterns; these were then multiplied by the reported panel sizes to extract linear meter panel outputs per week (with respective minutes to hours to week conversions). The resulting number was divided by the linear wall meters of the one-bedroom common unit of measurement extract output per week results. This was multiplied by the previously calculated offsite percentage for open panel construction to arrive at the normalised offsite output per week. The input was calculated in labour-hours by multiplication of working hours per week by the number of staff reported working on the shop floor. This allowed for differentiations in numbers and durations of production shifts per day to be represented in the final results.

Table 24. 1-bedroom living unit dimensions schedule.

Product	**Length (m)**	**Width (m)**	**Height / Depth (m)**	**Area (m^2)**
Volumetric module	13.5	4.2	3	44.8 (internal living)
Floor panel	13.5	4.1	0.25	55.4
Ceiling panel	13.5	4.1	0.25	55.4
Wall panel 1	13.0	2.4	0.35	31.2
Wall panel 2	13.0	2.4	0.35	31.2
Wall panel 3	4.1	2.4	0.35	9.8
Wall panel 4	4.1	2.4	0.35	9.8
Partition panel 1	3.5	2.4	0.1	8.4
Partition panel 2	3.5	2.4	0.1	8.4
Partition panel 3	2.9	2.4	0.1	7
Partition panel 4	2.3	2.4	0.1	5.5

Finally, according to **Equation 5** the output and input were divided to arrive at a figure for labour productivity, comparable across the surveyed ten manufacturers. The results from the pilot comparative productivity analysis are shown in **Table 25**. The thus formed findings were validated were validated by the respective interviewees by their reviewing of extracts from results and analysis relevant to their respective manufacturer.

$$Lp1 = \frac{P1 \ x \ OC1\%}{Lh1} \qquad \text{Equation 5}$$

Adapted from (Fried, Lovell & Schmidth, 1993:p.4)

Where:

Lp1= Labour productivity (1-bedroom living unit equivalent per labour hour)

P1 = Production in 1-bedroom living unit per week

OC1% = Offsite Completion Percentage (reported); and

Lh1= Labour hours per week

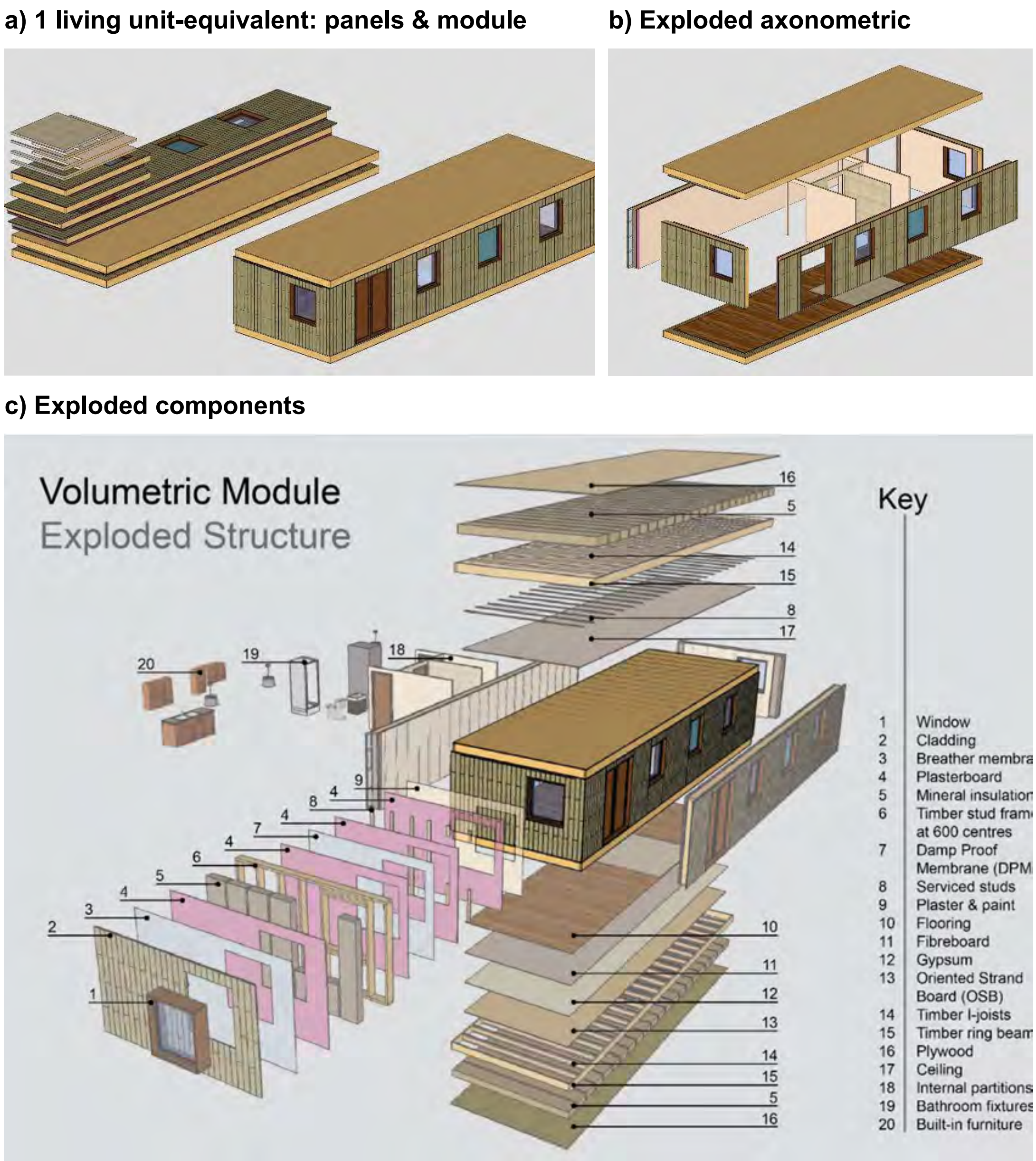


Figure 71. Pilot 1-bedroom living unit equivalent visualisations. Authors' own work, includes adapted Trimble Sketch Up stock furniture models and is based on publicly available data (SINTEF, 2013).

Table 25. Comparative production and productivity analysis for 1-bedroom living unit (see Equation 5 for variable explanations).

Variable	UK P1	UK P2	UK P3	UK V1	UK V2	UK V3	EU V1	EU V2	EU V3	EU V4	UK P	UK V	EU V	AVRG
P1	25.2	11.8	20.9	0.7	0.5	4.5	31.5	13.5	18	10.8	19.3	1.9	18.5	13.7
OC1%	45%	25%	29%	82%	90%	90%	90%	90%	90%	90%	33%	87%	90%	72%
Lh1 per week (10^3)	2.2	1	3.2	0.4	0.8	2.4	3.2	1.6	2	4	2.1	1.2	2.7	2.1

2-bedroom living unit with calculated offsite percentage estimates

The selection of a common unit of measurement was an important consideration for this research study and the identified common unit was analysis of methodologies applied in previous research studies in the field (Monahan & Powell, 2011; Quale *et al.*, 2012; Smith *et al.*, 2013). Previous research by Monahan and Powell utilised a three-bedroom, two-storey case study house in the context of UK; Quale and colleagues based their findings on a 4-module 2,000 square foot (185 m^2) two-storey house in a hypothetical context; whereas Smith and colleagues evaluated 'homes/units' outputs irrespective of the differences in home sizes. To decide the living unit-equivalent utilised in this study the data from literature was triangulated with results from the market opportunities and product type sections; technical volumetric specifications available from SINTEF; and data from national statistical records (National Record of Scotland, 2013; Nordhus, 2013; Office for National Statistics, 2018), as shown in **Figure 72**. In addition, the selection of a neutral living unit of measurement, mitigated the potential impact on the results in favour of the one company.

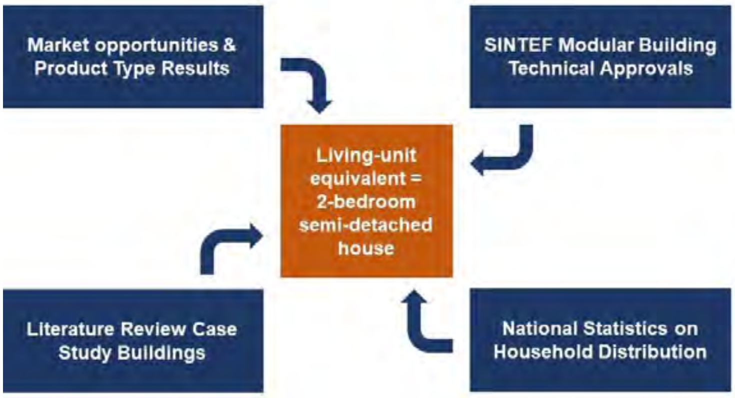


Figure 72. Living unit-equivalent selection methodology applied in this research.

On observation of the latest available UK census data from 2011 in **Figure 73** it could be speculated that the most typical in the UK households were two- and three-bedroom households. In addition, dimensions guidance was sourced from modular building technical approvals. Moreover, a more complex 2-bedroom semi-detached living unit would incorporate findings from previous studies that volumetric construction results in double walls/floor elements, which could result in approximately a 25% difference in materials input in buildings, whereas in this study the difference was 13% as seen in **Table 26** (Quale *et al.*, 2012). Moreover, to make the results comparable to previous offsite reviews, the output units were changed to living unit-equivalent per annum and the labour units were altered to number of staff (Smith *et al.*, 2013). These alterations were calculated using **Equation 6**.

$$Lp2 = \frac{P2 \ x \ OC2\%}{Lr} \qquad \text{Equation 6}$$

Adapted from (Fried, Lovell & Schmidth, 1993:p.4)

Where:
Lp2= Labour productivity (2-bedroom living unit equivalent per labour resource)

P2 = Production in 2-bedroom living unit per annum

OC2% = Offsite Completion Percentage (calculated); and

Lr= Labour resources per manufacturer

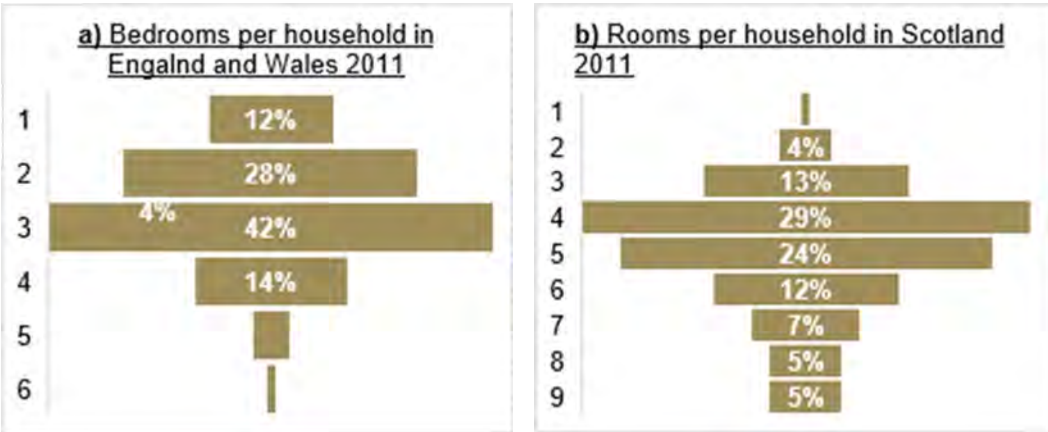


Figure 73. Household distribution in the UK: a) England and Wales, b) Scotland. Data sources: (Office for National Statistics, 2018; National Record of Scotland, 2013).

Table 26. 2-bedroom living unit dimensions schedule.

Product	**Length (m)**	**Width (m)**	**Height / Depth (m)**	**Area (m^2)**	**Number of**
Volumetric module	13.5	4.2	3	44.8 (internal living)	2
Floor panel	13.5	4.1	0.25	55.4	2
Ceiling panel	13.5	4.1	0.25	55.4	1
Wall panel 1	13.0	2.4	0.35	31.2	2
Wall panel 2	13.0	2.4	0.35	31.2	2
Wall panel 3	4.1	2.4	0.35	9.8	2
Wall panel 4	4.1	2.4	0.35	9.8	2
Partition panel 1	3.5	2.4	0.1	8.4	2
Partition panel 2	3.5	2.4	0.1	8.4	2
Partition panel 3	2.9	2.4	0.1	7	2
Partition panel 4	2.3	2.4	0.1	5.5	2

The results from the data transformation are shown in **Table 27** and **Figure 74**. This analysis suggested that the EUV manufacturers' productivity was the highest, with approximately 5.45 two-bedroom living unit-equivalent output per labour resource per annum, whereas the UKP average was approximately 70% that of EU and the UKV was approximately 18% that of EUV. The UKV manufacturers however tended to have lower production output rates compared to the other surveyed manufacturers, which suggests that these organisations had lower production capacity, which was in turn limiting their opportunities for productivity growth. The values of UKP3 and EUV1 were the highest by a large degree and this could be explained by their reporting of having full pipe-lines of work secured so that the factory experienced no down time.

However, this quantitative exploration of the data does to reflect the qualitative nuances between the surveyed companies. For example, the quantitative productivity comparison did not accommodate for differences in business models among the surveyed manufacturers. EUV4 employed a significantly higher number of production staff; 5 times more than EUV3. The EUV4 workforce costs were significantly less per hour compared to their market country, where they exported and constructed modules. Therefore, in their case the strategy to employ more people to increase production was practical.

Moreover, UKV2, UKV3 and EUV2 outsourced CLT, SIP and CLT panels (respectively), which in theory reduced the activities in the factory and therefore reduced the manufacturing time per module within the factory. Indeed, the UKV3 and EUV2 productivity rates were similar, however UKV2's productivity was lower. The difference can be explained by the smaller size and the smaller number of workforce of UKV2 compared to EUV2 and UKV3; combined with the establishment of EUV2 as a daughter company to a much larger organisation, which would have made available more initial resources and more extensive experience in this field.

The productivity rates should furthermore be explored through the lenses of automation, mechanisation and lean improvement potential. The highest opportunities for automation were observed in the panel production stages, whereas the volumetric production stages included manual workmanship of services and finishes. Therefore, it could have been expected that the labour productivity of the panelised timber manufacturers would be higher than that of volumetric timber manufacturers, whose work included in addition highly manual labour-intensive tasks. However, the results from this sample suggest that labour efficiency in modular production similar to that of panelised timber production is possible. Increased labour productivity in certain manufacturers such as EUV1 and may be connected to higher output capacity due to a high number of years in trading with associated opportunities for growth and investment in R&D.

Table 27. Comparative production and productivity analysis for 2-bedroom living unit equivalent.

V	UK P1	UK P2	UK P3	UK V1	UK V2	UK V3	EU V1	EU V2	EU V3	EU V4	UK P	UK V	EU V	AV RG
P2	231	225	532	12	8	83	595	259	345	213	329	34	353	**239**
OC2 (%)	19	22	34	58	63	67	68	69	69	71	25	63	69	**54**
Lr	86	140	74	10	20	60	80	40	50	220	100	30	98	**76**
Lp2	**2.7**	**1.6**	**7.2**	**1.2**	**0.4**	**1.4**	**7.4**	**6.5**	**6.9**	**1.0**	**3.8**	**1.0**	**5.5**	**4.5**

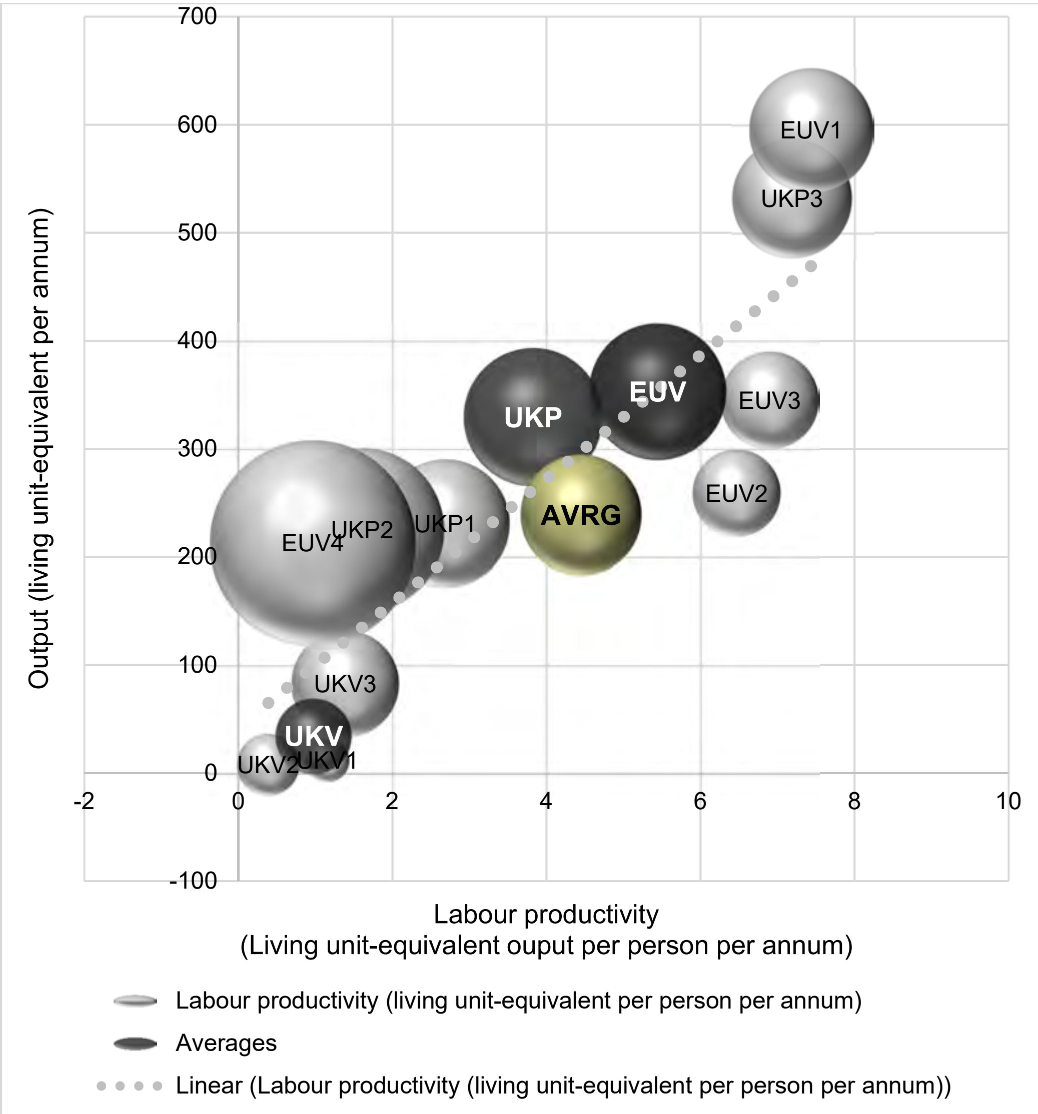


Figure 74.Comparative productivity analysis for 2-bedroom living unit equivalent, where the gold colour indicates the data average.

Assumptions

a) Where the figures were originally stated per year a 50-week working year was assumed, this was selected to account for holiday periods such as the winter holidays and other national holidays when production would be discontinued.

b) Where a maximum capacity per year was stated the number was multiplied by the manufacturers' estimated achievable production of 80%, which was the most commonly reported capacity of operation among the surveyed manufacturers.

c) Practical considerations regarding the international regulations on transport load dimensions in individual countries and their effect on the possibility of producing this unit in each surveyed country were not included in this production calculation.

d) Because this method is intended for comparison of different management strategies and their effect on production output, opposed to calculating and predicting actual capacity rates, the individual logistics legislation was outside of the research scope.

e) Please note that the impact of the double walls in the living unit of measurement used in this study was significant but did not result in drastic changes in the rankings of manufacturers (13.5 linear meters, or 13% of total 185.6 linear meters). The sensitivities of this observation should moreover be considered when drawing conclusions.

Benchmark of offsite manufacturing productivity

The *Strategic review of the Offsite Sector in Scotland* research results may be used as a benchmark for this research study as shown in **Figure 75** (Smith *et al.*, 2013). The values comparison suggests that the findings are comparable to those by Smith and colleagues for panelised timber manufacturers, however the UK volumetric timber manufacturers' productivity was significantly lower. This is in line with previous observations that the UK volumetric timber manufacturing represents a small segments of the UK manufacturing capacity. Moreover, the findings demonstrated potential for increased capacity and productivity of volumetric timber manufacturers in the UK, which will however require an increase in the volumetric timber market maturity.

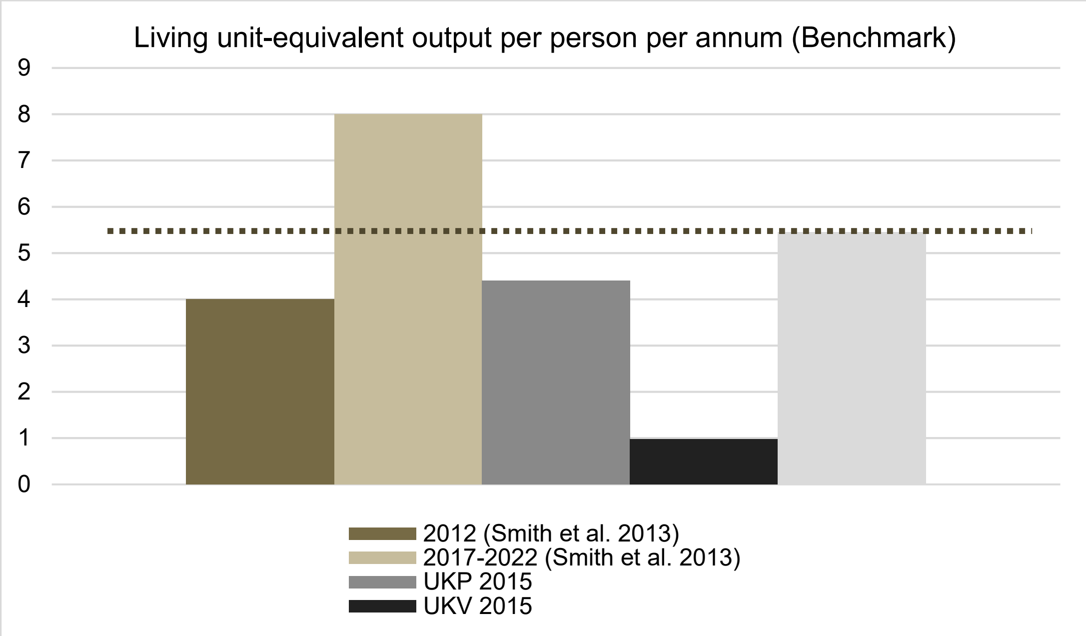


Figure 75. Benchmark of labour productivity results (Smith *et al.*, 2013).

Sensitivity analyses

Through the exploration of different methods for offsite completion percentage calculation and the differences in productivity calculations using different living-unit equivalents, this thesis has explored the sensitivities of the methods. The rankings of manufacturers' productivity differed between the two utilised methods as shown in **Table 28**, which suggests that the difference between reported offsite percentage completion and calculated offsite completion percentage had the largest impact on the differences in ranking, which ultimately lead to EUV manufacturers being ranked on average higher than UKP manufacturers in the updated benchmark-able metrics. Because of the discrepancies, it is suggested that UKP and EUV manufacturers have similar labour productivity rates, which leads to a gap for potential productivity growth of UKV manufacturers.

Table 28. Labour productivity ranking sensitivity analysis.

Rank	UK P1	UK P2	UK P3	UK V1	UK V2	UK V3	EU V1	EU V2	EU V3	EU V4	UK P	UK V	**EU V**
Lp1	1	2	6	9	10	8	3	5	4	7	1	3	**2**
Lp2	5	6	2	8	9	7	1	4	3	10	2	3	**1**
Lp1-Lp2	-4	-4	4	1	1	1	2	1	1	-3	-1	0	**1**
Lp Average	**3**	**4**	**4**	**9**	**10**	**8**	**2**	**5**	**4**	**9**	**2**	**3**	**2**

The low productivity of UKV companies may be explained by construction market issues. For example, an observation was made that the surveyed companies with higher productivity tended to have been operating for longer and within more market types. This could be speculated to be a sign of a need for high resilience to fluctuations in the market, typical for the UK. In Scotland for instance in 2015 timber panel construction represented three-quarters of new built homes (The NHBC Foundation, 2016), which in turn represented 75% of Scottish construction. Moreover, the (Smith *et al.*, 2013) study identified the distribution of offsite systems as 81% panelised systems versus 19% volumetric systems. Open timber panels represented 44% of the offsite market turnover, whereas volumetric construction with insulation, services and finishes represented 11%, the highest among the volumetric categories. Therefore, it can be speculated that panelised timber market had a high maturity, whereas the volumetric timber market had a low maturity and scope to grow.

With the low volumetric market maturity, it could be speculated that companies would have lower opportunities for investment in productivity improvement. Moreover, if the manufacturers had not been trading for many years, they could have been limited by the physical size and available shop floor space of their company. This however indicates opportunities for growth and expansion among the surveyed UKV companies, who moreover demonstrated the potential to apply automation, upskilling, lean process waste reduction, and implementation of BIM processes and technologies to high standards.

5.5 Additional international examples

The purpose of the additional international examples was dual in nature; to identify whether trends observed in the main survey were also observed in other economic contexts, and to highlight best practice offsite timber manufacturing strategies that could be adopted to a UK context.

5.5.1 Canadian offsite timber industry

Volumetric timber

The author participated in a research trip to attend the *Modular and Offsite Construction Summit* in 2016 in Edmonton, Alberta, Canada.

The Modular Housing Association in Canada is the main industry association representative of volumetric timber manufacturing there, and each region has an MHA branch, who provide training, building code advice, governmental consultation, road regulations mandating and public image promotion. The evolution of volumetric or ‘modular’ manufacturing in Canada was developed in parallel with the changing road regulations there (Provinces, 2015). For instance, in the 1950s modular homes had a maximum width of 10ft (3m) and length 48ft (14.5), but with gradual campaigning the regulations have gradually changed to the current-day maximum permitted modules with a maximum width of 30ft (9m) and length 76ft (23m). This is approximately twice the size of typical practices observed in the UK and Mainland Europe.

These buildings are most commonly produced in manufacturing facilities with stationary benches, more representative of the workshop typology other than the factory production line typology observed in the UK and Mainland Europe. A typical modular homes manufacture envelope specification would be as follows (Grandeur, 2016):

- ‘14″ Webbed Floor Joists
- Joist, Stud & Truss Spacing – 16″ O.C.
- 19/32″ Tongue & Groove Floor Decking
- Underlayment Beneath Sheet Flooring
- Tarped Underbelly (for Transport)
- 3/8″ Roof & Wall Sheathing
- Calculated Insulation Values – Walls R-24, Roof R-50
- 6 mil Vapour Barrier (CGSB)
- 4/12 Roof Pitch (Hinged roof required)’

Figure 76. Example typical volumetric house interior and exterior.

Closed timber panels

With respect to closed timber panels, the below is a summary of the production processes observed at a closed timber panel manufacturer near Calgary, who in addition produced modular roofs as part of their traditional process, as shown in **Figure 77**.

Figure 77. Laminated Strand Lumber panels and a modular roof observed in Canada.

Timber

Two types were used, natural timber, also referred to as dimensional lumber, and an engineered timber product called Laminated Strand Lumber (LSL), which was predominantly used in the frames. Compared to natural timber, LSL had the advantages of dimensional accuracy, consistent structure, no knots, a straight profile and a longer profile. But as any other engineered timber product, it requires advanced processing and lamination.

The LSL was manufactured and supplied locally and the manufacturer used it initially only for the top and bottom plates of the walls. But after successful trails, they decided to use LSL for the entire frames. LSL cost them more than natural timber, but this was compensated by reducing the waste in the factory by 33% per year and transportation costs by $46,000 (£26,700) per year.

BIM and CAM

BIM enabled the company to achieve high productivity they stated it was essential to their operation. The company used the software platform SEMA, which originated in Europe and it enabled timber frame design with a high level of detail. SEMA had an export option for various automated machines used at the factory, providing a direct CAD/CAM interface.

Manufacturing stages

The company had two approximately equal in size warehouses which shared a courtyard. In the sequence below the letter ‘A’ indicates that a semi-automated machine was used at that stage and the letter ‘M’ indicates that a mechanised machine was used at that stage. Interestingly, the company representative stated that using for panels instead of one on the butterfly table increased their productivity from 6,000 sq. ft. (550 m^2) to 13,000 sq. ft. (1,200 m^2) per day.

Panels

- Stage 1A - Cutting. Every cut piece had a labelled ID with a barcode so that the workers knew which manufacturing station it should go to next.
- Stage 2A - Component frame assembly.
- Stage 3 - Insulation.
- Stage 4A - Sheet cutting using an optimized cutting list to minimize waste.
- Stage 5A - Nailing of sheets to the timber frame using a nailing bridge.
- Stage 6M - Flip the panels using a butterfly table with more than 4,000 lbs (1,800 kg) capacity.
- Stage 7 - Vertical rail storage for open panels, which are ready for transport.
- Stage 8 - Closed panel vertical line, at which windows and doors were fitted and cladding was installed.
- Stage 9M - Transport trailer storage.

Roofs

- Stage 10 - Staircases. Built on a jig including all walls that were connected to the staircase. This ensured a fit on site.
- Stage 11 - Roof construction using several jigs. One person was responsible to construct the base exactly according to the house plans, to ensure a fit on site.
- Stage 12 - Floor panel construction. An automated machine was recently installed to aid the materials cutting and sorting.
- Stage 13 – Transportation. Truckloads are prepared in the factory. One loaded truck was seen exiting the factory at the time of visit.

Onsite time

The installation took approximately 1.5 days per house, installed by a dedicated site team. A mobile crane was used because the panels and roof elements were relatively lightweight.

Laminated timber

Laminated timber systems are increasingly competing with the steel and concrete industries in Canada, where mass timber is used for increasingly larger span structures. One example was a local council health centre in a suburb of Calgary, where a combination of BIM and Glulam construction were utilised to create a healthy building promoting overall well-being. The building was visited during construction, as the cladding, roof cladding, and internal works were progressing, shortly after the last glulam beams had been installed. The project had an organic curvature profile, shown in **Figure 78**, which reflected the profiles of the surrounding hills and which would create a landmark building for the local community. The organic 3-dimensional shape was rationalised for glulam timber beam production by utilising a radial grid plan overlay. The beams maintained identical curvature and depth, whereas the varying forms and sized of the beams was achieved by variation beam length dimensions.

Building Information Modelling (BIM) technology was key to the success of the project. The team used Autodesk Glue to collate the information models produced by different stakeholders. The engineers used Tekla Structures and the architects used Autodesk Revit. Early stakeholder collaboration via the federated model was essential and the input of otherwise downstream stakeholders was included from the initial designs. For example, the timber glulam manufacturer was included in the early discussions and in the timber structural optimisation process.

The beams were engineered as double timber beams connected with steel plate and bolt connections. A clip-type connection was considered but was not used because the plate and bolts connection was more cost-efficient and provided the same engineering robustness. Each beam consists of eight timber section, or four pairs of timber sections with width 300 mm, depth 1,500 mm and length 20,000 mm. As shown in

Figure **79**, glulam purlins span across the beams, and in the south-eastern part of the building, a larger span for basketball courts required a beam connection with a steel plate between double glulam beams.

Figure 78. Community health centre in Canada: exterior showing organic profile.
Figure 79. Community health centre in Canada: interior showing glulam beams.

5.5.2 Swedish offsite timber industry

Volumetric timber

The author participated in an offsite timber learning trip in 2017 to Sweden organised by

Swedish Wood.

Offsite timber construction was at the epicentre of the housing construction industry in Sweden. This was due to a combination of a long-standing tradition of sawmill family-owned businesses who expanded into house manufacturing in the mid-20th century and are currently supported by organisations such as the *Swedish Wood Building Council*. In addition, an increasing number of municipalities have implemented ‘wood first’ policies, where due to the low environmental impact of wooden construction, it was preferred over other building systems. The municipality of Skeleftea implemented such a strategy in 2004 with an aim to drive change in the local construction industry towards reduced climate change impact, increased local business productivity and enhanced social value.

The housing market in Sweden consisted largely of a mixture of single-family dwellings and relatively large from a UK perspective apartment blocks with highly repetitive design, which are both well-suited to volumetric timber production. One manufacturer who provided a factory tour implemented a sophisticated Lean system to manage between 15 and 20 projects at a time with approximately 2,700 volumetric units. This was achieved by a design team of 30 people represented, 12 of whom structural engineers, by use of a customised lean tool and 15-minute daily morning meetings, where a combination of digital and analogue project management were techniques were used, as shown in **Figure 80**. In addition, the manufacturer worked with designs provided by external architects, which represented 80% of active projects at the time of visit.

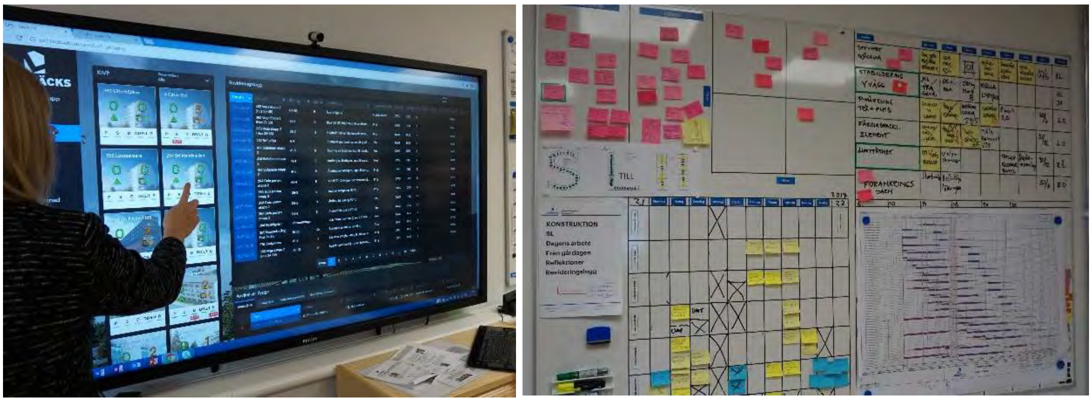


Figure 80. Lean tool developed by a volumetric timber manufacturer in Sweden. Author’s own images. June 2017.

The manufacturer used a combination of automated, mechanised and manual production methods on the shop floor. The process started with a framing station using timber components pre-cut to size by the supplier, followed by installation of the windows on the same framing station. Then the panels moved on to be sheeted with 2 layers of 15mm plasterboard, and a nailing bridge with two coils for streamlined tool reloading was used to cut openings and nail the plasterboard to the frame. Afterwards the panel proceeded to insulation and wiring on a bench, and to a plastering station with a drying buffer. From this point onwards, the modules were assembled using the prefabricated panelised components, and this operated on a takt-time system, where each unit was re-located to the next station every 55 minutes. The module assembly stages included only manual operations. Samples of the panel and module assembly stages are shown in **Figure 81**.

This manufacturer's strategy differed in two ways from the observed examples in the UK and the EU, the production staff were industrial workers instead of carpenters and they used smaller-sized modules with large openings to form bigger rooms, so that the modules could be transported two at a time on the back of a standard lorry.

Figure 81. Volumetric timber manufacturing process in Sweden: panelised and modules. Author's own images. June 2017.

Closed timber panels

In line with the emphasis on timber resourcing in Sweden, the observed closed timber panel manufacturer was part of a larger group, which covered all parts of the timber supply chain. This was their main marketing selling point, with emphasis on sustainability from sapling to the finished 'wooden house'. The group traced its history to 1964, when the first family sawmill was purchased, and remained a 3rd generation family-owned business at the time of visit (2017). Both these points differentiated the Swedish manufacturer from the practices observed in the UK and mainland Europe in the main survey of this chapter.

Environmental sustainability was incorporated in four main aspects of the timber group's business model. The integration of the entire timber supply chain enabled utilisation of all parts of the felled trees, which contributed to high timber materials resource-efficiency. In addition, the detailing of the closed timber houses was centred on energy-efficiency, including a triple layer of insulation and to Passivhaus standards. To bridge the gap between as-designed and as-built values, the company focused on quality assurance at each stage of the manufacturing process. Lastly, increasing numbers of councils were adopting woo-first policies, and this was creating increased demand for sustainable timber construction including buildings up to 7 storeys. Overall, environmental awareness was a significant driver in the Swedish construction industry and this was exemplified with the visited manufacturer.

The second significant characteristic of the Swedish timber frame house company was integration of digitization at each stage of the project: permission, design, production and construction. Most councils in Sweden accepted digital drawings, which enabled paperless communication for land development permission applications. The group owned 4,000 development rights at the time of visit, where they owned the land and the rights for residential construction. The interface with clients was also digital, and potential customers could use an on-line tool to design their own home in 3D with photorealistic visualisations. This was typically the first step potential customers took and afterwards contacted the manufacturer via phone. The manufacturer's design and manufacturing process was digitally integrated through a customised digital platform, which required maintenance and constant improvement with the development of new technology. The system allowed for high repetition of methods and processes, which lead to opportunities for improvement within an established workflow structure. The rigorous building methodology was based on 25 highly customisable building types, which were purchased from several architects. Interestingly, at first the external architects would design houses unsuitable for offsite panelised production, however with some explanation they quickly adapted DfMA principles to their designs. The customers visited the factory to see how they house was produced. An *OptiCad* saw was used to cut simple square components, and a *Hundegger* saw with 5-axis cutting and tools to create opening was used for the more complex components. Insulation and OSB was pre-cut as well, before proceeding the wall assembly lines.

The production took place across 5 industrial buildings in a space shared with the sawmill, which occupied several other buildings. The first building included material storage, 3 manual assembly benches, and vertical storage with rollers on rails. The second building had three cladding benches, and a panel assembly line with a framing station, shown in **Figure 82**, a nailing sheeting station and insulation fitting station, as well as windows and materials storage. The 3rd building contained benches for battens and cladding, and an 'opticut' saw which printed a stamp with a unique identification code on each component; the 5-axis saw and timber picking and sorting space. The 4th building had several manual assembly benches for production of custom designs and components using traditional carpentry skills, shown in **Figure 82**. The final 5th building included benches for manufacturing of roof components, and saws with some materials storage, and a despatch area for the finishes wall, floor and roof components. With this approach the company could produce up to 1,300 houses per year. However, driven by market demand and a construction skill gap, the group had recently established a new volumetric product. Parallels be drawn between this company and the findings from **4.2.4 Supply** and **5.2.3 Factory management** regarding the skills gap as a driver for increased offsite construction.

Figure 82. Closed timber panel production in Sweden: automated assembly line and manual benches. Author's own images. June 2017.

Laminated timber

In Sweden, a sawmill and CLT producer demonstrated their CLT manufacturing process. Similarly to other Swedish timber companies, this one started with a family sawmill started in 1929, and in the 1960s progressed towards glulam production, followed by bridge production in 1989, and finally introduction of CLT production in 2003 with a new purpose built facility in 2017. A unique market sector CLT was the construction of additional floors on top of existing concrete buildings, which was enabled by the lightweight and precision-engineered CLT construction. An example is shown in **Figure 83**, where a hotel owner commissioned three additional floors, which were increased to four half-way mid construction due to the high satisfaction of the client with the clean and sustainable building method, combined with the superior strength properties of CLT compared to timber frame.

The company produced CLT with either 3, 5 or 7 layers, with overall thickness between 60mm and 300mm, width up to 3m and length 16m. The first step was to check, sort and feed the timber sawn material. This was followed by lay out of timber planks according to the specified lamellae size and orientation, then these were transported via rollers to an adhesive and pressure application machine, for approximately 10 to 20 minutes per lamellae layer, as shown in **Figure 84**. Following this, the panels progressed to a CNC saw machine and despatch vertically using custom multi-purpose lifting clips to streamline the loading process.

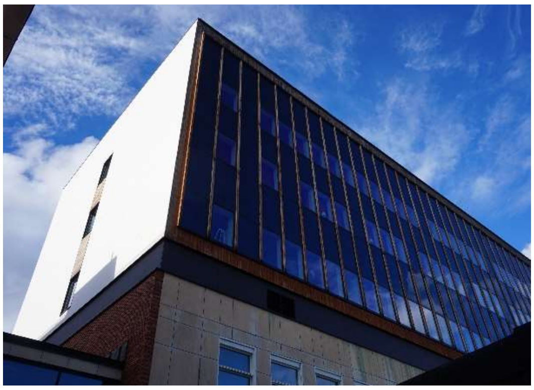


Figure 83. Hotel with lightweight CLT extension of four storeys. Author's own images. June 2017.

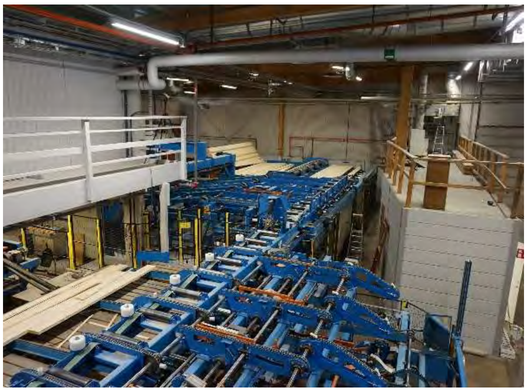


Figure 84. CLT manufacturing examples: sorting, and adhesive & pressure machine. Author's own images. June 2017.

5.5.3 International examples outcome

The international examples demonstrated some similarities with the main manufacturing survey, such as the utilisation of lightweight offsite timber construction to build on top of existing buildings, or in other words for retrofit of the existing building stock. In addition, several of the observed manufacturers utilised an automation and mechanisation extensively, with the addition of manual production methods only for a-typical components. On the another hand, key differences were identified as best practices which could be integrated within the UK, namely the construction of modular roofs in combination with panelised timber construction for reduction of risks when working at heights, and the implementation of lean techniques such as tract-time in volumetric timber production to optimise efficiency. A higher level of integration with the sawmilling industry was also observed in Sweden, which may be utilised to enhance offsite timber business models in the UK.

5.6 Manufacturing survey summary

Ten different offsite timber systems manufacturers were investigated in this qualitative survey to compare and contrast different offsite systems, project delivery and management strategies and to investigate variations in management strategies and their labour productivity (output per labour resource). The manufacturers varied in product type (panel, volumetric, stud frame, CLT, SIP), year of establishment (between 1986 and 2013) and number of production staff (between 10 and 200). The ten surveyed companies were from the UK and mainland Europe and therefore captured different economic and market contexts, which have common aspects with the global context of developing economies. The methodologies for data collection and analysis were rigorously designed with consideration of methods used in previous similar research studies in order to increase the validity of the findings. The sensitivity of labour productivity calculation alternatives was explored through a benchmarked comparative productivity analysis, and use of different units of measurement for factory outputs. Qualitative data analysis of manufacturing lines, automation, mechanisation, and lean implementation, and Design for Assembly + Disassembly (DfMA+D) was utilised to hypothesise their potential effects on productivity.

Overall the EUV and UKP manufacturers shared similar productivity rates of five 2-bedroom living unit-equivalent outputs per labour resource per annum. Yet EUV manufacturers' products had a higher offsite completion percentage, up to approximately 70% of materials and work, compared to approximately 25% for UKP. These results suggest that for the surveyed sample, similar productivity improvement potential exists despite the low opportunities for automation in the module assembly stages. In addition, the example of the EUV labour productivity results suggest that the UKV manufacturers have a large potential for growth in both market size and productivity in the UK. In addition, the craftsmanship and advanced technological applications of UKV manufacturers must not be underestimated through use of quantitative productivity comparisons.

Regarding market aspects, this research study demonstrated that a variety of building and market types were suitable for offsite timber construction, including residential, healthcare, education and commercial. However volumetric timber manufacturers who participated in this survey mainly operated in the residential market. All companies reported market fluctuations as a challenge to growth, particularly in the residential market. Therefore, it could be theorised that operation in a higher number of market segments could potentially increase the resilience of the offsite manufacturers to market fluctuations by providing alternative sources of work in times of residential demand decrease. This suggestion confirms previous research findings that market fluctuations can lead to significant cash flow issues in volumetric timber construction due to the high requirement for capital investment (Lawson, Ogden & Goodier, 2014). The results have also suggested that offsite timber construction is suitable for a wide spectrum of residential market segments, across the affordable, middle and high-end ranges.

European manufacturers tended to construct extensions to existing buildings using volumetric timber construction. This potential to retro-fit existing building fabric using offsite construction methods seems to be under-used in the UK considering that £1.9 billion of the UK construction output is due to refurbishment of existing housing (ONS, 2016a; Lawson, Ogden & Goodier, 2014). Moreover, the companies tailored each project to the specific brief to achieve the design intent specified by the client. These findings contradict the prevailing offsite association in the UK with 'prefab' monotonous post-war housing estates (Edge *et al.*, 2002; Pan & Sidwell, 2011). Instead, the results in this manufacturing survey showed that offsite timber products can have high quality and high energy-efficiency, therefore suggesting that 'offsite' should instead be associated with use of technology and efficiency improvement similar to the perception of offsite in Japan (Dalgarno, 2015).

Based on the results from this survey, volumetric timber construction seems to be more suitable for application of DfMA+D production principles, which could increase the whole-life cycle resource efficiency of buildings. In addition, there seemed to be engagement from offsite timber manufacturers in BIM implementation, mostly through use of digital design using 3D components with attached information linked to CAM equipment. There was one example of a UK volumetric manufacturer who had applied all 7 BIM dimensions. Overall there are great technological opportunities in advanced offsite timber manufacturing, which could in turn result in increased productivity. This study has highlighted a disconnection between designs received by the manufacturers and the offsite system to be used in construction, which ultimately resulted in some design re-work. The findings from this chapter may be summarised in five main observations shown in **Table 29**. The additional international explorations of offsite timber manufacturing industries in Sweden and Canada confirmed the similarities between the studies panelised and volumetric timber sample, and international standard practice.

Table 29. Finding summaries regarding the studied manufacturing sample.

N*	Finding summary	Chapter section reference
1	Logistics and site restrictions should be the first consideration for offsite projects, these will determine the options for offsite systems utilisation.	Within 5.2.1 - Size, weight and transport
2	In projects where energy performance is a main concern to the client, volumetric timber could be the more suitable system due to the higher opportunities for correct handling of insulation materials, workmanship of taping, resulting from implementation of Quality Management Systems (QMS).	Within 5.2.2 - Energy-efficiency
3	Wherever possible, collaborative contracts should be utilised, in which the design stage is informed by the subsequent manufacturing and construction activities with a view to optimise labour and material resources utilisation. This emphasises the need for early communication between the design, production and construction stakeholders.	Within 5.2.3 - Design management and production management
4	Volumetric timber systems application should not be limited to low-rise residential construction in the UK, there are additional opportunities for volumetric timber projects in the educational (especially nurseries), retail, office, healthcare and retro-fit markets.	Within 5.2.2 - Market opportunities
5	Where a project may be designed as repetition of identically sized modules (or variations of combinations with standard module sizes), the project will be more favourable to volumetric timber construction. The modules may be mass-customised with client-specific internal finishes and specifications.	Within 5.2.2 - Cost-efficiency and repetitive design elements

N= number

Chapter 6: Construction productivity pilot case study: low-rise residential

6.1 Methodology

The construction case studies used in this PhD study were interpreted and analysed using the Operation Research discipline, otherwise known as 'management science' (Eiselt & Sandblom, 2010). A combination of soft and hard dynamic operational research approaches were applied (Kunc, 2018). The constructability analysis involved the collection of data from various sources and the creation of a synthesised conceptual model for each of the main offsite construction project stages, and therefore a soft perspective was applied. This is characterised by the combination of multiple data sources (qualitative and quantitative) to provide a structured understanding of a problem. In the labour productivity analysis, the focus fell on the analysis of labour-hour productivity through a numerical model, and therefore a hard perspective was applied, which is characterised by a mathematical representation of reality (Kunc, 2018).

An exploratory comparative case study methodology was applied in this phase of the doctoral research (Yin, 2014). According to the comparative case study method, one instance is analysed in detail with reference to another instance, as opposed to the conventional high-level analysis of statistical data-sets. The case study approach was selected because of its suitability to understand in-depth causalities and other dependencies between different elements of a system. Due to the complexity of the research project , it was considered best practice to undertake a smaller scale *pilot* study prior to the implementation of a detailed case study (Schreiber, 2012). In the context of collaborative sustainable design, a *Modulares* process framework was developed and piloted within a previous doctoral research project completed in 2016, and this thesis proposes a similar method of a multi-factor productivity measure development through a pilot project (Zurlo, dos Guimarães & Nunes, 2016).

6.1.1 Sampling

The depth of data collection and analysis naturally imposed practical limitations on the quantity of case study projects which could be included. Knowledge on innovative and conventional offsite timber projects was utilised to create a *snowball* (or *chain-referral*) sampling strategy, where manufacturing survey participants provided details and introductions to team members of soon to be live offsite timber projects (Biernacki & Waldorf, 1981). This followed best practices identified by previous similar research in the area of health and safety in construction and energy simulation, where snowball sampling was applied to identify in-depth cases sampling following a larger-sample survey research phase (Lingard *et al.*, 2015; Rae, 2016). The sampling approach also followed best practice sampling strategies in comparative case studies, where one conventional case was paired with one innovative case, and the descriptive characteristics were targeted to be as similar as possible within the pairs, including client, time of construction and building typologies (Yin, 2014). Therefore, two of the identified projects were pioneering in nature, and their aim was to demonstrate the suitability of advanced offsite timber systems in the Scottish market: volumetric SIPs and CLT.

Through a further layer of snowball effect sampling, projects constructed using established Scottish offsite timber methods were sought, whose attributes were comparative to the innovative case studies. The Volumetric Timber Construction (VTC) case study was paired with an Open Timber Panel (OTP) case study, because the two projects were constructed for one and the same client, scheduled mainly during one and the same year (2016/partial 2017), and were nearly equal in number of plots and variety of building types. The other pair were also built for one and the same client, by the same main contractor, in the same city, and were constructed mainly the same year (2017), however with differences in plot numbers as explained in the following chapter.

The study was therefore separated into a pilot study comparing volumetric timber construction with open timber panel construction for low-rise residential projects, during which the productivity measurement methodology was developed. After this a second detailed comparative analysis of CLT and closed timber panel build systems for medium-rise residential projects was undertaken. The initials case studies investigated in-depth the offsite installation process, whereas the second detailed investigation covered the entire construction process from floor slab installation to hand-over and landscape completions

This chapter examines the first and pilot case study projects, the volumetric and open panel case studies, whose main attributes are summarised in **Table 30.** Selected images from the case studies are shown in **Figure 85.**

Table 30. Key comparative pilot case study project descriptors.

Factor	Volumetric	Open Panel
Construction start date	February 2016	January 2016
Construction end date	September 2017	May 2017
N plots (housing units) overall	48	49
N row houses	0	19
N detached houses	2	0
N semi-detached houses	30	4
N bungalows	0	4
N apartments	16	22
Cladding materials	Render, timber and stonework	Red brick
Site area (m^2)	8,485	n/a
Gross internal floor area (m^2)	n/a	4,050
Location	Rural town	Urban outskirts

Figure 85. VTC and OTP case studies overview.

6.1.2 Variables

The aim of the multi-factor productivity method was to understand the performance of offsite timber systems in the current UK economic context. To achieve this, the ten factors identified in the literature review were proposed as the foundation for the multi-factor productivity framework. An additional requirement was placed, that the WBS and the analysis method would account for differences in offsite completion in the factory. Components such as windows installation for example would normally be associated with the onsite activities of panelised systems, however some enhanced products may include glazing in the offsite completion of the closed panels. Of interest was the interface between the offsite and onsite activities, upon which the transfer of the build quality from the factory environment into the final product depended. To resolve these requirements a data sourcing and analysis plan was created for the comparative case studies, shown in **Table 31**. Because of the differences in data types and data availability, results from these case studies are not presented as a separate table, but each is discussed in the constructability analysis, productivity analysis and summary sections of this chapter.

Table 31. Inputs data sourcing and analysis plan, construction pilot case studies, based upon Table 2.

N	MFP variable	Data sources	Measures	Units
1	Time	Programme. Site visits. Contractor's progress reports.	Build duration. Time of delays. Reasons for delays.	Number of working days. Qualitative explanations.
2	Cost	Bill of Quantities. Bid documentation. Interviews with clients.	General price per unit of built area	£ (GBP)
3	Labour-hours	Contractor records of labour and equipment. Clerk of Works reports.	Labour productivity per task; and per home.	Number of labour-hours.
4	Waste	Monthly waste reports. Site skip materials observations.	Efficiency of materials use on site.	Tonnes per unit of built area. % recycled + type

Table 30 (contd.)				
N	**Factor**	**Data sources**	**Measures**	**Units**
5	Quality	Clerk of work reports. Progress reports. Hand-over documents. Air tightness and U-value tests.	Finished product quality. Energy efficiency as-built compared to as-designed.	Number of defects. Number labour-hours for rework.
6	Health & Safety	Procedure documents. Site visits with site manager.	Risks for site workers	Number of reported accidents. Examples of good practice observed.
7	Installation	Time study observations. Interviews. Procedure documents.	Processes N. Process maps. Time per process. Labour-hours and tools per process.	Hrs:min. Number of labour-hours. Number of tools.
8	Logistics	Route plans. Suppliers list. Deliveries schedules.	Lead-in times. Distance.	Number of working days. km.
9	Interface	Observations. Interviews.	Streamline of offsite-onsite between offsite production and onsite installation	Qualitative
10	General	Contract. Interviews. Project meetings.	Site-specific issues	Qualitative

6.1.3 Data collection and analysis methods

The data collection stage was based upon the variables and their respective data sources, outlined in the data plan. Therefore, a combination of qualitative, quantitative and visual data were utilised in the analysis and reporting (Mason, 1996; Bazeley, 2013; Lucko *et al.*, 2014). Participation in monthly site progress meetings and weekly access to site was arranged with the clients and the main contractors. The site walk-around dates were synchronised with important site activities: offsite systems installation, staged building inspections, and hand-over dates. In addition, informal interviews were conducted in the field with the offsite system installers, logistics operators, clerks of work, site managers, architects, engineers and external inspectors. The narrative data was combined with observations on site, collected in Excel spreadsheets and documented using photographs and videography for validation and further analysis. The type and number of data collection primary sources is outlined in **Table 32**.

Table 32. Primary data sources and their quantities

Case study	Volumetric timber	Open timber panel
Number of site visits	26	20
Number of interviews	19	13
Number of photographs	4,000+	2,000+
Number of videos	15+	10+

Overall the requested documents were made available to the researcher within a reasonable time frame. This was achieved through structured project progress meetings and regular site visits. Where documents containing the requested information were not available, it was found that interviews with the relevant sub-contractor or project stake-holder provided sufficient quantitative and qualitative data to enable the comparative analysis. The exact data availability for the two case studies can be found in **Appendix 6A - Data availability low-rise case studies**.

The audio-visual materials have been taken by the thesis author using an Olympus DSLR camera and a Manfrotto compact tripod, with intermittent use of a smartphone camera for capture of photography and video simultaneously using separate devices. An iPad mini 4 tablet was utilised in the BIM-based data collection trial phase of the fieldwork.

Initially hand-written field notes were taken in a research journal, accumulating to several volumes during the project. These were however discovered to be challenging and labour-intensive to analyse and therefore more structured data collection methods were tested, as outlined below. The resolution of this challenge was the creation of a novel multi-factor data collection analysis method was developed as outlined in **Appendix 6B - Data collection and analysis method development process.** The outcome of the development was the selection of Excel spreadsheets for data collection in combination with Project for construction works modelling and analysis of time and labour results. The incorporation of waste, health and safety and other data into a single tool remained as area for further work.

6.3 Productivity results and analysis

The following results and analysis are based upon a constructability analysis of offsite timber systems installation presented in **Appendix 6C.**

6.3.1 Time and labour results

As proposed OTP

The as proposed construction programme for the OTP case study is shown in **Figure 86**.

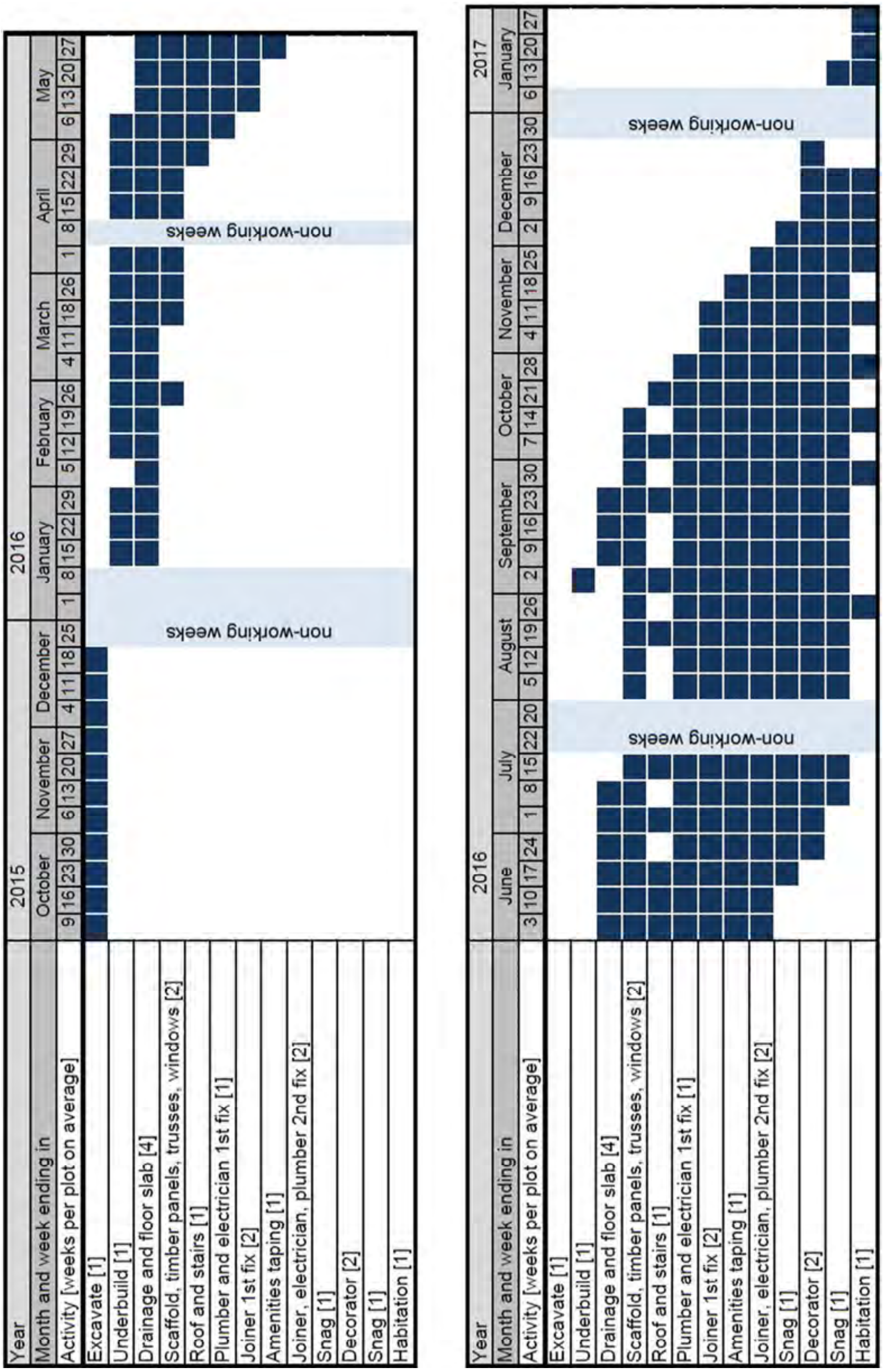


Figure 86. OTP case study as proposed construction. Adapted from contractor's programme.

Actual OTP

Overall it can be said that the OTP case study progressed smoothly with minor disruptions to the construction programme. The observed delays to the build programme are shown in **Table 33**, based on site visits combined with attendance at site progress meetings. The last hand-overs were completed on April 24th 2017, resulting in an overall programme delay of 12 weeks.

Table 33. OTP case study delays to construction programme.

Plots	Date	Delay (w. days)	Stakeholder	Description
28-31	24/08/16	10	Engineer	Steel structure added in garage due to discrepancy between architects and engineers drawing
32-49	24/08/16	10	Architect	Fans in wet zones above showers not specified correctly
11-12	07/12/16	5	Engineer	Drawings incorrect for garden wall construction details
28-31	07/12/16	35	Engineer	Driveways lifted because the house plot levels did not match door levels when constructed per drawings
24-27	15/02/17	10	Engineer	Issue with the ground floor slab, had to be deconstructed and re-constructed in the shared staircase area

As proposed VTC

The construction schedule provided at the start of construction works was modelled in MS Project using the WBS developed in this thesis to pilot this quantitative data analysis method, this was termed ‘as proposed’ and **Figure 87** to **Figure 89** show the ‘as proposed’ schedule at three different task levels.

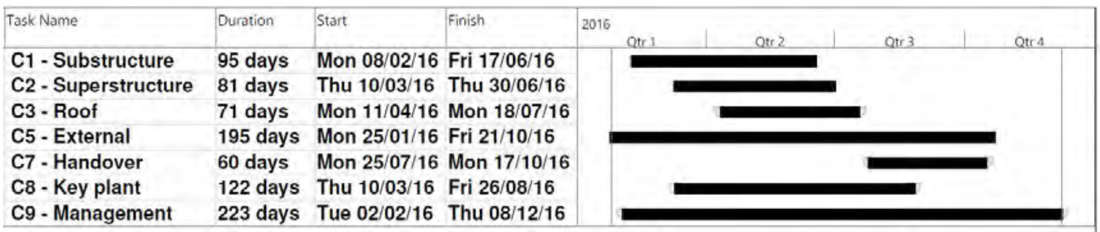
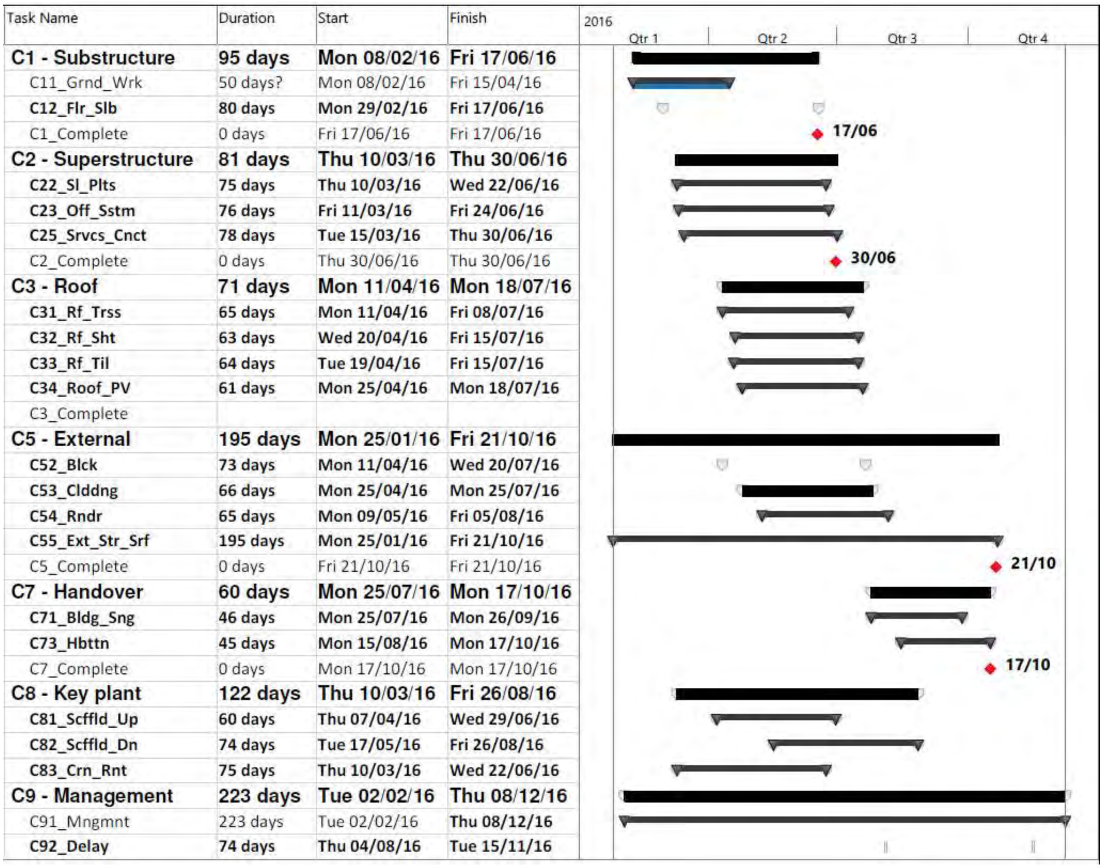
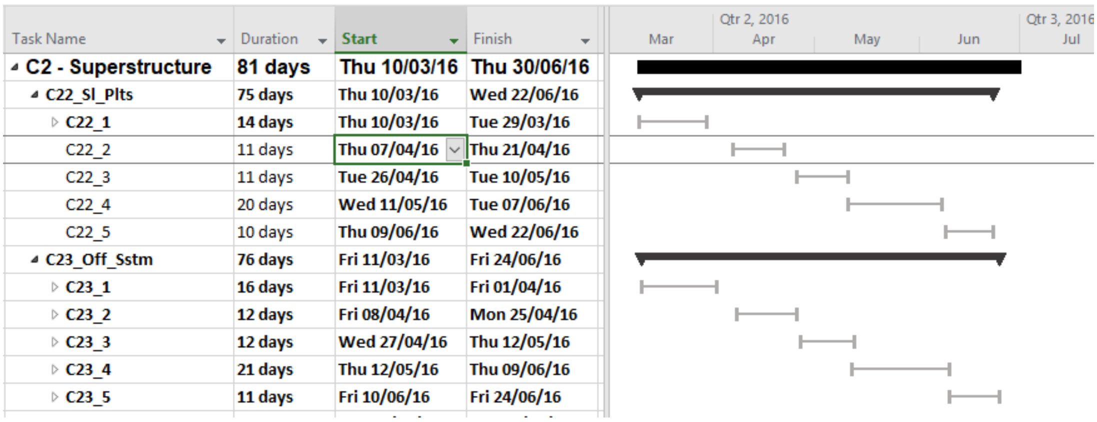


Figure 87. Summary task level data entry and reporting pilot: volumetric case study.



Task Name	Duration	Start	Finish
C1 - Substructure	95 days	Mon 08/02/16	Fri 17/06/16
C11_Grnd_Wrk	50 days?	Mon 08/02/16	Fri 15/04/16
C12_Flr_Slb	80 days	Mon 29/02/16	Fri 17/06/16
C1_Complete	0 days	Fri 17/06/16	Fri 17/06/16
C2 - Superstructure	81 days	Thu 10/03/16	Thu 30/06/16
C22_Sl_Plts	75 days	Thu 10/03/16	Wed 22/06/16
C23_Off_Sstm	76 days	Fri 11/03/16	Fri 24/06/16
C25_Srvcs_Cnct	78 days	Tue 15/03/16	Thu 30/06/16
C2_Complete	0 days	Thu 30/06/16	Thu 30/06/16
C3 - Roof	71 days	Mon 11/04/16	Mon 18/07/16
C31_Rf_Trss	65 days	Mon 11/04/16	Fri 08/07/16
C32_Rf_Sht	63 days	Wed 20/04/16	Fri 15/07/16
C33_Rf_Til	64 days	Tue 19/04/16	Fri 15/07/16
C34_Roof_PV	61 days	Mon 25/04/16	Mon 18/07/16
C3_Complete			
C5 - External	195 days	Mon 25/01/16	Fri 21/10/16
C52_Blck	73 days	Mon 11/04/16	Wed 20/07/16
C53_Clddng	66 days	Mon 25/04/16	Mon 25/07/16
C54_Rndr	65 days	Mon 09/05/16	Fri 05/08/16
C55_Ext_Str_Srf	195 days	Mon 25/01/16	Fri 21/10/16
C5_Complete	0 days	Fri 21/10/16	Fri 21/10/16
C7 - Handover	60 days	Mon 25/07/16	Mon 17/10/16
C71_Bldg_Sng	46 days	Mon 25/07/16	Mon 26/09/16
C73_Hbttn	45 days	Mon 15/08/16	Mon 17/10/16
C7_Complete	0 days	Mon 17/10/16	Mon 17/10/16
C8 - Key plant	122 days	Thu 10/03/16	Fri 26/08/16
C81_Scffld_Up	60 days	Thu 07/04/16	Wed 29/06/16
C82_Scffld_Dn	74 days	Tue 17/05/16	Fri 26/08/16
C83_Crn_Rnt	75 days	Thu 10/03/16	Wed 22/06/16
C9 - Management	223 days	Tue 02/02/16	Thu 08/12/16
C91_Mngmnt	223 days	Tue 02/02/16	Thu 08/12/16
C92_Delay	74 days	Thu 04/08/16	Tue 15/11/16

Figure 88. Task level data entry and reporting pilot: volumetric case study with minor bugs in C12 and C52.



Task Name	Duration	Start	Finish
C2 - Superstructure	81 days	Thu 10/03/16	Thu 30/06/16
C22_Sl_Plts	75 days	Thu 10/03/16	Wed 22/06/16
C22_1	14 days	Thu 10/03/16	Tue 29/03/16
C22_2	11 days	Thu 07/04/16	Thu 21/04/16
C22_3	11 days	Tue 26/04/16	Tue 10/05/16
C22_4	20 days	Wed 11/05/16	Tue 07/06/16
C22_5	10 days	Thu 09/06/16	Wed 22/06/16
C23_Off_Sstm	76 days	Fri 11/03/16	Fri 24/06/16
C23_1	16 days	Fri 11/03/16	Fri 01/04/16
C23_2	12 days	Fri 08/04/16	Mon 25/04/16
C23_3	12 days	Wed 27/04/16	Thu 12/05/16
C23_4	21 days	Thu 12/05/16	Thu 09/06/16
C23_5	11 days	Fri 10/06/16	Fri 24/06/16

Figure 89. Sub-task level data entry and reporting pilot: volumetric case study, where _1 to _5 identify construction project phases 1 to 5.

What was observed from the images, was that the results were much more helpful and instantly represented in the project management platform using Gantt charts at different levels, and that the aggregated categories were effortlessly exported by the software, compared to the labour-intensive manual spreadsheet data transformation. Therefore, the MS

Project-based method was selected for use in the detailed medium rise comparative case study and detailed investigation and labour calculation validation were left for further work using the second detailed phase of the comparative case studies.

Actual VTC

The focus of this research phase was on the volumetric units, whose onsite installation was termed *landing of the pods*, summarised in **Table 34**, where the significant difference between the first and the second phase delays becomes obvious. The table is supplemented by a plan sketch in **Figure 90**, which shows the actual landing dates per plot based on the collected photographic database of construction progress. Overall the final hand-overs were completed a year later than initially proposed, mainly due to a range of supply chain challenges.

Table 34. Volumetric units' installation (pod landing) dates in VTC case study.

	Planned		Actual		Delay (w. days)	
Phase (plots)	**Start**	**End**	**Start**	**End**	**Start**	**End**
Phase 1 (42-48)	26/04/2016	24/05/2016	27/04/2016	25/05/2016	1	1
Phase 2 (9-20)	24/05/2016	01/07/2016	22/06/2016	13/07/2016	17	8
Phase 3 (1-8)	06/07/2016	19/07/2016	20/07/2016	17/08/2016	9	20
Phase 4 (21-32)	25/07/2016	12/08/2016	31/08/2016	09/11/2016	26	62
Phase 5 (34-41)	29/08/2016	16/09/2016	26/10/2016	30/11/2016	41	53

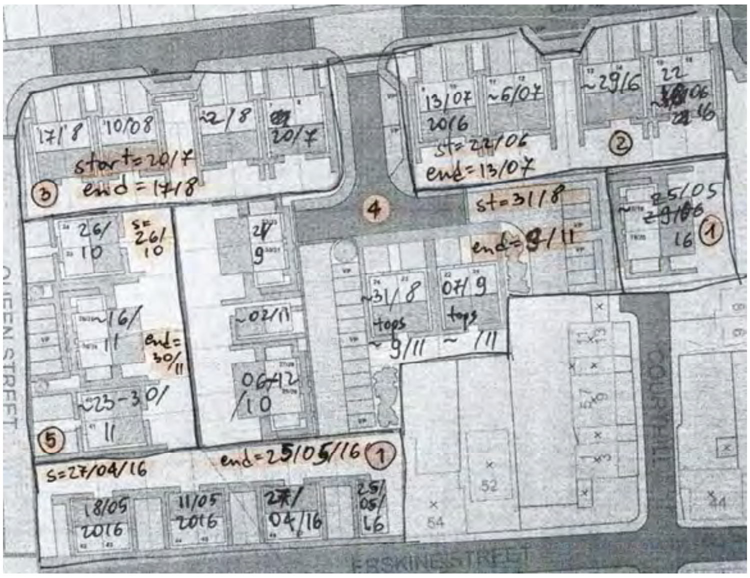


Figure 90. Hand-drawn sketch plan sketch of actual volumetric unit installation dates.

In the beginning the programme progressed according to plan and the first phase was landed and completed successfully in front of an audience of several stakeholders. However unfortunately as time progressed, the construction progress on this project was disrupted by major supply-chain issues with the volumetric units manufacturing, which resulted in progressively increasing delays to the proposed build programme. In the later stages of the works, the project work was ongoing without reference to a project programme due to the highly reactive nature of the works in context of rapidly changing issues. Examples of supply chain issues included windows sourcing and delivering, volumetric modules delivered uncompleted from site and significantly delayed mains networks connections. Admittedly, these factors could be said to be out of the immediate control of the project stakeholders.

From approximately the mid-point of the project onwards, an executive decision was made to transport the modules incomplete to site, therefore extensive finishing works were required in addition to the originally planned construction activities. Examples of these additional finishing activities were staircases construction (limiting access to upper floors to inspect modules), heat recovery unit installation, finishes and kitchen units. These however caused significant disruption and delay, as would be expected. Lastly, several complexities followed, including requests for loan extensions, announcement of bankruptcy by the volumetric manufacturer and legal action between two of the parties involved. Therefore, these project stages are excluded from the analysis of this thesis.

6.3.2 Multi-factor productivity analysis

Because of the significant delays with the VTC project in the later phases, as works progressed it became gradually clear that this site had too many specific issues to be generalizable to volumetric timber application across Scotland. In addition, there were gaps in the productivity data for the open timber panel case study due to the more limited availability of data from site visits. These gaps prohibited a rigorous quantitative labour productivity comparison. Yet the challenges experienced by the innovative volumetric case study on a project level compared to the smoother operations of the open panel case study project, provided important project management comparison data.

Time

The open timber panel case study outperformed the volumetric timber case study with respect to programmes time, 12 weeks delay compared to 52 weeks (1 year). The OTP case study handover dates were established long in advance of issuing the client, and in general the phased handover progressed smoothly and with minor delays compared to the original proposed milestones. In contrast, the volumetric timber case study had significant delays and required several changes to the handover milestones, which ultimately resulted in the client rejecting the phased handover option and having to communicate move-in date uncertainties to their prospective tenants.

Yet, the installation of the volumetric timber system on-site was rapid, which was a time-related advantage. The VTC modules were wind-and water-tight in the same day of their installation, whereas the OTP case study required 4 weeks to construct a wind- and water-tight structure following the offsite system installation. When compared to the literature review data, this difference is increasingly larger than that reported in **Figure 12** (Lawson, Ogden & Goodier, 2014).

Cost

Costs were not examined in detail due to the sensitivity of the topic, however overall the VTC case study was funded through Government grant and a loan from a bank, which supported initiatives with social sustainability, whereas the open timber panel case study was funded through traditional routes without additional external support. The VTC case study experienced cost pressures due to police escort payments and later stage module remediation works, however these were resolved in co-operation with the funders. Both projects delivered the final properties in accordance with the regulations on affordable housing for social landlords.

Labour-hours

Exact calculations of labour-hours were not possible with the pilot case study due to its explorative nature and the research challenges of collecting accurate labour resourcing data on a task level, including the labour-intensity of triangulating data from sing-in sheets, clerk of works reports and the photographic database.

Waste

Waste reports were available for the VTC case study site, however the OTP case study was part of a larger development and separate waste reports for the researched affordable housing site were not calculated. Because of the mixture of market and building types of the site, the trialled waste estimations for the OTP case study were judged to be a potentially inaccurate representation of the site's waste due to the large assumptions of splitting waste on average between all plots in the larger development.

The VTC case study waste was as shown in **Figure 91**, where the total waste generated from February 2016 to May 2017 (excluding 4 months of the final works) was a total of 214 tonnes, or only 2.5 tonnes per plot, of which approximately 73% were diverted from landfill. This is estimated to be relatively low waste generation, however accurate evaluations would require complete project waste data, whose analysis findings could have been benchmarked against LCA studies on volumetric construction.

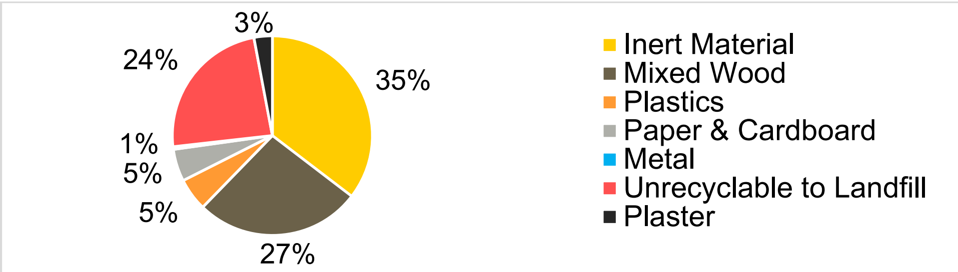


Figure 91. Waste type distribution on average for VTC case study, 02/2016 to 05/2017.

Quality and energy

The higher build quality of the open panel system could be speculated due to reduced need for rework onsite compared to the example of the volumetric timber case study, where acoustic, MEP and air tightness remediation works were needed. This difference can be said to be very anecdotal however, due to the volumetric sub-contractor announcing bankruptcy approximately two-thirds through the project and supply chain issues. On average, the OTP case study had 23 snagging items per plot (minor) issues (total approximately 1,140 items), whereas the VTC case study had to postpone several pre-snagging inspections due to too many snagging items on trial plot inspections. With this said, the volumetric timber case study did achieve Scottish Gold Level standards, including strict standards for air tightness, insulation, water pressure and acoustics. The OTP case study in comparison was designed to Silver standard.

Health & Safety

See *Constructability* sections. A visualisation of the highest-risk observed activity is shown in **Figure 92**, where a red mark-up indicates potential danger to the hand of the operative while adjusting the module connections alignment. Following a near-miss incident the main contractor required the use of timber spacers and thus the risk was promptly mitigated.

Figure 92. High-risk activity near-miss installation scenario instance marked in red.

Installation process

See **Appendix 6C.**

Logistics

The VTC case study had more challenging logistics, including transportation of volumetric units a distance of approximately 340 miles by road across three countries in the UK, Scotland, England and Wales, whose transportation regulations had differences in police escort requirements. These differences resulted in delays due to loads waiting for escort vehicles and restrictions on times during which load transport was allowed. In addition, in the VTC case study there were supply chain issues with the windows, which could be sourced only from one manufacturer due to their specific performance criteria.

In both case studies a visual management system was used by the site managers, in the form of a whiteboard or other full-wall table with information on deliveries, as the examples shown in **Figure 93**. In the OTP case study this was extensive and included all scheduled deliveries, whereas in the VTC case study the day's activities and deliveries were displayed.

Figure 93. Example visual management boards used in the VTC and OTP case studies.

Interface offsite – onsite

In the first phase of the VTC case study the interface between offsite and onsite activities was relatively smooth, with efficient module installation on time, albeit without a rigorously scheduled completions sequence. In the later phases, where incomplete modules were delivered the interface was more challenging and extensive remediation activities were undertaken, nearly diminishing the theoretical benefits of guaranteed product quality. In contracts, in the OTP case study, the offsite system installation was part of an established structured activities sequence, familiar to the trades and overseen by the site managers.

Digitisation

The digital technologies used on both case study project were standard practice printed site drawings produced in CAD software were used for reference during the site works. In interviews the architects and engineers discussed the opportunities, which BIM could bring to future volumetric timber projects, with emphasis on component-based modelling and automated quantity take-off for windows, doors and other schedules.

General

The VTC houses look like 'normal houses' in the eyes of the tenants, which can be an indication that the stigma to 'prefab' from the post-war construction phases has been reduced through this project's high-technology energy system and varied site-specific architecture.

The VTC case study had two main contractors, which resulted in increased adversity of the relationship between the offsite manufacturing company and the local contractor who was responsible for the ground-works, and external finishes. In addition, the internal works of the modules were the responsibility of the offsite manufacturing company after the module landing, whereas the exterior elements (cladding, roof, landscaping, etc.) were responsibility of the general contractor. Subsequently, two separate hand-overs were required, for the external and internal fabric of the building, which was a complication. The bi-main contractual relationship was the single biggest issue on the project that would be changed in future projects, identified during a focus group project stakeholder meeting and with one on one informal interviews with key stakeholders (clients, developers, architect).

6.4 VTC and OTP case studies summary

A multi-factor labour productivity method was developed and piloted using two comparative case studies, volumetric timber and open timber panels. The results and analysis suggested that although the VTC case study should have outperformed the OTP case study in terms of time on-site and labour productivity, the better-known open panels system had better multi-factor productivity credentials. The constructability of the two systems may be used to explain this performance difference. Specifically, the completions of the VTC system were initially estimated at three working days, however as the work progressed the delays became several weeks, exasperated by the decision to deliver the modules incomplete from the factory. Due to several supply chain complexities, this was the only viable option to completing the project and understandably the final completions were significantly delayed as a consequence. Some examples included late windows deliveries, police escorting issues, need for acoustic remediation and the bankruptcy of the modular manufacturer. The environmental sustainability of the VTC case study however outperformed the OPT case study, by achieved Gold versus Silver accreditation according to the Scottish Building Regulations.

Therefore, it could be summarised that the innovative nature of the VTC case study experienced several pressures and challenges, which could serve as lessons for future volumetric timber construction projects.

Among the piloted data collection and analysis methods, the use of Excel spreadsheets in combination with MS Project were selected for utilisation in the following pair of case studies, where the complete construction programme was studies in detail.

Chapter 7: Construction productivity detailed comparative case study: mid-rise residential

7.1 Introduction

The constructability and labour productivity data analysis methods outlined in the previous chapter were applied to the second set of case studies, involving medium-rise residential construction utilising two panelised systems: Cross Laminated Timber (CLT) and Closed Timber Panel (CTP).

A combination of qualitative, quantitative and visual data was used in the analysis and reporting (Mason, 1996; Bazeley, 2013; Lucko *et al.*, 2014). Interviews were conducted with CLT and closed timber panel engineers, erectors, site managers and workers. The narrative data was combined with observations on site, collected in Excel spreadsheets and documented using photographs and videography for validation and further analysis. Quantitative data on labour hours was gathered from sign in sheets in the CLT-panels project combined with information from site visits, interviews with the site manager and the project's work programmes. Labour data was gathered from the CTP project through interviews with the site manager, site visits and work programmes review. Sign-in sheet data analysis was not possible at the CTP project, because this study focused on only one block within a larger regeneration construction project and sign-in sheets were used for the construction site as a whole. The type and number of collected data is outlined in **Table 35**.

Table 35. Data collection descriptors

	Cross-laminated timber (CLT) panels case study	Closed timber panels (CTP) case study
Number of site visits	21	20
Number of interviews	25	18
Number of photographs	1,306	1,580
Number of videos	54	43

Overall the requested documents were made available to the researcher within a reasonable time frame. This was achieved through structured project progress meetings and regular site visits. Where documents containing the requested information were not available, it was found that interviews with the relevant sub-contractor or project stake-holder provided sufficient quantitative and qualitative data to enable the comparative analysis. The exact data availability for the two case studies can be found in **Appendix 7A**. The audio-visual material has been taken using a Sony Alfa5000 camera and a Manfrotto compact tripod, unless otherwise identified in the captions. A standard data collection form was developed for use in the project analysis, based on the data collection form used in the low-rise case studies, and was supplemented with audio-visual material. The collected data was entered as soon as possible after the site visit into an Excel spreadsheet with a separate tab for entry of each variable with predetermined properties, and this spreadsheet was used in combination with MS Project for analysis in these detailed construction case studies.

7.2 Case study buildings

Previously in Scotland CLT had not been implemented in tall buildings until the construction of the 7-storey building in Glasgow described in this case study. This innovative case study was paired with a comparative CTP project, also in Glasgow. Both projects shared a main contractor and client, other factors are described in **Table 36**.

Table 36: CLT and CTP projects descriptors.

Factor	CLT panels case study	CTP case study
Levels	7	4
N accommodation units	42	24
Accommodation type	1-bed apartment x 2 2-bed accessible apartment x 4 2-bed apartment x 33 3-bed apartment x 3	2-bed apartment x 24
Offsite system	CLT	Closed panel
Secondary structure	Steel	Concrete block
Section 7 Sustainability	Silver	Silver
Cladding	Brick slips	Brick
Floor slab	Poured	Pre-fabricated
Building type	Apartment block	Apartment block within larger development of 206 apartments across 5 blocks
Location	Urban periphery	Urban central
Housing type	Affordable Mid-market Let	Affordable Mid-market Let
Construction start	Oct 2016	Mar 2016 (foundations) Feb 2017 (excavation)
Construction end	March 2018	Feb 2018

7.2.1 CLT panels case study

The CLT project used in this research project was a 7-storey apartment building block shown in **Figure 94**. It was the tallest CLT building in Scotland and was oriented along the north-south axis with a T shape. There are 42 apartments in the building, two one-bedroom, four two-bedroom accessible, 33x two-bedroom and 3x 3-bedroom apartments and are aimed at mid-market affordable rent. The cladding materials used are brick-slips and panels in earthy colours. In terms of sustainability, it was designed and constructed to the Silver sustainability standard from Section 7 of the Scottish Building Regulations. The typical layout maximised the use of CLT, and used steel columns and beams for structural reinforcement in door lintels and in-between floors with different apartments.

Figure 94. CLT project: overview, typical layout and during construction.

7.2.2 CTP case study

The CTP project was typical for high-density mid-rise residential construction in Glasgow and it represented a part of the last construction phase in the area's regeneration, and captured one building block with 24 out of 206 plots (or living units, or homes). Overall five building blocks were constructed with different proportions of private and affordable housing. The development focused on place-making with landscaped areas between residential blocks to create a sense of community and a direct connection with the city-centre office areas, also framing views of historic iconic buildings in the urban city scape. A visualisation of the project as-built and a typical floor layout are shown in **Figure 95**. The building was constructed with blockwork for the common areas and closed timber panels for the apartments, with four levels of six apartments each.

Figure 95. CTP project: overview, typical layout and during construction.

7.3 Productivity results

The following labour productivity results and analysis are based on the data found in **Appendix 7B – CLT and CTP case studies constructability**, where the step-by-step CTP and CLT construction processes were outlined with labour and equipment usage, and were compared to identify similarities and differences in each of the major project management stages. The full description of each task and labour code are also depicted in Appendix 7B.

7.3.1 CLT case study productivity results

CLT as planned programme

Firstly, the CLT project was modelled as originally programmed by the main contractor prior to work starting onsite. **Figure 96** shows the original programme, transformed for comparative productivity analysis, where the grey rows (C44_Insltn, C83_Crn_Rnt, C84_Lift_Instll and C91_Mngmnt) indicate tasks, which according to the original programme were included within other tasks, but have been modelled separately for the comparative analysis. Milestones in red indicate the target completion dates for each of the task groups (C1-level).

Figure 96. CLT as planned C11-level coded programme.

CLT actual programme

The actual programme was modelled based on interviews with the site manager, engineers on site and photographs and videos taken during regular site visits.

When presenting the actual CLT programme results, the original construction end date of 23/10/2017 was used as a benchmark for the construction progress. **Figure 97** presents a task group (C1-level) percentage of work completion on this benchmark date. Overall task groups C1 to C4 were 100% completed, which means that the building was wind and water-tight, however tasks groups from C5 to C9 varied from 0% to 76% complete. Task group C5 – External therefore had the lowest percentage of work completed at this point in time.

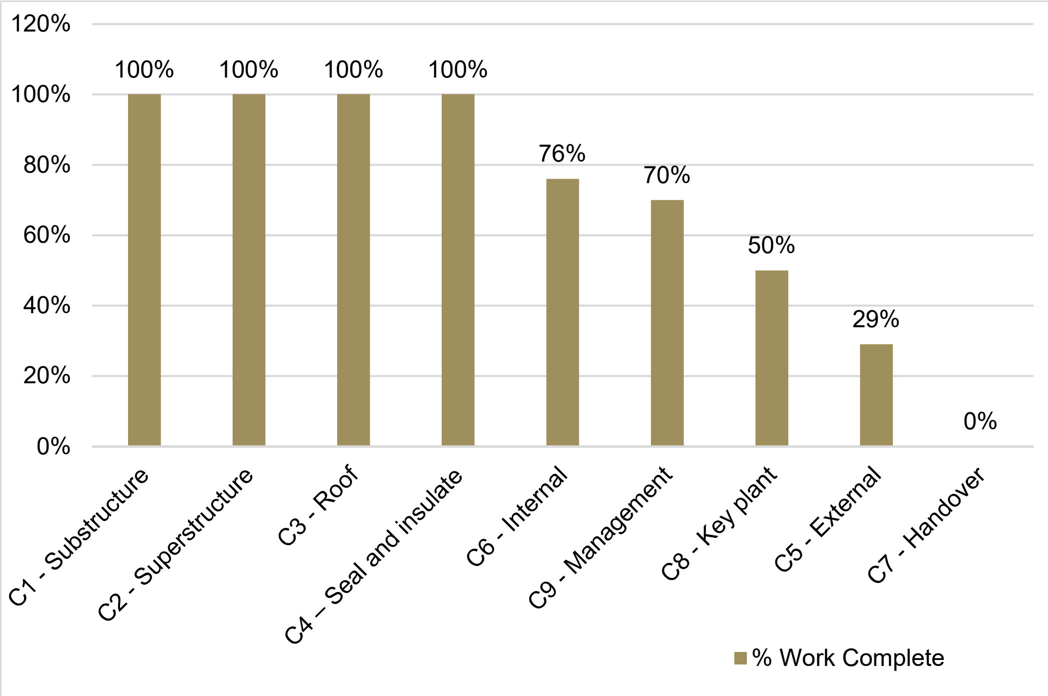


Figure 97. CLT percent work complete per task, actual values on 23/10/2017.

The actual CLT programme is shown in the Gantt chart in **Figure 98**, where the red vertical line indicates the originally scheduled practical completion date. From the Gantt chart it can be observed that on the original end date, approximately two-thirds of the cladding installation was still pending, the internal works for the 3rd Fix were pending, the handover had not started and the scaffold still had to be dropped.

This observation corresponded to the tasks with the highest remaining labour-hours, highlighted in red within **Table 37**. The resources with the highest labour-hours for the project were joiners and cladders, at eight and six times more than decorators, who utilised the third-most labour-hours, as shown in **Figure 99**.

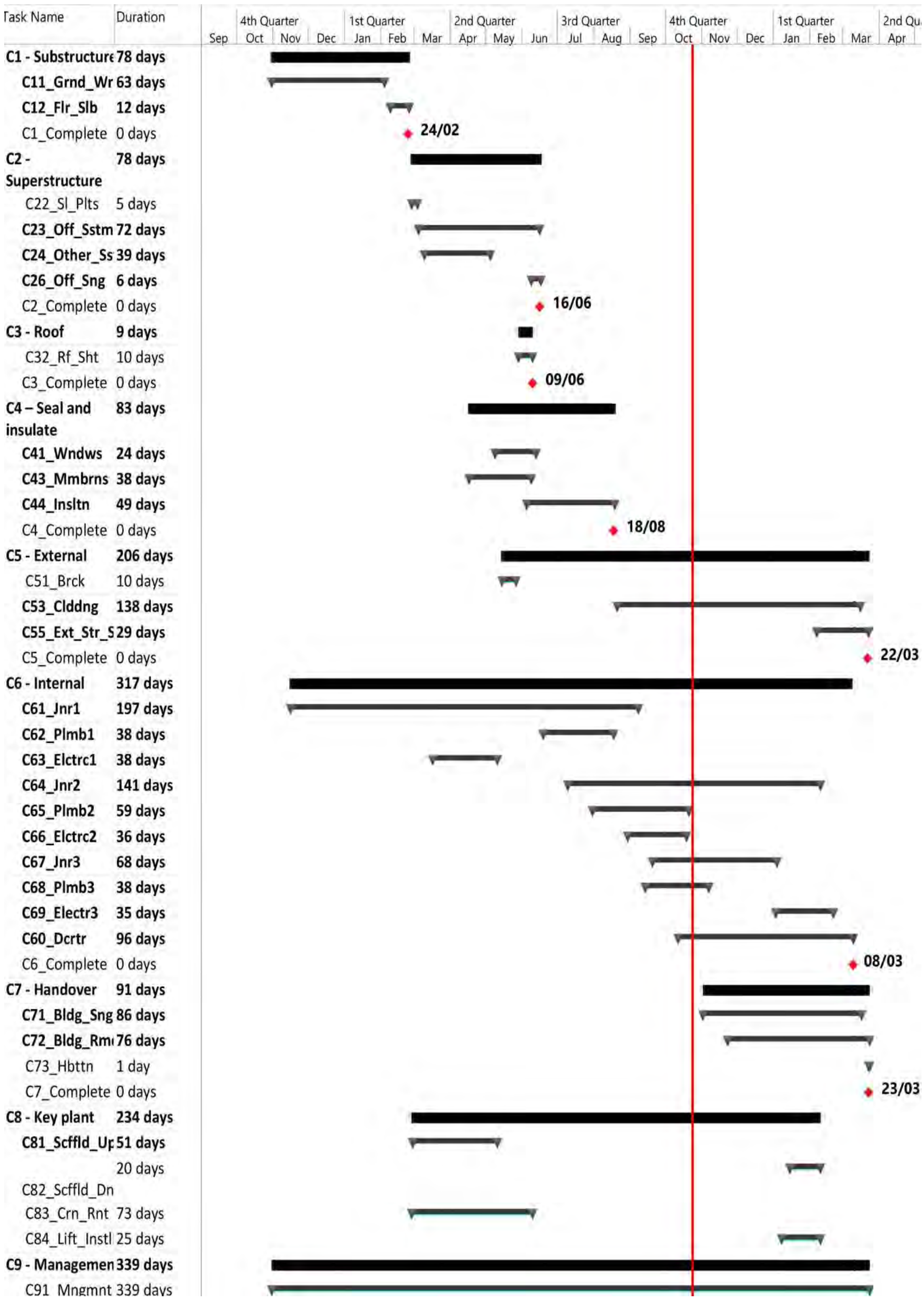


Figure 98. Actual CLT Gantt Chart with original completion date marked using a red line.

Table 37: Actual CLT work and remaining work for 23/10/2017 & total work and duration per task				
Name	**Actual Work**	**Remaining Work**	**Work**	**Duration**
C11_Grnd_Wrk	2,809 hrs	0 hrs	2,809 hrs	63
C12_Flr_Slb	376 hrs	0 hrs	376 hrs	12
C22_Sl_Plts	240 hrs	0 hrs	240 hrs	5
C23_Off_Sstm	3,493 hrs	0 hrs	3,493 hrs	72
C24_Other_Sstm	0 hrs	0 hrs	0 hrs	39
C26_Off_Sng	256 hrs	0 hrs	256 hrs	6
C32_Rf_Sht	237 hrs	0 hrs	237 hrs	10
C41_Wndws	203 hrs	0 hrs	203 hrs	24
C43_Mmbrns	330 hrs	0 hrs	330 hrs	38
C44_Insltn	6,908 hrs	0 hrs	6,908 hrs	49
C51_Brck	525 hrs	0 hrs	525 hrs	10
C53_Clddng	8,287 hrs	19,854.5 hrs	28,142 hrs	138
C55_Ext_Str_Srf	0 hrs	1,482 hrs	1,482 hrs	29
C61_Jnr1	17,108 hrs	0 hrs	17,108 hrs	197
C62_Plmb1	1,470 hrs	0 hrs	1,470 hrs	38
C63_Elctrc1	1,079 hrs	0 hrs	1,079 hrs	38
C64_Jnr2	14,842 hrs	0 hrs	14,842 hrs	141
C65_Plmb2	3,595 hrs	0 hrs	3,595 hrs	59
C66_Elctrc2	687 hrs	0 hrs	687 hrs	36
C67_Jnr3	2,187 hrs	3,565 hrs	5,752 hrs	68
C68_Plmb3	272 hrs	96 hrs	368 hrs	38
C69_Electr3	0 hrs	4,026 hrs	368 hrs	35
C60_Dcrtr	159 hrs	5,689 hrs	4,026 hrs	96
C71_Bldg_Sng	0 hrs	3,824 hrs	3,824 hrs	86
C72_Bldg_Rmd	0 hrs	4,777.5 hrs	4,778 hrs	76
C73_Hbttn	0 hrs	24 hrs	24 hrs	1
C81_Scffld_Up	209 hrs	0 hrs	209 hrs	51
C82_Scffld_Dn	0 hrs	367 hrs	367 hrs	20
C83_Crn_Rnt	544 hrs	0 hrs	544 hrs	73
C84_Lift_Instll	0 hrs	400 hrs	400 hrs	25
C91_Mngmnt	2,312 hrs	968 hrs	3248 hrs	339

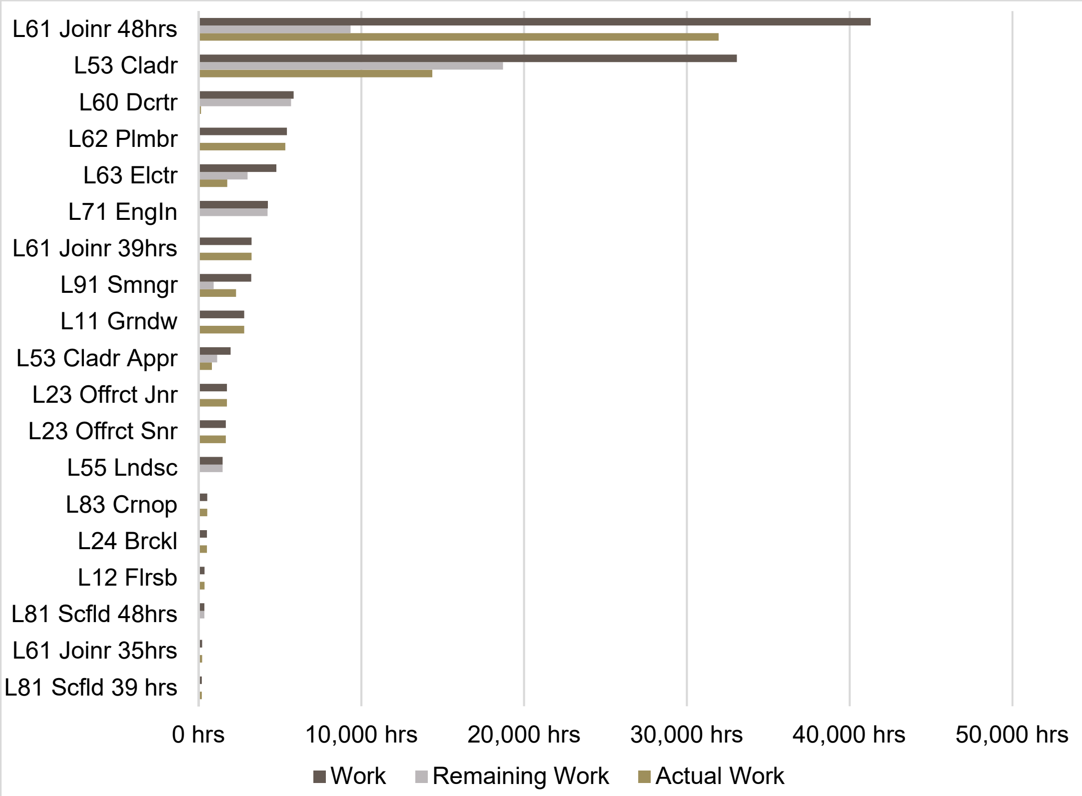


Figure 99. CLT Actual work and remaining work for 23/10/2017, and total work per resource.

7.3.2 CTP case study productivity results

Because the CTP project did not have an original build programme, only the actual programme was modelled, and actual resources were assigned to each sub-task. The resulting comparative Gantt chart is shown in **Figure 100**. The start date, duration and labour-hours per task are presented in **Table 38**.

Through observation of the Gantt chart and the table, it can be seen that the offsite system installation was actually a marginal part of the programme, with approximately 770 labour-hours excluding the sole plates and approximately 1,000 labour-hours including the sole plates. This is highlighted within **Table 38**. In contrast, the tasks with the longest duration and the highest number of labour-hours were the joiner 1st fix, decoration, the joiner 2nd fix, the external surfaces and the brickwork, in order from the highest to lower labour-hour values.

These extreme differences are reflected in the work (labour-hours) per resource shown in **Figure 101**. Within the bar chart the joiners, labourers, bricklayers and landscapers are indicated as the resources with the highest labour-hours, up to 600% more compared to the offsite erectors. In comparison, plumbers, electricians and scaffolders have medium labour-hours, whereas resources such as ground-works, floor slab installers and roof erectors have low labour-hours.

Task Name	Duration	Start
C1 - Substructure	41 days	16/02/17
C11_Grnd_Wrk	22 days	16/02/17
C12_Flr_Slb	2 days	12/04/17
C1_Complete	0 days	13/04/17
C2 - Superstructure	60 days	18/04/17
C22_Sl_Plts	4 days	18/04/17
C23_Off_Sstm	12 days	24/04/17
C24_Other_Sstm	16 days	19/06/17
C26_Off_Sng	5 days	17/05/17
C2_Complete	0 days	12/07/17
C3 - Roof	28 days	11/07/17
C31_Rf_Trss	5 days	11/07/17
C33_Rf_Til	3 days	31/07/17
C34_Roof_PV	5.5 days	19/07/17
C3_Complete	0 days	19/08/17
C4 – Seal and insulat	8 days	11/09/17
C42_Drs	8 days	11/09/17
C4_Complete	0 days	21/09/17
C5 - External	185 days	22/05/17
C51_Brck	29 days	22/05/17
C53_Clddng	25 days	24/07/17
C55_Ext_Str_Srf	67 days	06/11/17
C5_Complete	0 days	09/02/18
C6 - Internal	83 days	24/07/17
C61_Jnr1	32 days	24/07/17
C62_Plmb1	17 days	08/08/17
C63_Elctrc1	20 days	14/08/17
C64_Jnr2	32 days	21/08/17
C65_Plmb2	17 days	28/08/17
C66_Elctrc2	17 days	18/09/17
C67_Jnr3	17 days	23/10/17
C68_Elctrc3	17 days	09/10/17
C69_Plmb3	17 days	02/10/17
C60_Dcrtr	40 days	18/09/17
C6_Complete	0 days	17/11/17
C7 - Handover	63 days	06/11/17
C71_Bldg_Sng	39 days	06/11/17
C72_Bldg_Rmd	39 days	13/11/17
C73_Hbttn	15 days	23/01/18
C7_Complete	0 days	12/02/18
C8 - Key plant	162 days	20/03/17
C81_Scffld_Up	18 days	10/04/17
C82_Scffld_Dn	11 days	23/10/17
C83_Crn_Rnt	79 days	20/03/17
C9 - Management	247 days	16/02/17
C91_Mngmnt	247 days	16/02/17

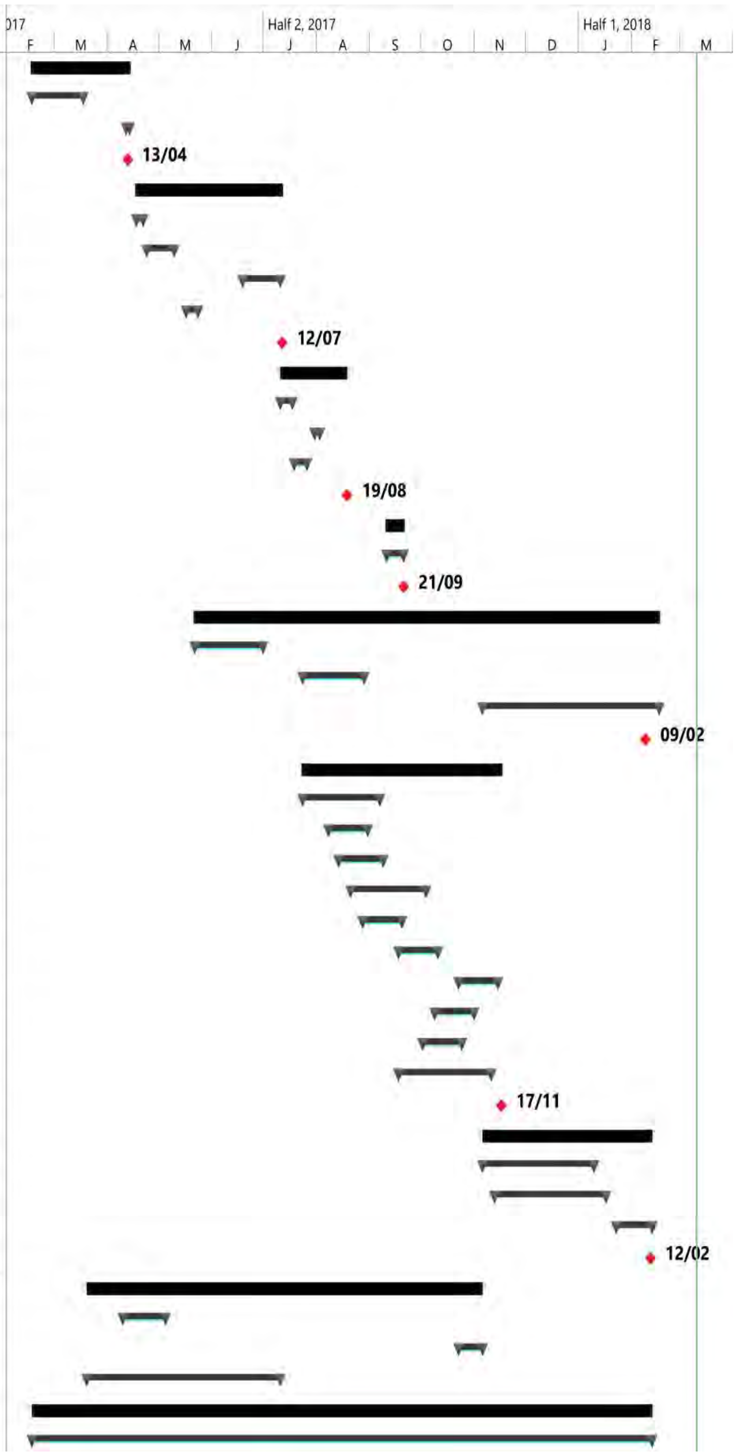


Figure 100. CTP project actual Gantt chart.

Table 38. CTP project: start, duration and work			
Name	**Start (date)**	**Duration (working days)**	**Work (labour-hours)**
C11_Grnd_Wrk	16/02/17	22 days	464 hrs
C12_Flr_Slb	12/04/17	2 days	64 hrs
C22_Sl_Plts	18/04/17	4 days	192 hrs
C23_Off_Sstm	24/04/17	12 days	768 hrs
C24_Other_Sstm	19/06/17	16 days	1,112 hrs
C26_Off_Sng	17/05/17	5 days	20 hrs
C31_Rf_Trss	11/07/17	5 days	272 hrs
C33_Rf_Til	31/07/17	3 days	96 hrs
C34_Roof_PV	19/07/17	5.5 days	132 hrs
C42_Drs	11/09/17	8 days	144 hrs
C51_Brck	22/05/17	29 days	2,904 hrs
C53_Clddng	24/07/17	25 days	720 hrs
C55_Ext_Str_Srf	06/11/17	67 days	3,572 hrs
C61_Jnr1	24/07/17	32 days	7,544 hrs
C62_Plmb1	08/08/17	17 days	960 hrs
C63_Elctrc1	14/08/17	20 days	1,032 hrs
C64_Jnr2	21/08/17	32 days	3,744 hrs
C65_Plmb2	28/08/17	17 days	480 hrs
C66_Elctrc2	18/09/17	17 days	480 hrs
C67_Jnr3	23/10/17	17 days	160 hrs
C68_Elctrc3	09/10/17	17 days	480 hrs
C69_Plmb3	02/10/17	17 days	480 hrs
C60_Dcrtr	18/09/17	40 days	3,976 hrs
C6_Complete	17/11/17	0 days	0 hrs
C71_Bldg_Sng	06/11/17	39 days	640 hrs
C72_Bldg_Rmd	13/11/17	39 days	1,008 hrs
C73_Hbttn	23/01/18	15 days	224 hrs
C7_Complete	12/02/18	0 days	0 hrs
C81_Scffld_Up	10/04/17	18 days	880 hrs
C82_Scffld_Dn	23/10/17	11 days	784 hrs
C83_Crn_Rnt	20/03/17	79 days	904 hrs
C91_Mngmnt	16/02/17	247 days	2,368 hrs

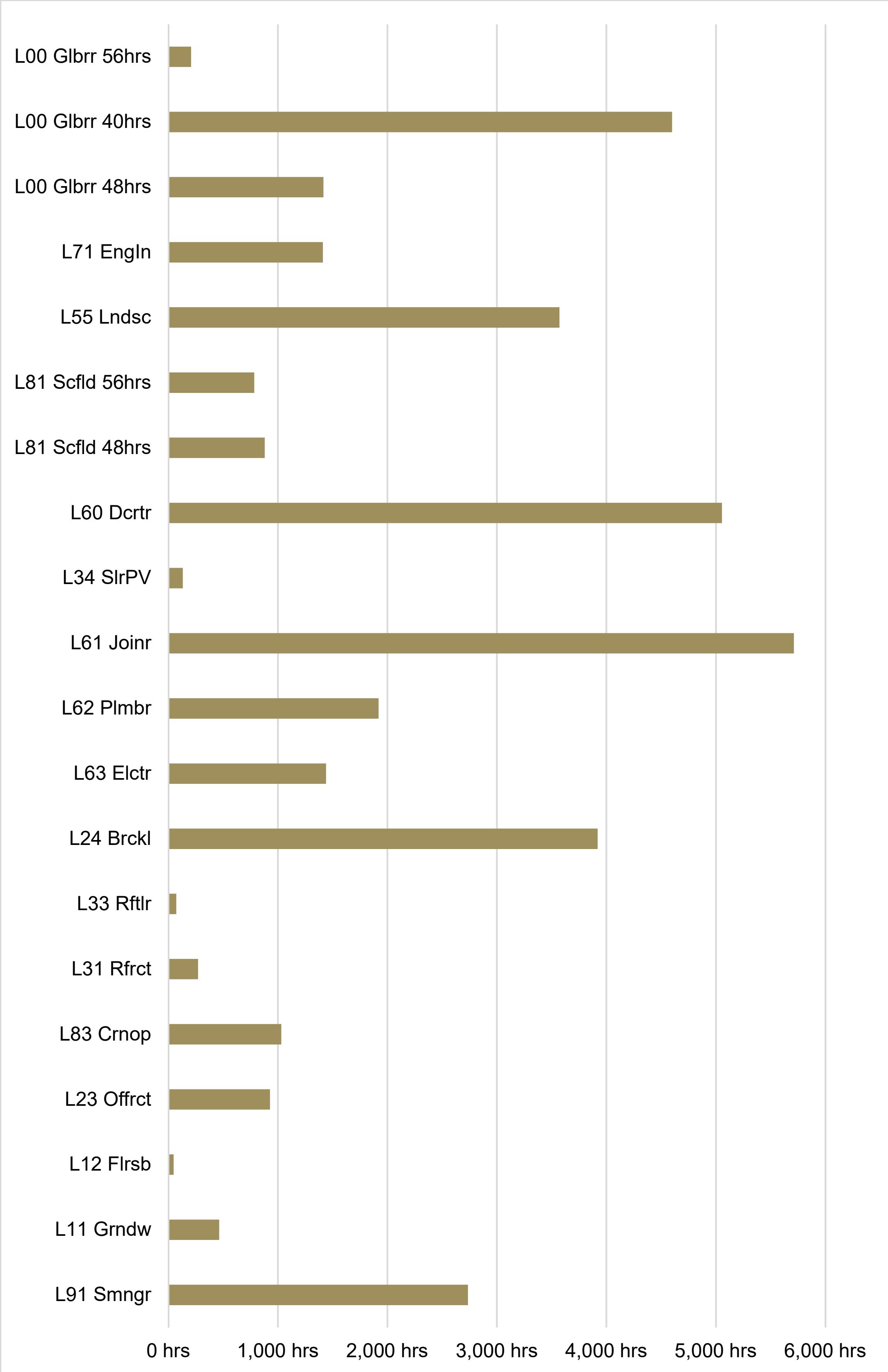


Figure 101. Closed timber panel project work (labour-hours) per resource.

7.4 Productivity analysis

7.4.1 Programme time CLT: planned versus actual

The results for the original compared to the actual CLT programme provide an insight into the aspects of a build that can lead to project overruns.

From the task group (C1-level) duration comparison shown in **Table 39** and **Figure 102**, it can be observed that the tasks with the largest increases in duration compared to the original programme, were the internal works with an approximately 200 working day overrun. Moreover, the handover phase took longer than planned to complete, which could be an indication that more re-work had to be done than expected.

Table 39. CLT task group duration comparison

Task Name	Duration (working days)		
	CLT Planned	CLT Actual	Difference
C1 - Substructure	78	78	0
C2 - Superstructure	68	78	-10
C3 - Roof	14	9	5
C4 – Seal and insulate	83	83	0
C5 - External	205	206	-1
C6 - Internal	108	317	-209
C7 - Handover	25	91	-66
C8 - Key plant	132	234	-102
C9 - Management	236	339	-103

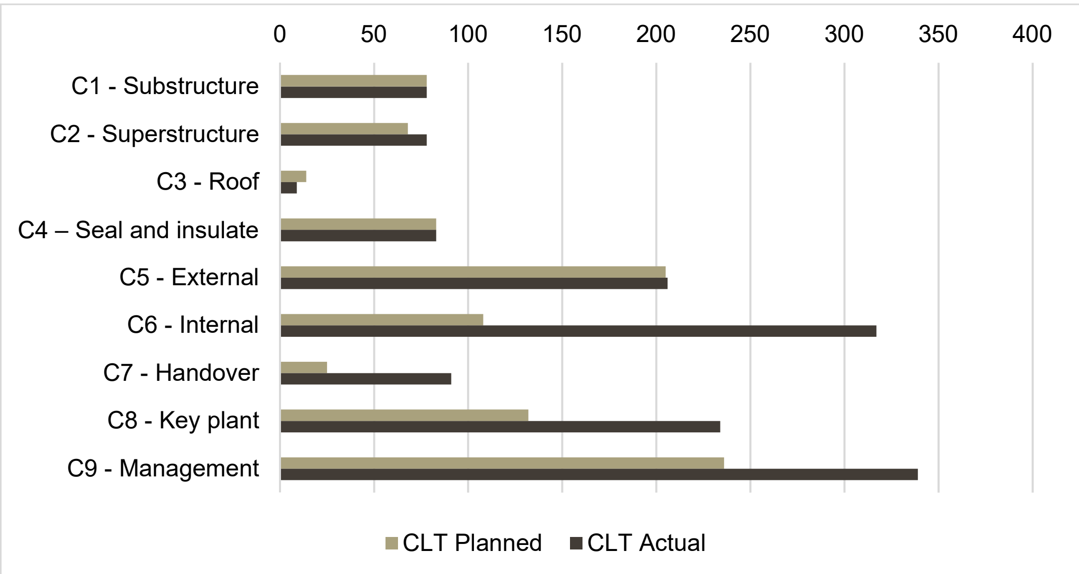


Figure 102. CLT task group duration: planned versus actual, measured in working days.

Task duration comparison CLT: planned versus actual

On closer investigation of the planned versus actual task durations, the cladding, joinery, decoration, snagging and remediation works had overruns, highlighted in **Table 40**.

This can be explained by the complexity of the project and the changes of the acoustic details, where the number of layers of plasterboard, the type of acoustic insulation and the support system for the acoustic insulation were changed during the construction works. Moreover, the joiner's second fix had five sub-tasks compared to an average of three sub-tasks for the other internal works. In contrast, the windows, membranes and insulation works were completed in less time than originally planned, highlighted in the table. The offsite system overran by approximately 13 days, which could be attributed to days with high winds when crane operations were not possible. These values are illustrated in **Figure 103**.

Table 40. CLT task duration comparison

	Duration (working days)		
Task Name	CLT Planned	CLT Actual	Difference
C11_Grnd_Wrk	58	63	-5
C12_Flr_Slb	20	12	8
C21_Reinforcement*	2	0	2
C22_Sl_Plts	5	5	0
C23_Off_Sstm	59	72	-13
C24_Other_Sstm	39	39	0
C26_Off_Sng	5	6	-1
C32_Rf_Sht	15	10	5
C41_Wndws	50	24	26
C43_Mmbrns	49	38	11
C44_Insltn	62	49	13
C51_Brck	10	10	0
C53_Clddng	68	138	-70
C55_Ext_Str_Srf*	205	29	176
C61_Jnr1	49	197	-148
C62_Plmb1	49	38	11
C63_Elctrc1	49	38	11
C64_Jnr2	49	141	-92
C65_Plmb2	49	59	-10
C66_Elctrc2	49	36	13
C67_Jnr3	56	68	-12
C68_Plmb3	50	38	12
C69_Electr3	49	35	14
C60_Dcrtr	50	96	-46
C71_Bldg_Sng	20	86	-66
C72_Bldg_Rmd	15	76	-61
C73_Hbttn	1	1	0
C81_Scffld_Up	40	51	-11
C82_Scffld_Dn	20	20	0
C83_Crn_Rnt	68	73	-5
C84_Lift_Instll	10	25	-15
C91_Mngmnt	236	339	-103

** Indicates tasks which had to be remodelled for the actual CLT programme because of labour-hour calculations. This resulted in discrepancies in the task durations.*

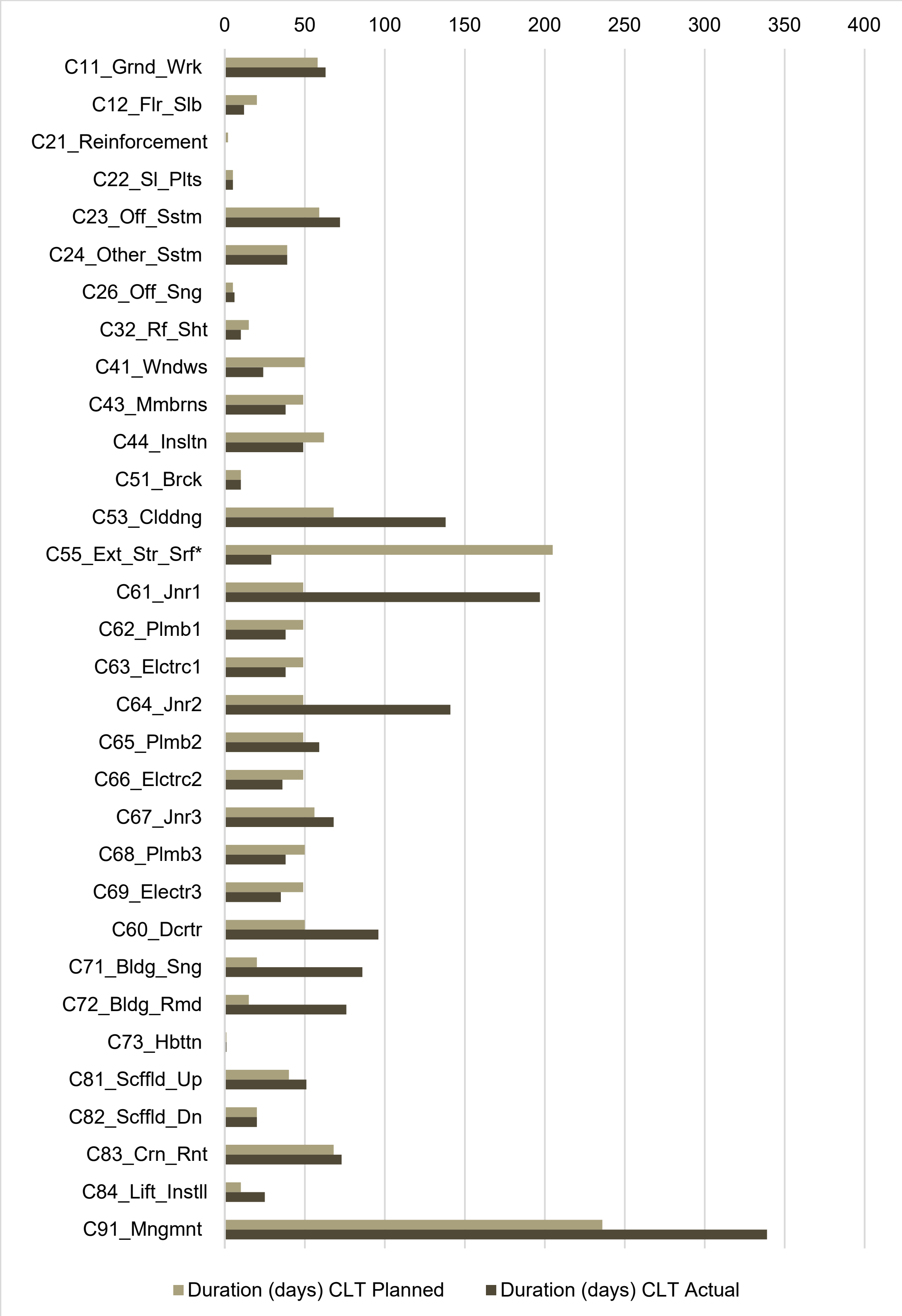


Figure 103. CLT task duration comparison as planned versus actual, measured in working days.

** Indicates tasks which had to be remodelled for the actual CLT programme because of labour-hour calculations. This resulted in discrepancies in the task durations.*

Task start and end date comparison CLT: planned versus actual

The start and end dates for the task groups add a further layer understanding about the project. In **Table 41** and **Figure 104**, where the difference between the start date and end date is low, such as in task groups C1 to C4. This indicates that the task groups ran approximately as originally planned. In the case of C5, however, the start and end date have similar but also high differences, meaning the task group was completed with an as planned duration, but its start was delayed.

Table 41. CLT task group duration comparison

Task Name	Task start date			Task end date		
	CLT Planned	**CLT Actual**	**Difference (w.days)**	**CLT Planned**	**CLT Actual**	**Difference (w.days)**
C1 - Substructure	31/10/16	31/10/16	0	24/02/17	24/02/17	0
C2 - Superstructure	27/02/17	27/02/17	0	02/06/17	16/06/17	10
C3 - Roof	29/05/17	29/05/17	0	16/06/17	09/06/17	-7
C4 – Seal and insulate	13/03/17	17/04/17	25	07/07/17	18/08/17	30
C5 - External	12/12/16	15/05/17	110	20/10/17	22/03/18	108
C6 - Internal	25/04/17	17/03/17	-29	09/10/17	09/03/18	108
C7 - Handover	19/09/17	02/11/17	32	23/10/17	23/03/18	108
C8 - Key plant	20/02/17	27/02/17	5	08/09/17	09/02/18	109
C9 - Management	31/10/16	31/10/16	0	23/10/17	23/03/18	108

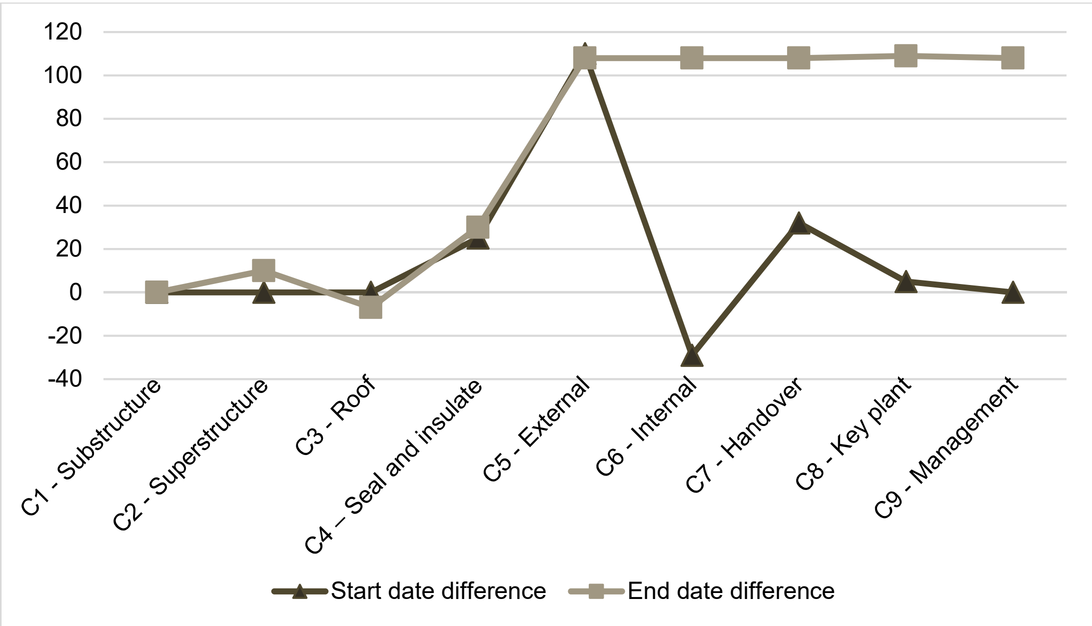


Figure 104. Task group CLT start and end date difference comparison, measured in working days.

The internal works group C6, however started ahead of schedule and was completed approximately 100 working days after its original end date, signifying that this was the most problematic task group within the project. Task groups C7 and C8 had start dates close to the original schedule, however were not completed until approximately 100 days after their original end dates. The similarities in end date difference values for group tasks C5 to C9 can be explained as the difference between the overall project's planned and actual end date. As these task groups continued until the project's end date.

Using the same line of reasoning in the task start and end dates comparison shown in **Figure 105 and Table 42**, the joiner's second fix, decoration, cladding, snagging and remediation works were differentiated as the tasks, which would have caused the largest overall delays to the build programme. It is of note that the offsite system installation had a 13 working day difference between its original and actual end dates, which could be explained by high-wind days which prevented installation, and perhaps by the CLT superstructure snagging prior to handover to the main contractor.

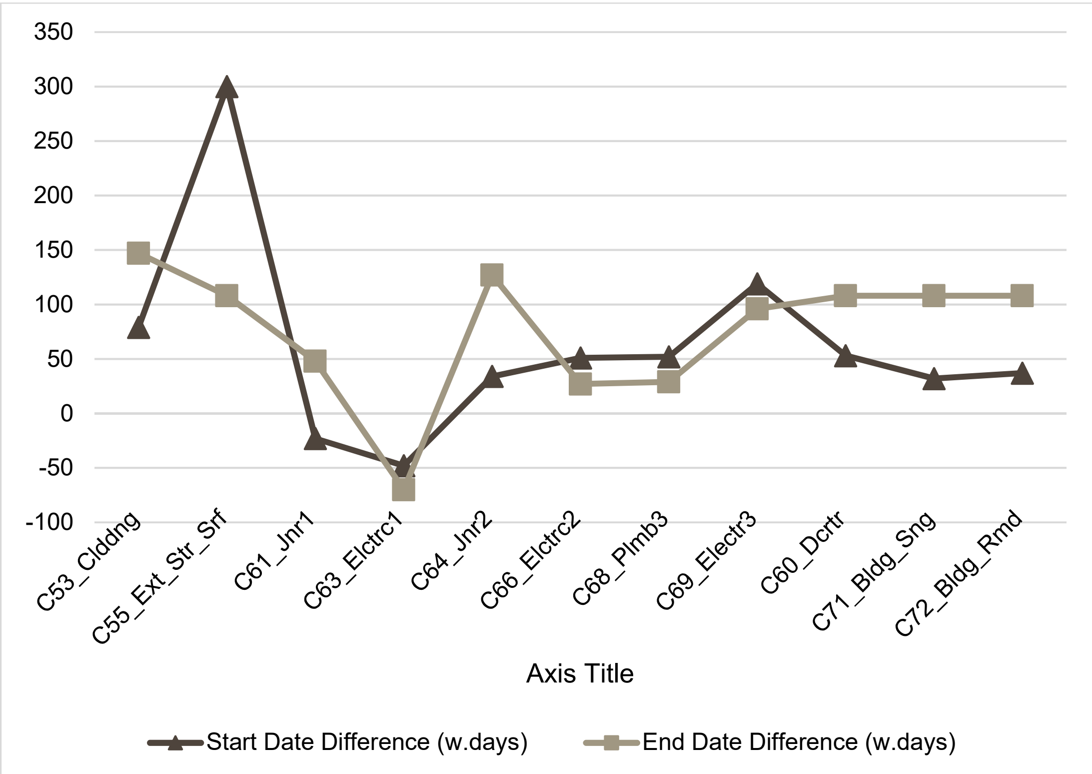


Figure 105. Selected tasks start and end date difference comparison, measure in working days.

Table 42. CLT task duration comparison

Task Name	Task start date: CLT Planned	CLT Actual	Difference (w.days)	Task end date: CLT Planned	CLT Actual	Difference (w.days)
C11_Grnd_Wrk	31/10/16	31/10/16	0	27/01/17	03/02/17	5
C12_Flr_Slb	30/01/17	09/02/17	8	24/02/17	24/02/17	0
C22_Sl_Plts	27/02/17	27/02/17	0	03/03/17	03/03/17	0
C23_Off_Sstm	06/03/17	05/03/17	-1	26/05/17	15/06/17	14
C24_Other_Sstm	10/03/17	10/03/17	0	04/05/17	04/05/17	0
C26_Off_Sng	26/05/17	09/06/17	10	02/06/17	16/06/17	10
C32_Rf_Sht	29/05/17	29/05/17	0	16/06/17	09/06/17	-7
C41_Wndws	22/03/17	09/05/17	34	01/06/17	12/06/17	7
C43_Mmbrns	13/03/17	17/04/17	25	19/05/17	08/06/17	14
C44_Insltn	11/04/17	05/06/17	39	07/07/17	18/08/17	30
C51_Brck	15/05/17	15/05/17	0	26/05/17	26/05/17	0
C53_Clddng	02/05/17	21/08/17	79	21/08/17	15/03/18	147
C55_Ext_Str_Srf*	12/12/16	07/02/18	300	20/10/17	22/03/18	108
C61_Jnr1	25/04/17	27/03/17	-23	03/07/17	07/09/17	48
C62_Plmb1	09/05/17	19/06/17	29	31/07/17	17/08/17	13
C63_Elctrc1	22/05/17	17/03/17	-48	14/08/17	10/05/17	-70
C64_Jnr2	23/05/17	10/07/17	34	15/08/17	09/02/18	127
C65_Plmb2	06/06/17	31/07/17	39	28/08/17	20/10/17	39
C66_Elctrc2	20/06/17	30/08/17	51	11/09/17	18/10/17	27
C67_Jnr3	20/06/17	20/09/17	66	20/09/17	03/01/18	74
C68_Plmb3	04/07/17	14/09/17	52	26/09/17	06/11/17	29
C69_Electr3	18/07/17	03/01/18	119	06/10/17	20/02/18	96
C60_Dcrtr	31/07/17	12/10/17	53	09/10/17	09/03/18	108
C71_Bldg_Sng	19/09/17	02/11/17	32	16/10/17	16/03/18	108
C72_Bldg_Rmd	03/10/17	23/11/17	37	23/10/17	23/03/18	108
C73_Hbttn	23/10/17	23/03/18	107	23/10/17	23/03/18	108
C81_Scffld_Up	20/02/17	28/02/17	6	14/04/17	10/05/17	18
C82_Scffld_Dn	14/08/17	15/01/18	108	08/09/17	09/02/18	109
C83_Crn_Rnt	27/02/17	27/02/17	0	02/06/17	09/06/17	5
C84_Lift_Instll	08/08/17	08/01/18	107	21/08/17	09/02/18	123
C91_Mngmnt	31/10/16	31/10/16	0	23/10/17	23/03/18	109

** Indicates tasks which had to be remodelled for the actual CLT programme because of labour-hour calculations. This resulted in discrepancies in the task durations.*

Because the CTP project was not completely scheduled, but followed a pattern of work developed within the larger development, only the actual schedule was created for this research and therefore a comparison between the as proposed and actual programme was not possible.

7.4.2 Comparative multi-factor productivity analysis of the CLT and CTP case studies

In construction productivity analysis it is recognised that both labour-hours per unit of measurement and the task duration are important factors. The two variables are typically inversely proportional, in that with increases in the resources for a task, the labour-hours will increase, and the task duration will decrease. For this reason, to present a more holistic representation of labour-productivity, the durations of the tasks are included alongside task labour-hour data. To maintain consistent units of measurement the durations per tasks were transformed from working days, to working hours assuming an 8-hour work day. Because in this research study a bottom-up approach was used to calculate the productivity per task, the comparative productivity results are presented to include both a high level of detail and an overview of the project as a whole.

Task labour-hours per plot & duration per plot: CLT vs CTP

Table 43 shows a productivity comparison measure in time (working hours, w. hours) and labour input (labour-hours, l-hours). From the comparison it becomes apparent that the tasks in which more labour-hours were used per plot for the CLT project, compared to the CTP project are the following 14 tasks (indicated in red within the table).

- C11_Ground work
- C12_Floor slab
- C23_Offsite assembly
- C26_Offsite snag
- C43_Membranes
- C44_Insulation
- C53_Cladding
- C61_Joiner 1st fix
- C64_Joiner 2nd fix
- C65_Plumber 2nd
- C67_Joiner 3rd fix
- C68_Plumber 3rd fix
- C72_Building Remediation
- C73_Habbitation

Whereas the tasks, where the CTP project utilised more labour-hours per task than the CLT project were the following 13 tasks (indicated in red within the table):

- C22_Sole Plates
- C51_Brickwork
- C55_External Structures & Surfaces
- C62_Plumber 1st fix
- C63_Electrician 1st fix
- C66_ Electrician 2nd fix
- C69_ Electrician 3rd fix
- C60_Decorator
- C71_Building snag
- C81_Scaffold up
- C82_Scaffold down
- C83_Crane rental
- C91_Management

Table 43. Productivity comparison CLT and Closed timber panel case studies

	Duration (w. hours per plot)		Productivity (l-hours per plot)	
Task Name	**CLT**	**CTP**	**CLT**	**CTP**
C11_Grnd_Wrk	12	7	67	19
C12_Flr_Slb	2	1	9	3
C22_Sl_Plts	1	1	6	8
C23_Off_Sstm	14	4	83	32
C24_Other_Sstm	7	5	n/a	46
C26_Off_Sng	1	2	6	1
C31_Rf_Trss	n/a	2	n/a	11
C32_Rf_Sht	2	n/a	6	n/a
C33_Rf_Til	n/a	1	n/a	4
C34_Roof_PV	n/a	2	n/a	6
C41_Wndws	5	n/a	5	n/a
C42_Drs	0	3	0	6
C43_Mmbrns	7	n/a	8	n/a
C44_Insltn	9	n/a	164	n/a
C51_Brck	2	10	13	121
C53_Clddng	26	8	670	30
C55_Ext_Str_Srf	6	22	35	149
C61_Jnr1	38	11	407	314
C62_Plmb1	7	6	35	40
C63_Elctrc1	7	7	26	43
C64_Jnr2	27	11	353	156
C65_Plmb2	11	6	86	20
C66_Elctrc2	7	6	16	20
C67_Jnr3	13	6	137	7
C68_Plmb3	7	6	67	20
C69_Electr3	7	6	9	20
C60_Dcrtr	18	13	96	166
C71_Bldg_Sng	16	13	0	27
C72_Bldg_Rmd	14	13	91	42
C73_Hbttn	0	5	114	9
C81_Scffld_Up	10	6	0	37
C82_Scffld_Dn	4	4	5	33
C83_Crn_Rnt	14	26	9	38
C84_Lift_Instll	5	n/a	13	n/a
C91_Mngmnt	65	82	10	99

From Figure 107 it can be observed that the largest differences between the task labour-hour utilisation of the two projects, were in the cladding, and joiner 2nd and 3rd fixes (C53, C64 & C67). For these tasks the CTP project had lower labour utilisation. If only the offsite system installation productivity is compared, the CTP system had labour utilisation of 32 labour-hours per plot, which was approximately 40% of the CLT labour utilisation. Moreover, the CLT system utilised approximately 164 labour-hours per plot for insulation installation, whereas the CTP system contained integrated insulation in the offsite product.

The opposite effect was true for the brickwork; the CLT system utilised two lightweight cladding systems, whereas in the CTP project 121 labour-hours per plot were utilised for bricklaying, as the main cladding system in the project. The different methods for the floor slab construction are also reflected in the results. The CLT project used a concrete slab, whose levelling required high precision because of the smaller floor slab tolerances. The CTP project used prefabricated insulated slabs with larger levelling and overhang tolerances.

These differences can be explained by the different levels of offsite completion for the CLT panels compared with the CTPs. Although the CLT panels included openings for windows and boiler pipes, the CTP system included the insulation, pre-fitted windows and for the external wall panels also plasterboard on the interior. Logically, this resulted in reduced labour demand for these tasks onsite. Moreover, the CTP project represented the contractor's standard offsite manufacturing and construction practice, and therefore the system and its sub-tasks were more familiar to the workers and managers compared with the combination of innovative superstructure, acoustic insulation and cladding systems used in the CLT project. In innovative projects however it is expected that labour utilisation will be higher because of the deviation from standard practice.

From the chart the task durations can be considered in combination with the task durations. In some cases where the labour utilisation was high, but the task duration was low it could be postulated that efficiency was sacrificed to complete the task sooner. In other cases, where both the task duration and labour utilisation for one project were higher than the other, areas with potential for productivity optimisation could start to be defined. Some such examples for the CLT project were the ground-works, cladding and joiner 1st fix (C11, C53 & C61_Jnr1).

Figure 106. Task productivity and duration per task, measured in hours per plot

Task group comparison: work per plot & duration per plot

The effect of the differences in labour productivity and duration of individual tasks on the project's productivity are described below. Overall in both case studies the task groups with the largest labour utilisation were C5 – External and C6 – Internal. **Figure 107** shows that in the CLT project the labour hours for these two task groups were 27% for C5 and 48% for C6, of the overall labour-hours utilised in the project. In the CTP project, these values were 20% for C5 and 53% for C6, of the overall labour-hours. In other words, the labour hours for the external and internal works represented on average 74% of the overall labour-hours in both the case studies (CLT = 75% and CTP = 73%). In comparison, the offsite systems, which were the main focus of this study, had only marginal labour-hour utilisation in both cases: 3% in the CLT project and 6% in the CTP project, from the overall labour utilisation.

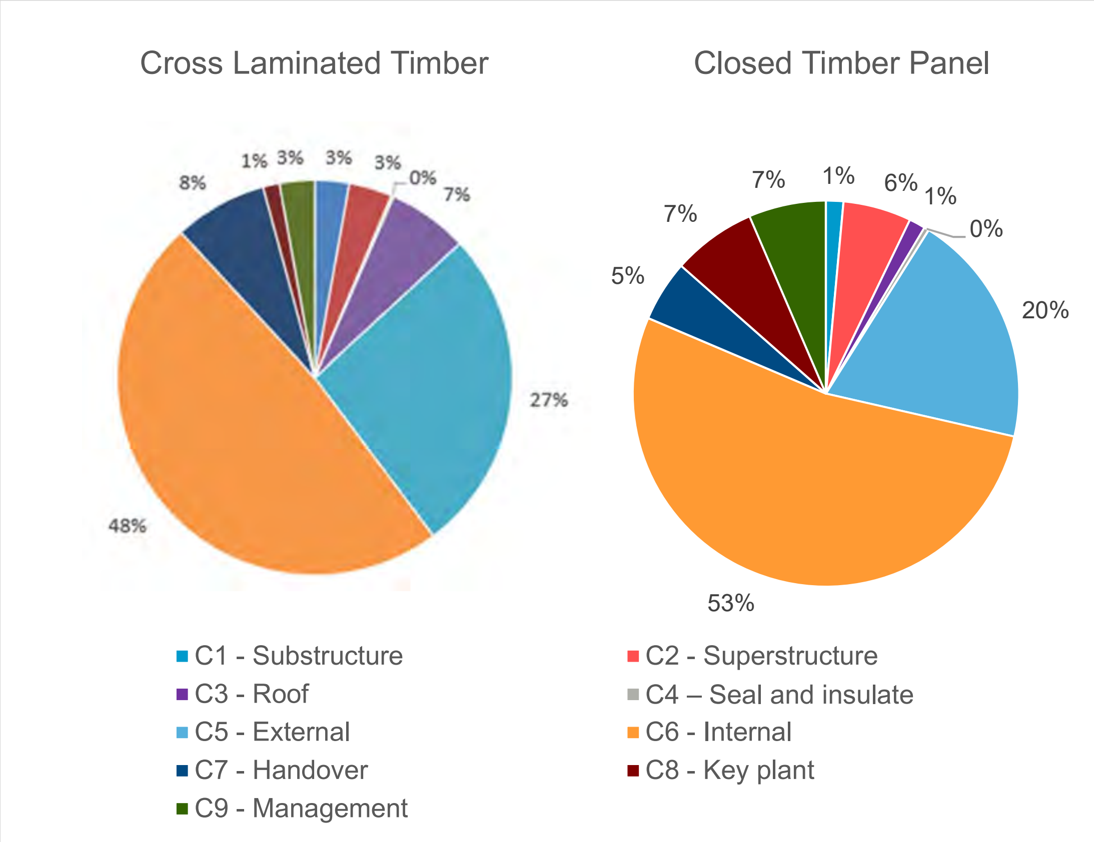


Figure 107. Labour-hour utilisation per work group as a percentage of overall project labour-hours.

The task group labour-hours utilisation and task group are shown in **Figure 108**.

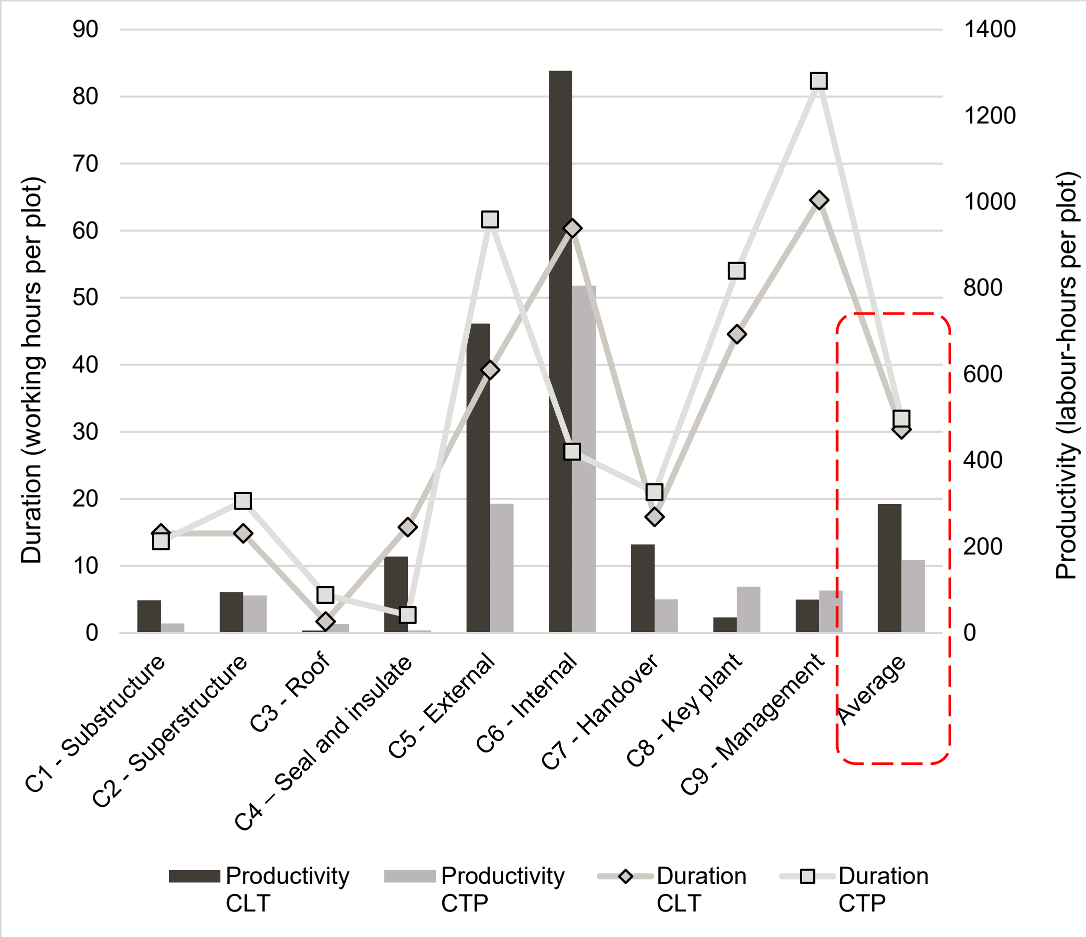


Figure 108. Task group productivity comparison: CTP and CTP projects.

From the graph it can be observed that for the superstructure (C2) the differences in labour-hour utilisation between the two projects were marginal, however the differences in their duration are more pronounced. The CLT project utilised slightly more resources for the superstructure, but it was completed in 5 working days less than in the CTP project. Overall it could be said that the CLT superstructure system was more efficient than the combination of CTPs apartments and concrete block shared circulation areas, used in the CTP project. However, the CLT project also required airtightness taping of the CLT joints and insulation on site, which was omitted in the CTP project because of the higher level of prefabrication of the closed timber panels.

For the external works (C5) the labour utilisation in the CLT project was higher, however its duration was lower than in the CTP project. These results were influenced by the incorporation of the road surfacing in the ground-works programme done before the superstructure construction, whereas in the CTP project they were included in the external works completed at the end of the project. This meant that in the CLT project the roadworks were not a bottle-neck for the handover process.

The results for the internal works (C6) was more definitive – the CLT system utilised significantly more labour-hours and was completed with a significantly higher duration, than in the CTP project. This can be explained again with the higher degree of prefabrication of the CTP system, where internal linings were included in the prefabricated panels and the standardised details for acoustic and fire prevention strategies, which would have been utilised. In contrast, the CLT system required specialist integrated details for the acoustic and fire strategy, with an emphasis on impact sound diffusion due to flanking sound travel within solid timber. Another possible reason for this difference was the difference in resource management for a familiar system and for a new system. In the latter case, it is expected that tasks would be performed at a slower rate compared to a known build system. The innovative aspect of the CLT project was exemplified in the more demanding inspection and final approval process, including fire brigade inspections passed with very positive feedback.

On average, the task group durations for the two case studies were similar but the CLT project utilised more labour-hours per plot than the CTP project. This can be attributed to the trend of higher labour utilisation in the CLT system observed in task groups C1, C2, C4, C5, C6 & C7.

In total the CLT and CTP projects had similar durations per plot – 8.1 working days and 10.3 working days, respectively (shown in **Table 44**). These figures were the result of dividing the total duration of the project in working days by the number of plots, i.e. this is not how long it took to complete a plot from start to finish in the projects. However, the difference in the labour utilisation per plot was more marked – 2,554 labour-hours and 1,525 labour-hours, respectively.

Table 44. Total comparison duration and work per plot: CLT vs CTP case studies.

Duration (working days per plot)		Work (Labour-hours per plot)	
CLT	**Closed Panel**	**CLT**	**Closed Panel**
8.1	10.3	2,544	1,525

Therefore, although the CLT project utilised more labour per plot, construction was completed in less time overall. The opposite is true for the CTP project – less labour was utilised per plot, but the duration was higher. These observations are shown in **Figure 109** and **Figure 110**.

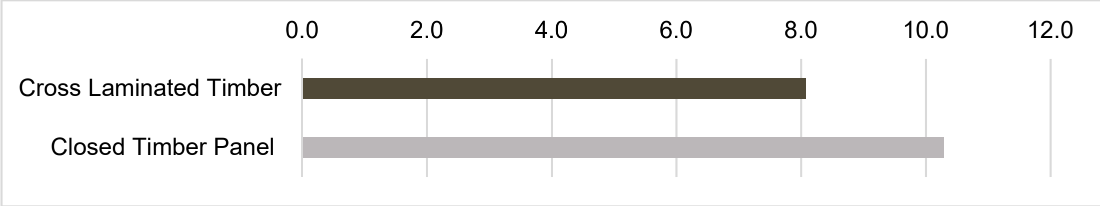


Figure 109. Total working days per plot.

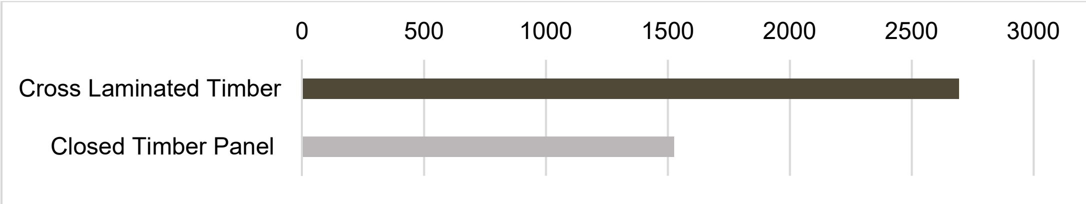


Figure 110. Total labour-hours per plot.

Overall, because the difference in duration is much smaller than in labour utilisation, it can be said that the CTP project had higher labour productivity than the innovative CLT project. Because of the high influence of the internal works on the overall results, the difference in labour productivity can be attributed to the more complex internal programme of the CLT project, which had 26 items, whereas the CTP internal works programme had 13 items. The labour-intensive cladding system and the innovative nature of the CLT system would have also contributed to this productivity difference.

Cost of work for the CLT and CTP projects

The aim of the cost exercise was to pave the way towards understanding the labour-cost impacts on projects using offsite timber systems with different levels of completion in the factory. The CLT panels were massive timber, with pre-cut openings for windows and boilers, but without any insulation. In contrast, the CTP system included internal sheeting (plasterboard), windows and door frames. Therefore it was expected that the CTP project would require less labour on site, and therefore have lower associated labour cost.

Within **Table 45** the same method used in Section 5.2.1 (**Chapter 5**) was utilised to evaluate the offsite completion percentage of the case studies. In short within this calculation **Equation 4** was applied to the offsite system components list shown in the table. Within the list 1 indicates that the system included this component in the factory work, 0.5 indicates that it included it in some instances, and 0 and that it was not included in the work done in the factory. A sum is then taken and the offsite system percentage calculated with using the maximum components included in the factory as 90% (the maximum estimated for volumetric construction in literature). According to the results, the CLT case study would represent approximately 25% work done in the factory, compared to 46% for the CTP system' offsite completion percentage estimate. But how that could impact the difference in labour cost measured in GBP per 1 living-unit (plot) was uncertain.

Table 45. Construction case studies offsite completion percentage estimates.

Component	**Number**	**OTP**	**VTC**	**CLT**	**CTP**
Structure	c_1	1	1	1	1
Insulation	c_2	0	1	0	1
Airtight mbr	c_3	1	1	0	1
Int finishes	c_4	0	1	0	0.5
Cladding	c_5	0	0	0	0
Windows	c_6	0	0.5	0	1
Doors	c_7	0	1	0	1
MEP	c_8	0	0.8	0.1	0.1
Fittings	c_9	0	1	0	0
Furniture	c_{10}	0	1	0	0
Staircase	c_{11}	0	0.8	1	0
Roof	c_{12}	0	0	1	0
Porch	c_{13}	0	0	0	0
Sum		2	9.1	3.1	5.6
Offsite completion % estimate		16%	74%	25%	46%

***0.5 and 0.8 indicate that these components were included in a proportion (but not all) of the living units. 0.1 indicates that openings were provided for some MEP services.*

Labour costs were estimated for the two case studies using MS Project, where the labour-hours per resource were multiplied by the input cost per hour. The cost per hour data for the different trades is shown in **Table 46**, was extracted from the latest edition of the Spon's price book (AECOM, 2017). Overtime and regular work hours were not differentiated when calculating the costs, this was to avoid collecting sensitive data on overtime payment rates and to maintain the simplicity of the model. These are therefore baseline costs only and do not cover additional expenses such as overheads, pension contributions, national insurance and other taxes. For the L91 and L71 resources cost data was not found and estimates were therefore based on general knowledge. Because of uncertainty over the cost per hour (sensitive information) specialist installers and concrete slab contractors in the CLT panels project, average prices found in Spon's were utilised. When reading these results it should also be considered that the CLT case study was more innovative in nature, whereas the CTP case study was standard practice and therefore this could have also influenced some of the labour-cost differences. In addition, the overall contract value for the CLT project was £5.5m, or approximately £131,000 per plot. The overall contract value for the CTP case study development was reported as £50m for the entire development of 542 plots, or equalling approximately £92,251 per plot. The difference between these estimates is approximately +/- £19,000.

Table 46. Calendar and cost settings per resource – see Appendix 7B for full resource names.

Resource Name	Std. Rate	Base Calendar	Spon's location factor
L91 Smngr	£25.00/hr	Mon-Sat 48 hrs	n/a
L11 Grndw	£11.21/hr	Mon-Fri 40 hrs	0.87
L12 Flrsb	£11.81/hr	Mon-Fri 40 hrs	0.87
L23 Offrct	£12.64/hr	Mon-Fri 40 hrs	0.87
L83 Crnop	£11.81/hr	Mon-Fri 40 hrs	0.87
L31 Rfrct	£12.64/hr	Mon-Fri 40 hrs	0.87
L33 Rftlr	£13.82/hr	Mon-Fri 40 hrs	0.87
L24 Brckl	£13.82/hr	Mon-Sat 48 hrs	0.87
L63 Elctr	£10.97/hr	Mon-Sat 48 hrs	0.87
L62 Plmbr	£10.97/hr	Mon-Sat 48 hrs	0.87
L61 Joinr	£13.82/hr	Mon-Sat 48 hrs	0.87
L34 SlrPV	£13.14/hr	Mon-Fri 40 hrs	0.87
L60 Dcrtr	£13.82/hr	Mon-Sat 48 hrs	0.87
L81 Scfld 48hrs	£13.82/hr	Mon-Sat 48 hrs	0.87
L81 Scfld 56hrs	£13.82/hr	Mon-Sun 56 hrs	0.87
L55 Lndsc	£13.14/hr	Mon-Sat 48 hrs	0.87
L71 EngIn	£30.00/hr	Mon-Fri 40 hrs	n/a
L00 Glbrr 48hrs	£7.80/hr	Mon-Sat 48 hrs	0.87
L00 Glbrr 40hrs	£7.80/hr	Mon-Fri 40 hrs	0.87
L00 Glbrr 56hrs	£7.80/hr	Mon-Sun 56 hrs	0.87

Overall, the estimated costs per task group shown are in **Figure 111** and demonstrate that the cost estimates vary little in variable behaviour from the labour-hour calculation. In task groups where the labour-hours per task are higher in one project than the other, the labour costs are also proportionally higher. This could be attributed to the small differences in labour costs per hour for the majority of the trades. The task groups with the highest cost were C5 – Internal and C6 – External for both case studies. The CLT project had cost significantly higher than the CTP project costs in groups C4, C5, C6 & C7 and because these groups were also the highest in cost, on average the CLT project cost was nearly twice as much as the CTP project, per plot.

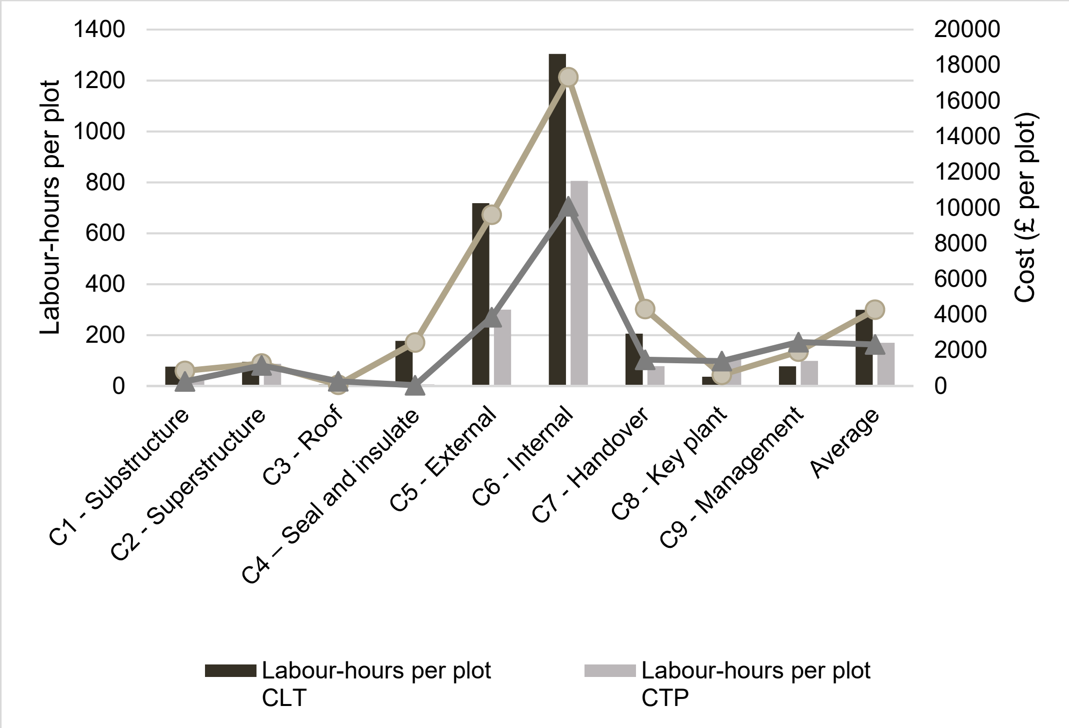


Figure 111. Base task group cost and labour-hours: CLT vs CTP case studies.

Table 47 however shows that on a task level, the CLT project cost lower than the CTP project in 18 tasks out of 35, indicated in green in the table. In other words, although the CLT project had lower costs for half of the tasks, these were tasks with small contributions to the total labour costs and the total base labour costs per plot were lower in the CTP than in the CLT project. Overall, the CLT project had an estimate labour base cost per plot of £38,476, and the CTP project had an estimated labour base cost of £21,039. The difference between the two base costs is significant, £17,437 or 45% of the CLT labour costs and 82% of the CTP labour costs. The difference in offsite completion percentage between the two projects was approximately 21%, therefore it could be said that in these two case studied an estimated baseline labour cost difference of £830 was observed for each percentile difference in work completed in the factory. This approach would need to be extended with further potentially international case studies to understand the more generalised difference in labour-cost that could be utilised to more accurately estimate increased offsite completion percentage benefits to the economic factors of construction projects.

Table 47. Cost comparison per task (per plot)

Task Name	CLT, *a* (GBP £ per plot)	CTP, *b* (GBP £ per plot)	Difference, *a-b* (GBP £ per plot)
C11_Grnd_Wrk	750	217	533
C12_Flr_Slb	106	44	62
C22_Sl_Plts	76	101	- 26
C23_Off_Sstm	1,107	400	707
C24_Other_Sstm	-	636	- 636
C26_Off_Sng	87	25	62
C31_Rf_Trss	-	143	- 143
C32_Rf_Sht	78	-	78
C33_Rf_Til	-	55	- 55
C34_Roof_PV	-	72	- 72
C41_Wndws	67	-	67
C42_Drs	-	47	- 47
C43_Mmbrns	109	-	109
C44_Insltn	2,273	-	2,273
C51_Brck	173	1,672	- 1,499
C53_Clddng	8,977	234	8,743
C55_Ext_Str_Srf	464	1,956	- 1,492
C61_Jnr1	5,629	3,712	1,917
C62_Plmb1	384	439	- 55
C63_Elctrc1	282	399	- 117
C64_Jnr2	4,884	2,370	2,513
C65_Plmb2	939	219	720
C66_Elctrc2	179	219	- 40
C67_Jnr3	1,893	92	1,801
C68_Plmb3	96	219	- 123
C69_Electr3	1,120	219	900
C60_Dcrtr	1,924	2,199	- 275
C71_Bldg_Sng	2,731	800	1,931
C72_Bldg_Rmd	1,572	591	981
C73_Hbttn	17	88	- 70
C81_Scffld_Up	69	507	- 438
C82_Scffld_Dn	121	451	- 331
C83_Crn_Rnt	153	445	- 292
C84_Lift_Instll	286	-	286
C91_Mngmnt	1,933	2,467	- 534
Totals (£ per plot)	**38,476**	**21,039**	**17,437**
Offsite completion %	**25%**	**46%**	**-21%**
Cost (£ per plot) per offsite completion %	**1,539**	**457**	**830**

The speculated reasons for the higher CLT project estimated base labour costs are the same as those for the high number of labour-hours in the C4 to C7 CLT task groups – the lower degree of prefabrication, the innovative nature of the product and the atypical acoustic and cladding specifications.

Building Information Management (BIM)

BIM Level 2 was utilised on the CLT project, where a 3D centre snap-point was identified to enable overlay of the architectural, structural and assembly models in a single model. This was a novel approach for the architects, who wanted to be BIM-ready for the requirement for a central-government funded project to demonstrate BIM Level 2 expertise. One of the technical challenges with the software of choice was the façade modelling and this was modelled using manual drawing tools, as opposed to the component-based CLT model. The main benefit of the BIM process was the speed and efficiency of information management, including enabling component clash detections between the different disciplines in the model. In addition, 4D BIM images were used to communicate the superstructure installation programme between the CLT installers and the main contractor, which was commented as an effective information communication tool.

In the CTP project, the building was designed using traditional 2D and 3D drafting method such as AutoCAD and HSB CAD for the timber frame design. The HSB file was then used in the automated production of the panels.

Waste

The waste reports were provided by the main contractor for the two projects. The CTP building was part of a larger development with a homogenous type of building types, mainly 2 and 3-bedroom apartments, and therefore the waste data was divided per plot to produce comparable waste analysis figures. The CLT building represented the entire development and therefore a separate waste report was available for it, whose results were considered marginally more representative of reality than the averaged according to number of plots data for the CTP project.

In the CTP project approximately 5.24 tonnes of waste were produced per plot, of which approximately 1 tonne per plot was timber, as shown in **Figure 112** (the categories 'scrap', 'inert' and 'rubble' had an estimate of 0% and were excluded from the graph). During the CLT project's construction approximately 4.41 tonnes of waste was produced per plot, of which approximately 0.6 tonnes per plot were timber. These figures suggest that the CLT project building had a higher materials efficiency, because it produced approximately 19% less materials waste per plot. When the timber waste percentage in the CLT project was explored for an explanation, it became obvious that this was due to the timber waste-free

CLT installation. In the CTP project timber waste was collected over a 17-month period, dispersed throughout the build with the exception of the peripheral few months which were dedicated to ground-works and surfacing. In contrast, in the CLT project timber waste was collected only six months, starting a month after the CLT superstructure hand-over and ending towards the completion of the internal works. The percentage of gyproc (plasterboard) waste was similar in both case studies, despite the CTPs including plasterboard on the external walls (therefore removing its waste to the factory process) and the double-layered plasterboard specification of the ceilings in the CLT project (which would have increased the plasterboard waste).

In future work materials waste data should be tagged to each of the main project stages C1 to C7 and attached to the schedule to create a multi-information model of the building, including construction time, labour productivity and materials waste data. The *materials* usage per resource in MS Project or other BIM-compatible software package could be used for this and the information could moreover be visualised using 4D+ building model graphics depicting time and other information overlays.

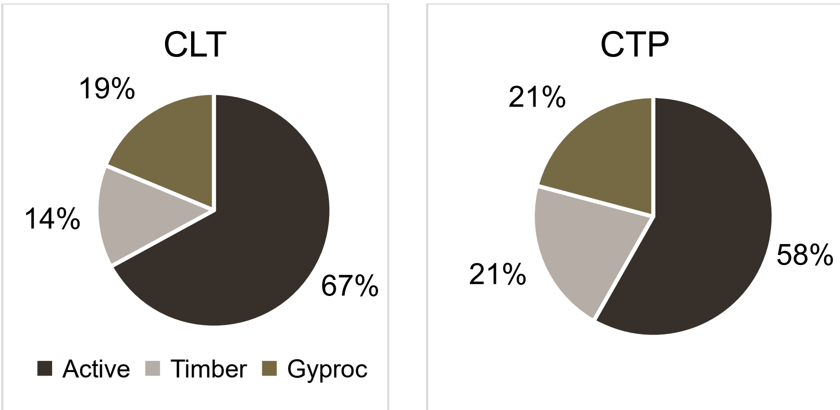


Figure 112. Waste distribution on average per plot.

Logistics

The logistics of the CTP case study were comparatively simpler than the CLT case study. This was mainly due to the difference in country of origin, with the CTPs being manufactured in the same city as the project site, whereas the CLT panels were manufactured in Germany and had to be transported by road, ferry and again road to the project site. The differences in logistics operations for the offsite components are shown in **Table 48**. The CTP case study however had the disadvantage of being located across a school in a busy urban centre, and therefore deliveries were restricted around 9:00 AM due to the safety of children arriving at school, and site plant had to be managed carefully on site.

Yet in both cases deliveries were synchronised with onsite activities via the just-in-time technique and resulted in an efficient interface between the offsite and onsite activities. In addition, the CLT project required flights from Cambridge and London for site inspections by the structural engineers.

Table 48. Logistics one-way journeys per case study

Case study	Type	Stage	Distance (km)
CLT	Road	1	710
CLT	Ferry	2	400
CLT	Road	3	440
CLT	Total offsite system deliveries		23
CLT	**Average offsite system (km per plot)**		**~ 850**
CTP	Road	1	11
CTP	Total offsite system deliveries		15
CTP	**Average offsite system (km per plot)**		**~7**

Carbon / Energy

Both systems were designed to the Scottish Section 7 Silver sustainability standard. Although the CLT case study combined a higher potential for carbon sequestration due to containing higher volumes of timber, some of this would be mitigated by the embodied carbon employed in the transport from mainland Europe. The energy performance and climate resilience of the CLT case study was investigated by the Scottish Energy Centre (SEC) based in Edinburgh and was reported on separately by their research team.

Build quality

Detailed snagging reports were not available for comparison between the two case study projects. The CLT engineers' reports provided an insight into the re-work required for the CLT installation. These demonstrated that the ground-floor brackets, the 45-degree screw connections on levels 1, 2 and 3; and the brackets with different nailing patterns tended to require more re-work than the other timber connections. In both projects, significant time was dedicated at the end of the build programme for snagging and quality inspections, which could potentially be reduced with increased quality inspection in the offsite and onsite processes.

Health & Safety (H&S)

Overall good health and safety practices were observed on both sites, with minor issues of workers not complying completely with the full set of Personal Protection Equipment (PPE). This was also observed in the pilot open timber frame panel case study project discussed in Chapter 6.

During interviews with the CLT installers, the challenges of installing some types of connectors were highlighted; large screws angled at 45 degrees sometimes at 100mm centres. From subsequent interviews with site engineers, it was hypothesised that these connections were associated with the high wind velocity conditions in the area. In comparison, the CTP case study utilised a standard system and therefore all connections installations were standard practice for the team and were executed efficiently.

The potential H&S implications of CLT connections specification were investigated using a simulation model with input data on number of panels and their locations from a BIM model, provided by the architects (Duncheva *et al.*, 2018). The panels and their specification were linked to input of the connector type, number and time spent using hand-arm vibration typical tools per connection. The latter data was extracted from an audio-visual database, created from direct observations of CLT panels. Wind data from a weather database was then utilised to consider the weather's influence of work delays, on days where the wind gusts and speed exceeded 30 m/h. The findings suggested that levels 1,2 and 3 could have been further optimised to decrease the potential of developing Hand-Arm Vibration Symptom (HAVS, or 'white finger'), however further research is needed to increase the accuracy of the potential percentage calculation to quantify the correlation between time spent installing challenging connectors, to increased likelihood of developing HAVS symptoms.

7.5 CLT and CTP case studies summary

The main finding from these two comparative projects was that although the labour productivity of the CTP project was higher than the CLT project, the overall impact of the offsite systems on the construction programmes was marginal. This could be connected to the higher offsite completion percentage of the CTP system, including pre-fitted insulation, plasterboard, windows and doors.

This purely quantitative labour productivity comparison does not tell the full story of the multi-factor productivity performance of the two investigated offsite timbers systems. The CLT case study project produced less waste per plot, including timber waste, and therefore could be said to be the more resource-efficient build system. Moreover, the fire inspections of the CLT case study were numerous and the inspectors commended the project's fire safety, which is important in the context of the recent concrete Grenfell tower fire and its potential consequence on building methods in the UK. Both case studies included lengthy final checking and snagging processes, which could perhaps be reduced with BIM tools-enabled quality inspections at different construction stages, especially in the internal works. The opportunities of collaborative BIM integration with advanced offsite methods were also demonstrated in the CLT case study.

Overall, the multi-factor productivity of the CLT and CTP case studies varied according to the key 10 variables as may be summarised in Table 49, where:

a = duration (hrs/per plot)

b = number of people working (labour)

*c = a*b = offsite system installation productivity (labour-hours per plot)*

d = mean overall duration per plot (hrs/plot)

e = mean overall labour-productivity (labour-hours per plot)

f = mean baseline labour cost (£/plot)

g = overall contract cost (£/plot)

h = offsite completion percentage estimate (%)

i = BIM level

j = waste materials (tonnes/plot)

k = timber waste as a percentage of all waste (%)

*l = h*i = timber waste per plot*

m = offsite system transportation mean (km/plot)

n = Scottish building regulations level, 1 = bronze, 2 = silver, 3 = gold

and subscripts indicate:

1 = offsite system installation

2 = cladding

3 = internal finishes

Table 49.Multi-factor productivity comparison CLT and CTP case studies

Variable (unit)	CLT	CTP	Difference (CLT - CTP)	Higher productivity
a_1 (hrs/plot)	4	14	-10	CLT
b_1 (labour)	8	3	2	CTP
c_1 (labour-hours/plot)	32	52	-32	CLT
a_2 (hrs/plot)	28	18	10	CTP
b_2 (labour)	18	5	13	CTP
c_2 (labour-hours/plot)	504	72	432	CTP
a_3 (hrs/plot)	60	27	33	CTP
b_3 (labour)	21	30	-9	CLT
c_3 (labour-hours/plot)	1260	810	450	CTP
d (hrs/plot)	28	31	-3	CLT
e (labour-hours/plot)	598	311	284	CTP
f (£/plot)	38,476	21,039	17,437	CTP
g (£/plot)	131,000	92,000	38,701	CTP
h (%)	25%	46%	-0.21	CTP
i (level)	2	1	1	CLT
j (tonnes/plot)	4.41	5.24	-0.83	CLT
k (%)	14	21	-7	CLT
l (tonnes/plot)	0.6	1.1	-0.5	CLT
m (km/plot)	~ 850	~7	~ 843	CTP
n (level)	2	2	0	-

In addition, the overall contract value for the CLT project was £5.5m, or approximately £131,000 per plot. The overall contract value for the CTP case study was reported as £50m for the entire development of 542 plots, or equalling approximately £92,251 per plot. The difference between these estimates is approximately +/- £19,000.

From the table above it can be observed that seven variables have a negative sign, indicating that the CTP case study outperformed the CLT case study, whereas the CTP case was more productive according to ten variables. Therefore overall, the CTP case study with higher offsite completion percentage could be said to have been more multi-factor productive than the CLT case study. However, the CLT case study internal and external finishes labour-productivity values could be improved in future projects through lessons learnt from innovation. Furthermore, several productivity variables were included which could have skewed the results in favour of the system with the higher labour-productivity.

Therefore, when configured to the variables as identified in the literature review and presented in the methodology, the overall multi-factor productivity results for these two case studies may be summarised as shown in Table 50. From this summary both case studies performed equally well in terms of MFP, although the CTP case study outperformed the case study in terms of pure labour productivity. The nuances in MFP performance results could start to collect information to aid decision-making for offsite timber system utilisation. For example, if in a similar context simplified logistics or reduced costs were a project priority, then CTPs might be the more appropriate offsite timber system. In contrast, if optimisation of waste materials, time on-site or digitisation were a priority, then the CLT panelised system would be more suited to that project. The percentage in difference from the mean value was also calculated per main variable as listed in the table, and can be utilised to judge the degree of difference in performance. The CTP case study seemed to have a higher degree of performance advantage on average across all main variables. These results may also be utilised to guide the creation of an offsite timber systems MFP index in the following chapter.

Table 50.Multi-factor productivity summary CLT and CTP case studies, showing difference in percentage from the average value in favour of the indicated case study.

CLT	MFP variable	CTP
10%	time (d)	
	labour productivity (e)	63%
	cost (g)	35%
67%	BIM (i)	
17%	waste (j)	
	logistics (m)	197%
0%	sustainability (n)	0%
3	number of variables with higher performance	3

With regards to labour productivity specifically, the construction task groups with the highest impact on labour utilisation in both case studies were the internal works and external works, which combined accounted for approximately two-thirds of the total project labour-hours in both cases studies. Therefore, there is a need to reconsider the completion percentages attributed to different offsite systems in literature (Lawson, Ogden & Goodier, 2014). It is hypothesised that with labour-hour data-based redistribution of the offsite completion percentages of the four main offsite timber systems (open panels, closed panels, mass timber panels and volumetric), the difference between the closed timber panel and the volumetric systems will increase, and the gap between closed panels, mass timber panels and open panels will be reduced. Moreover, future construction work should focus on resource management optimisation in the external works and internal works, especially in the work of joiners and cladding specialists. The innovative Location-Based Management technique can be applied to improve the flow of tasks in the internal works scheduling, and of the project overall (Seppänen, Evinger & Mouflard, 2014).

A further level of detail to the offsite construction productivity analysis can be added by the creation of a detailed simulation model with inputs and outputs of both materials and labour, to create scenarios for improved decision-making in construction management of offsite timber systems. Additional work in this area can also progress to the inclusion of the manufacturing process within the simulation model. The model can then be used to predict the effect of different design and engineering solutions on the duration, labour utilisation and materials waste percentage of the project. During the project definition and design phases, the decisions of the client can have a significant impact of the specification of offsite systems (Hedgren & Stehn, 2014).

The overall labour productivity finding of this chapter was similar to a high-level comparative productivity research undertaken in Auckland, New Zealand, which reported that the maximum productivity improvements of offsite systems was 11% (Shahzad, Mbachu & Domingo, 2015). This was with reference to a sample of mixed building types, 45% of which were constructed using 2D offsite systems, 25% 3D offsite system and 20% hybrid 2D+3D offsite systems. It can be speculated that the final results were reduced due to the marginal impact of offsite systems on the total project productivity in 2D systems, as exemplified in this research study.

Chapter 8: Discussion

8.1 Multi-factor productivity analysis of offsite timber systems

During this doctoral thesis the identified ten MFP variables in offsite timber systems were reviewed using different research methods as summarised in **Table 51**. These MFP variables are reviewed in the following sections from the perspectives the literature review, market survey, manufacturing survey and construction case studies, and an overall over-arching comment is provided in the context of previous findings. These will form the basis of a proposal for a novel MFP index for offsite timber systems, which is the main contribution to knowledge in this thesis.

Table 51. Ten MFP variables investigated in the chapters of this thesis.

N	Variable name	Literature review	Market survey	Manufacturing survey	Construction case studies
1	*Time*	✓	✓	✓	✓
2	*Cost*	✓	✓	✓	✓
3	*Labour productivity*	✓	✓	✓	✓
4	*Logistics*	✓	✓	✓	✓
5	*Waste*	✓	✓	✓	✓
6	*BIM*	✓	✓	✓	✓
7	*Specification & Installation*	✓	✓	✓	✓
8	*Carbon & Energy*	✓	✓	✓	✓
9	*Build quality*	✓	✓	✓	✓
10	*Health & Safety*	✓	✓	✓	✓

8.1.1 Time

Overall it can be said that there was a disconnection between the findings from the theoretical and practical time aspects of the research regarding the time of offsite timber systems, as can be seen in **Table 52**. In the literature and perception chapters' time was identified as the primary advantage of volumetric timber systems in the context of other offsite timber systems. In contrast, the manufacturing survey highlighted the lower production rate of the participating UKV manufacturers compared to the UKP and EUV manufacturers, whereas the innovative volumetric case study had the longest programme delay from the four studied projects. Therefore, it can be said that time savings is a potential advantage of offsite timber systems however it was not demonstrated to its highest potential in the surveyed cases, perhaps due to their innovative nature.

Table 52. Multi-factor variable: **Time**

N	Research phase	Main theme findings
1	*Literature review*	Offsite reduces the overall project time through increased efficiency and simultaneous production & construction. Estimates of project time savings vary from 20% to 60%. Volumetric modules are installed rapidly on site.
2	*Market perceptions survey*	Most highly ranked volumetric timber advantage in questionnaire and interviews.
3	*Manufacturing survey*	There are opportunities to manufacture up to 36 volumetric modules per work-week, however in the UK the surveyed manufacturers produced on average two modules per week. The surveyed panelised manufacturers had on average output higher than that of UK volumetric manufacturers.
4	*Construction case studies low-rise*	The innovative volumetric timber case study was delayed longer than the conventional open timber panel case study.
5	*Construction case studies mid-rise*	The innovative CLT case study had higher hand-over delays compared to the traditional closed panel case study, however the superstructure in both was installed efficiently.

8.1.2 Cost

Intriguingly, cost was reflected differently in each of the research phases as described in **Table 53**. According to the literature and some surveyed designers, costs for volumetric construction would be higher than in traditional building methods due to the high initial and maintenance capital investment in volumetric timber manufacturing plants. The manufacturing survey revealed that the final property costs were typically determined by the location, size and internal fit-out, rather than the building system. The construction case studies showed that even when this was the case, the costs for the developers in the innovative volumetric and CLT case studies could be higher than expected for the contractor/developer. Overall, it was said that VTC should be cost-neutral, however practical project issues, such as the insolvency of a volumetric manufacturer, could lead to cost issues.

Table 53. Multi-factor variable: **Cost**

N	Research phase	Main theme findings
1	*Literature review*	High capital costs due to manufacturing plant and equipment. Cost savings can be made through increased process efficiency.
2	*Market perceptions survey*	Overall cost of VTC was perceived as cost-neutral, this was also identified as a condition for selection of volumetric timber as a build system. However, some designers hypothesised that VTC would be more expensive than traditional build due to the high capital investment for production space and technology.
3	*Manufacturing survey*	Property costs were determined by location and internal specification rather than construction system. There is a challenge to comparing the costs for different offsite timber systems, including all labour and materials.
4	*Construction case studies low-rise*	The innovative volumetric timber case study experienced cost over-runs for the developer due to supply chain, logistics and contractual issues, whereas in the open timber panel case study a minor additional cost was needed due to incoherent drawing information for the garages of a house type.
5	*Construction case studies mid-rise*	The estimated labour costs for the innovative CLT case study were significantly higher than those estimated for the closed timber panel system per plot, mainly due to the internal and external works.

8.1.3 Labour productivity

Productivity was hypothesised as one of the main advantages of offsite timber construction in the literature, as summarised in **Table 54.** However there was a lack of multifactor productivity analyses of volumetric timber systems in the context of other offsite timber systems and this was addressed in this doctoral work. According to the designers' survey, VTC was perceived as more efficient than traditional methods, however there were infrastructural and cultural barriers to its implementation at scale. Intriguingly, in both the manufacturing survey and the construction case studies, the system which had lower productivity was that which included the internal MEP services and finishes. But in one of the case studies this was due to complications in contractual relationships.

In the manufacturing survey, the panelised manufacturers produced slightly more output per person than the volumetric manufacturers. In the mid-rise case studies the CTP system was found to be more resource-efficient than the innovative CLT method. The CLT project however included completion of all internal and external works onsite, whereas the CTP project had higher factory level completion and also included internal insulation, windows and plasterboard. In the VTC pilot project, the requirement to finish and remediate problems with the interior of the volumetric houses was the most significant reason for project completion date delays.

Although the VTC project studies in this thesis ran into significant difficulties, this observation is in line with previous findings and highlights a need for further research in the synchronisation of internal trades, where Lean, BIM and Location-based management tools can be utilised to improve the flow and productivity of labour resources in offsite timber construction projects. According to the VTC and OTP case studies, 4D BIM, constructability analysis, object-based modelling, collaborative working and continuous process improvement were the most relevant to mitigating existing project management challenges in volumetric timber construction in the UK.

Table 54. Multi-factor variable: **Labour productivity**

N	Research phase	Main theme findings
1	*Literature review*	The ratio between the inputs and outputs of a system. Labour productivity can be measured either as single-variate or multifactor measures, with common inputs labour-hours, workers and common outputs GVA or GDP. Typical levels of productivity measurement in construction are: industry, firm, project and activity. In the USA typically 250 labour-hours were needed to produce a 55 m^2 module.
2	*Market perceptions survey*	Sufficient manufacturing facilities, culture and logistics were one of the main barriers to increasing the specification (and therefore also the output) of UK volumetric timber construction. Panelised timber systems may be more appropriate for the UK market due to simplified logistics and existing capacity.
3	*Manufacturing survey*	Productivity in manufacturing should be calculated with consideration for offsite completion percentage. From the surveyed participants, the labour productivity of the UKP and EUV manufacturers was similar, whereas the UKV manufacturers had lower outputs and tended produce manually.
4	*Construction case studies low-rise*	The project labour productivity could not be calculated; however the modules were quickly and efficiently installed onsite. The efficiencies did not translate into the internal completion works.
5	*Construction case studies mid-rise*	The closed timber panel case study, with the higher factory completion percentage, was more labour-productive on a project level than the innovative CLT case study, however the installation of the two systems was similarly efficient.

8.1.4 Logistics

Similar to some of the previous themes, a positive representation of logistics in volumetric construction was present in the literature, however the research unravelled several challenging aspects of logistics in VTC, as may be seen in **Table 55**. In the manufacturing stage the design limitations in width and heights of the modules due to transport law emerged. Furthermore, in the construction projects studies the innovative system had significantly longer and more complex offsite transport routes, with several checkpoints where the mode of transport or the transport regulations enforcement changed (i.e. transport by boat or police escort). Interestingly, in the CLT case study, the logistical operations were not disrupted, despite the 1,000 mile+ journey to site. Overall logistics should be an important consideration of volumetric timber projects, specifically with respect to utilisation of standard or escorted, water and air transportation methods. This requires early identification of a volumetric manufacturer and the establishment of a collaborative working relationship significantly in advance of manufacturing start.

Table 55. Multi-factor variable: **Logistics**

N	Research phase	Main theme findings
1	*Literature review*	Number of vehicle movements per site can be reduced with VTC, and logistics optimisations in volumetric production have been linked to improved resource efficiency and subsequently also reduced materials waste.
2	*Market perceptions survey*	Transportation was the most significant perceived challenge to VTC implementation in the UK, and panelised systems have the advantage that they can be transported flat-packed within standard load restrictions.
3	*Manufacturing survey*	Logistics restrictions most often determine the maximum module sizes offered by manufacturers. The most often used mode of transport was road, where panelised systems had the flat-pack advantage. Some modular manufacturers used sea transport which was more accessible for sites near sea ports.
4	*Construction case studies low-rise*	In the low-rise projects, the volumetric logistics were a significant challenge and were the main reason behind not being able to increase the rate of modules installed per week. Police escort requirements changed during the life-time of the VTC project and added to the complexity of 300+ miles one-way journey of the modules between three UK areas.
5	*Construction case studies mid-rise*	The need to outsource CLT panels from mainland Europe increased the complexity of the logistics operations compared to the closed timber panel systems, however these were efficiently handled by the CLT installers.

8.1.5 Waste

The theme of *waste* is summarised in **Table 56**. Overall there was an agreement through all phases of the research that increased factory completion of components resulted in lower waste materials both onsite and offsite. This was exemplified by the rigorous waste minimisation strategies applied across the surveyed international offsite timber manufacturers. The installation of CLT panels was one of the lowest-waste activities and during its duration only 200kg of waste per plot were collected. In general, among the construction case studies the cleanliness of the sites seemed to follow the same patterns as the generalised labour productivity trends. During the manufacturing and offsite installation waste was in general minimal, exhibiting high resource-efficiency, however the waste materials generated tended to increase as the synchronisation of trades onsite increased in complexity. This mainly occurred in the internal and external work periods. Quantification of opportunities for waste material minimisation could be an area for future research.

Table 56. Multi-factor variable: **Waste**

N	Research phase	Main theme findings
1	*Literature review*	Offsite timber systems have the advantage of reduced waste materials generated during construction, varying between 40% and 90% estimations depending on the build system. Lean process wastes may also be reduced more easily with offsite production due to the inherent manufacturing efficiencies. When considering the whole life-cycle of the building, Design for Assembly + Disassembly (DfMA+D) can be applied to move construction towards a circular economy model.
2	*Market perceptions survey*	One of the main perceived advantages of VTC, and conceptually closely interlinked with quality control and build quality in construction via the use of CAM in production.
3	*Manufacturing survey*	Waste reduction principles were applied at each stage of the surveyed offsite timber systems, including just-in-time, optimised saws for materials efficiency, waste materials segregation and recycling and others.
4	*Construction case studies low-rise*	In general, low volumes of waste were generated by the volumetric case study, however these could not be compared with data from the open timber panel case study. Waste materials observations onsite increased as the completion level of modules delivered to site decreased.
5	*Construction case studies mid-rise*	Exemplar materials storage and waste minimisation were observed during the CLT superstructure installation and the quantities of waste produced per plot were smaller for the CLT case study, compared to the closed timber panel case study.

8.1.6 Building Information Management (BIM)

A summary of *BIM* is summarised in **Table 57**. Although the literature revealed numerous opportunities for BIM and VTC utilisation with cross-mutual benefit, this was sparsely represented in the market and manufacturing surveys, and construction case studies. In the medium-rise construction projects, the CLT installers used 4D BIM to communicate the build programme, whereas in the manufacturing survey one UKV manufacturers had used augmented reality in their quality control processes. Therefore, there are untapped opportunities for BIM and VTC integration to increase project efficiencies according to MFP variables, such as time, environmental credentials and cost analysis.

Table 57. Multi-factor variable: **BIM**

N	Research phase	Main theme findings
1	*Literature review*	There are theoretical overlaps between BIM and offsite manufacturing. 4D BIM has been utilised to optimise the productivity and sustainability of a volumetric manufacturing facility. Further BIM tools offer possibilities for efficiency improvement through more efficient information management.
2	*Market perceptions survey*	Overall BIM was perceived as a relevant opportunity for offsite manufacturing, however barriers such as cross-industry collaboration were identified as limiting. Participants had used component-based 3D modelling, however had not utilised 4D+ BIM dimensions analysis.
3	*Manufacturing survey*	There was uncertainty around the definition of BIM and manufacturers stated, it should not be confused with the selection of one software over another. Some manufacturers experimented with new BIM technologies, however most were interested in BIM from a regulatory point of view.
4	*Construction case studies low-rise*	BIM was not utilised however there were intentions to use BIM Level 2 on similar future projects.
5	*Construction case studies mid-rise*	BIM was used in the design and 4D BIM was used as an effective tool to communicate the CLT superstructure installation schedule.

8.1.7 Specification & Installation

Specification & installation are presented together because of their inter-connection, as the specification will influence the installation process, and the installation process should inform the product specification. Overall there was an identified gap in knowledge on DfMA information for offsite timber systems amongst built environment designers, and therefore this doctoral thesis has provided an in-depth production and construction process analysis of offsite timber systems – see **Table 58**. VTC was considered suitable for various building typologies in the UK, including educational, office and retro-fit projects in the UK. VTC and CLT installation processes were quantified and analysis showed they were both efficient.

Table 58. Multi-factor variable: **Specification & Installation**

N	Research phase	Main theme findings
1	*Literature review*	There are geographical differences in volumetric timbers systems specification and although some guidelines such as the RIBA DfMA Overlay to the Plan of Work existed, there was a gap in knowledge on practical specification DfMA+D guidelines applicable across different manufacturers.
2	*Market perceptions survey*	The specification of volumetric timber systems in residential projects was perceived as the most suitable building type for VTC. However, the views varied between applicability in large repeatable-design developments versus applicability limited to garden studios and other small, technically simple structures. The specification of VTC was perceived as advantageous for achieving increasingly strict environmental sustainability regulations. One potential barrier for VTC were fire regulations.
3	*Manufacturing survey*	The offsite products specification was mostly flexible to meet different client requirements, with some examples of standardised products. The volumetric timber systems' offsite completion percentage was approximately 60% (slightly lower in the EU and higher in the UK on average), whereas the average panelised offsite completion percentage was 25%.
4	*Construction case studies low-rise*	The installation of volumetric timber modules was efficient and required a low number of operatives on site. In three hours and thirty minutes four modules were installed, constructing two wind-tight and water-tight semi-detached two-bedroom houses. Plant used included a mobile crane and hand-held common tools with a crew of three crane operatives and three offsite system installers. The installation of open timber panels was also efficient and required less plant and less human-power for the panel installation. However, it required four weeks of intense work onsite to be wind-tight and water-tight.
5	*Construction case studies mid-rise*	The CLT installation process was structured efficiently and the team of eight on average were separated into four installers responsible for hoisting the panels and four trainees responsible for finishing the connections afterwards. One tower crane was hired for the CLT installation process. Building information Modelling was applied via a components-based model. The building specification details were completed in 2D CAD, which was considered best practice for drawing production efficiency.

8.1.8 Carbon & Energy

Overall, volumetric and CLT systems were shown to be advantageous for energy-efficiency of buildings, specifically in air tightness values. All investigated case study projects achieved their targeted environmental sustainability metrics, including air tightness, U-values, acoustics, water flow etc. In addition, the manufacturing survey revealed that that systems can be adjusted to fit the client and designers' sustainability requirements – see **Table 59**. When these findings are combined with environmental sustainability as one of the main emerging drivers for volumetric and offsite timber systems specification, it could be speculated that these building methods would be useful tools to achieving the increasingly stringent energy performance requirements using passive (energy-conserving) rather than active (energy-generating) energy reduction approaches.

Table 59. Multi-factor variable: **Carbon and energy**

N	Research phase	Main theme findings
1	*Literature review*	Several LCA studies have identified offsite timber systems as having lower climate change potential impact, however the CLT system has been shown to be advantageous for air tightness and operational energy.
2	*Market perceptions survey*	The low carbon agenda was perceived as a significant VTC enabler, in the context of increasingly stringent energy-efficiency requirements.
3	*Manufacturing survey*	The air tightness and U-values of surveyed volumetric timber manufacturers tended to be higher than those of panelised timber manufacturers, although Passivhaus specification was possible with both systems. Only one surveyed company took an interest in embodied carbon calculations.
4	*Construction case studies low-rise*	Section 7 Gold standard was achieved by the volumetric timber construction project. Post-occupancy study by SEC is pending.
5	*Construction case studies mid-rise*	The CLT system was advantageous in achieving high air tightness and high U-values. Scottish Section 7 Gold was not targeted, and the targeted Silver level was achieved. The embodied carbon was considered advantageous however an exact calculation was not made.

8.1.9 Build quality

Build quality was one of the most cited and perceived advantages of volumetric timber systems, and as can be seen in **Table 60**, this was confirmed by the manufacturing survey by the numerous examples of quality control systems, including third-party accreditation. In contrast, the construction projects revealed the increased complexity of dealing with build quality on site, and the challenges of its quantification. Overall it could be said that offsite timber systems have the potential to achieve high build quality, however complex connection, detail and component specifications, as well as supply chain issues, could result in build quality issues both in the offsite and onsite stages.

Table 60. Multi-factor variable: **Build quality**

N	Research phase	Main theme findings
1	*Literature review*	The build quality of VTC is inter-connected with building air tightness. VTC can reduce defects in construction, however even in strictly quality-controlled environments there is a chance for human error and lifting cracks in the plasterboard, which require re-work.
2	*Market perceptions survey*	VTC was perceived as having the opportunity to provide defect-free homes. This theme was interconnected with energy performance.
3	*Manufacturing survey*	Quality control procedures were in place for all offsite products prior to despatch and step-by-step quality control was applied by most surveyed volumetric timber manufacturers. Two organisations used third-party quality certification.
4	*Construction case studies low-rise*	Supply chain issues lead to manufactured product quality issues and although the traditional open timber panel pilot case study had on average 23 snag items, this was judged to outperform the build quality of the volumetric project.
5	*Construction case studies mid-rise*	Snagging and quality inspections were a significant part of both case study projects' programmes and could potentially be optimised with increased added value to products in the quality-controlled factory environment. In the CLT case study, the differences in nail-plate connections specification and the challenging installation of the levels 1, 2 and 3 wall-floor screw connections resulted in a need for re-work.

8.1.10 Health & Safety (H&S)

The literature, manufacturing and perceptions research phases confirmed the positive aspects of offsite timber construction with regards to H&S, including reduced strain due to heavy lifting and reduced need repetitive tasks due to automation. In the construction case studies, some H&S challenges of volumetric modules installation were revealed and a new H&S dimension to CLT connections installation was proposed for use by designers, which could be applicable across different offsite timber systems. Overall, it could be hypothesised that offsite timber systems have inherent potential for H&S optimisation, however the buildability of tasks should be analysed in detail and according training provided with further research– see **Table 61**.

Table 61. Multi-factor variable: **H&S**

N	Research phase	Main theme findings
1	*Literature review*	In general, offsite construction is portrayed to have improved health and safety through increase use of automation to remove repetitive and heavy handling tasks in the factory environment, and reduced need for work onsite.
2	*Market perceptions survey*	Improved Health and Safety was one of the perceived advantages of VTC however this was not one of the main factors.
3	*Manufacturing survey*	Increased H&S requirements can be a main driver for increased VTC specification.
4	*Construction case studies low-rise*	Some H&S challenges with volumetric units' installation had to be resolved onsite. Constructability analysis (a BIM tool) could have been applied to develop these solutions in advance. Minor OTP case study issues with wearing full PPE.
5	*Construction case studies mid-rise*	The CLT panels' installation was considered a high-risk activity due to the crane utilisation, however the system offered increased H&S through the use of an internal circulation staircase. In a separate study included in the Appendices, the potential hand-arm vibration syndrome effects of challenging CLT connections was estimated. Minor CTP case study issues with wearing full PPE.

8.1.11 Multi-factor productivity analysis summary

The knowledge from the multi-factor productivity analysis according to ten MFP variables was used as the foundation for the development of an offsite timber systems multi-factory productivity (MFP) index. This revealed that some variables were more important considerations and had higher quantification potential utilising typical construction documentation combined with site observations. A more in-depth investigation of the different measured variables and their applicability according the framework of productivity variables identified in the literature review was discussed in section **7.5 CLT and CTP case studies summary**. Two of the seven main identified variables, BIM and sustainability were measured only with reference to generalised levels. They were therefore dismissed from the MFP index inputs because of a need for more detailed measurement such as embodied CO_2-e per m^2, global warming potential, BIM level of details, workflows, dimensions and efficiency improvement. For this reason, it was decided to categorise these as secondary for qualitative analysis, along with build quality, health & safety and the interface between specification and installation. Therefore, the following five key MFP variables were identified from this multi-phased research for comparative productivity analysis of offsite timber systems:

- Time
- Cost
- Labour productivity
- Logistics
- Waste materials

8.2 Offsite timber systems multi-factor productivity index: a theoretical framework

In the literature review various methodologies for productivity measurement in construction were investigated, and at this stage two main guides by the OECD were utilised to outline a theoretical framework for an offsite timber construction MFP index: the *Handbook on Constructing Composite Indicators* and the *Better life index,* along with scientific publications in its support (OECD, 2008, 2018; Land, Michalos & Sirgy, 2012). (Land, Michalos & Sirgy, 2012). However, in contrast to the national analysis level of the Better life index, the proposed offsite timber systems multi-factor productivity of construction projects evaluates at a project level (Kenley, 2014)**.**

The aim of the offsite construction MFP index is to collect data from a range a case studies utilising offsite timber construction systems with different levels of completion in the factory. The collected anonymised database may be utilised to help decision-makers select the offsite timber system most suitable to their project priorities. It is anticipated that sub-assemblies, panelised and volumetric systems for example will have different strengths according to each of the five key variables. Having a robust data-base with consistent information about a range of case studies will be useful for construction decision-makers to inform the selection of construction systems on specific projects according to the stakeholders' priorities. It may also be useful for policy-makers to inform policies on stimulating the productivity of the construction industry. Primarily, it will be useful to researchers working in construction management and other similar fields, as a unique contribution to knowledge on understanding the MFP performance of different offsite construction systems.

8.2.1 Refined MFP variables

Based on the above research analysis and findings, the following theoretical framework for an MFP index for offsite timber systems is outlined, with five MFP variables as outlined in **Table 62**. Throughout the different stages of the research, these were identified as the variables with highest relevance to the investigated phenomenon, measurability and analytical reliability (OECD, 2008). The market survey analysis confirmed these factors' relevance to offsite timber systems application in the UK. The manufacturing survey and the construction case studies demonstrated that data could be collected from existing standard construction project documentation combined with additional data collection.

Table 62. Initial proposal for MFP index for offsite timber systems primary variables

N	Variable name	Design	Manufacturing	Construction
1	*Time*	Total design time. Design time per stage.	Production time per stage. Production time per complete product. Number of products per week.	Construction time per stage. Original hand-over date milestone versus actual hand-over date.
2	*Cost*	Design teams' structure. Planning application and other administrative costs.	Materials costs per module/panel on average. Labour costs per module/panel on average.	Labour costs per resource type and per construction task. Overall project costs if available.
3	*Labour productivity*	Labour-hours per occupation	Labour-hours per normalised unit output.	Labour-hours per trade and per task.
4	*Logistics*	Supply chain considerations. Transport distances from key materials' factories to site.	Number of supply chain partners. Average lead-in times per product category.	Number and distance of offsite system deliveries. Distance per transport route stage (offsite systems only).
5	*Waste*	Allowance for materials waste. Materials optimisation strategies.	Waste materials produced in the factory during project production.	Waste materials generated per plot. Percentage of recycled waste and waste sent to landfill.

The remaining five variables could be considered as secondary, and would more appropriately be investigated using qualitative methods with nominal categories, as their data availability varied highly across manufacturers and case studies. This created obstacles to the association of a comparative ranking or values associated with qualitative categories:

- BIM & Digitisation
- Specification & installation
- Carbon & energy
- Build quality
- Health & Safety

8.2.2 Composite variables normalisation, weight and aggregation

The comparability of variables is dependent upon their normalisation, weighting and aggregation which typically involve the adjustments of measurement scales (OECD, 2008).

The offsite timber construction MFP index includes five variables with different units if measurement across three separate project life-cycle stages, design, manufacturing and construction. Yet different units of measurement such as hours and tonnes should not be mixed together, and it is proposed that a normalised ordinal scale is utilised to mitigate this shortfall. An ordinal scale is one where *'the order of the values is what's important and significant, but the differences between each one is not really known'* (Man, 2017). In the case of quality of life measurement for example ordinal scales were recommended for composite measures due to their comparability between different cases (Land, Michalos & Sirgy, 2012). This type of scale allows for some quantitative analysis methods, although these are potentially limited depending on the normalised distribution of the values (Gray, 2004).

The proposed ordinal scale has the following definitions to allow for application across different scenarios, size of projects, units of measurement and others. It was derived using the established and widely-used Likert scale with the difference between the different categories based upon impact on project stakeholders' priorities. This was done to achieve the aim of utilising the MFP index to help guide decision-makers when selecting an offsite timber system according to their identified project priorities, and to pave the way towards collecting data on a range of case studies to construct and offsite timber construction MFP database:

- 1 = Very poor (significant project issues with impact on multiple stakeholders)

- 2 = Poor (significant project issues with impact on a single stakeholder)
- 3 = Neutral (minor project issues, mostly mitigated)
- 4 = Good (significant benefit to a single stakeholder)
- 5 = Very good (significant benefit to multiple stakeholders)

The weight of factors in composite indices is a critical consideration, and according to a study which compared the sustainability of 27 EU countries, the linear method of aggregation was the one most typically applied in composite indicators creation, where one and the same weight is assigned to each variable (Luzzati & Gucciardi, 2015). However, the authors opted for the 'concave mean aggregation', which allowed for good performance according to one variable to compensate for poor performance in another variable (Casadio Tarabusi & Palazzi, 2004).

In this thesis, any compensation for poor performance in one criteria by good performance in another criteria, could only be determined by the individual project stakeholders. Two example variables may be used to illustrate this: time on-site and waste materials. It is anticipated that most contractors' priority will be placed on time on-site, because they could not utilise low quantities of waste materials as an explanation to a client if a project runs over-time. However this is only an initial hypothesis and the true stakeholders'' priorities would need to be assessed in detail prior to detailed weighting of indicators and variables. If the five, or indeed ten, variables were to be weighted, several focus groups workshops with key industry stakeholders would be necessary and this falls within the scope of further work.

Therefore, to maintain simplicity, in this thesis linear aggregation is utilised, with the option for a workshop to be held with stakeholders prior to implementation of the index, to identify the stakeholders' priorities (Mishra, 2008; Gray, 2004). In the case of the *Better Life* index, for example, users set their priority levels for each of the indicators, according to which the online platform provides a ranking of different countries with detailed profiles available (OECD, 2018). With further work a similar user input prioritisation interface may be created for the offsite construction MFP index.

Although refining these variables into an MFP index equation with composite indicators falls within the scope of further work, the following can be proposed in this thesis as a methodology for evaluating the MFP of case study projects utilising offsite timber systems.

MFP input:

- time (T) = *mean overall duration per plot (hrs/living-unit equivalent)*

- labour (L1) = *mean overall labour-productivity (labour-hours per living-unit equivalent)*
- cost (C) = *overall contract cost (£/living-unit equivalent), may also be termed capital*
- waste (W) = *waste materials (tonnes/living-unit equivalent)*
- logistics (L2) = *offsite system transportation mean (km/living-unit equivalent)*

MFP output:

- 1 Living-Unit Equivalent (LUE, may also be termed 1 plot in site jargon, or 1 home for outreach materials)

$$MFP\ offsite = \frac{T}{LUE} + \frac{L1}{LUE} + \frac{C}{LUE} + \frac{W}{LUE} + \frac{L2}{LUE} \quad \text{Equation 7}$$

This may be utilised as a starting-point for the creation of an offsite timber systems MFP database The KLEMS MFP index took its name from an acronym of the main inputs, and if this is applied to the offsite timber systems MFP index, the name ‘W T C L^2’could be applied as an intermittent name.

With further work on the variables, their weighting and expression in equations, a more suitable name may be found for the index. In addition, the relationship between input and output was inverted in Equation 7, because it was deemed more useful to compare how much input was necessary to produce a single living-unit equivalent. This may reverted back to the established input to output relationship with further work on the development of an MFP index spanning design, manufacturing and construction.

8.2.3 Offsite MFP index visualisation

Figure 113 shows an early visual representation model of a construction project, developed by the author, where the baselines productivity was visualised as a circle with four segments: programme time, number of people, labour-hours and economic sustainability.

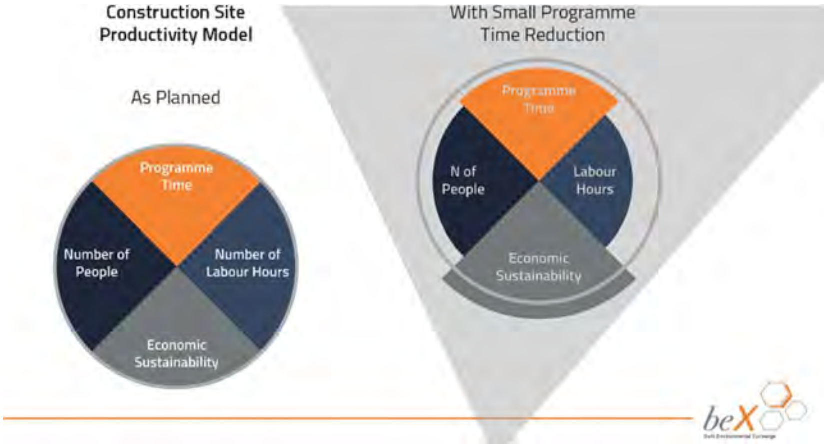


Figure 113. Construction project productivity conceptual model for offsite timber systems. Author's own work 2017.

Here the programme time segment acted as the keystone to the balance. For example, with a small reduction in programme time and subsequent optimisation of labour flow, the labour-hours required to construct the project could be reduced significantly. Therefore, with consideration for added advantages such as reduced loan durations and early revenue returns from the property, the economic sustainability of the construction projects could be significantly increased, as the second circle with a grey background in the figure shows.

These ideas were refined with established data visualisation techniques to arrive at the selection of the so-called 'spider diagram' (radar chart) as the most suitable results visualisation and communication medium with scientific publications (McCandles, 2009; Kirk, 2016). In this chart type each of the MFP variables is in concentric radial lines forming, and in the case of the *Offsite Housing Review* shown in **Figure 114**, where eight variables were used this formed a series of concentric octagons. The performance of each type of offsite system was then plotted in a different colour by connecting the values per category with a solid line. This way, the radar chart allows comparison of multi-factor performance in way that makes it easy to observe patterns.

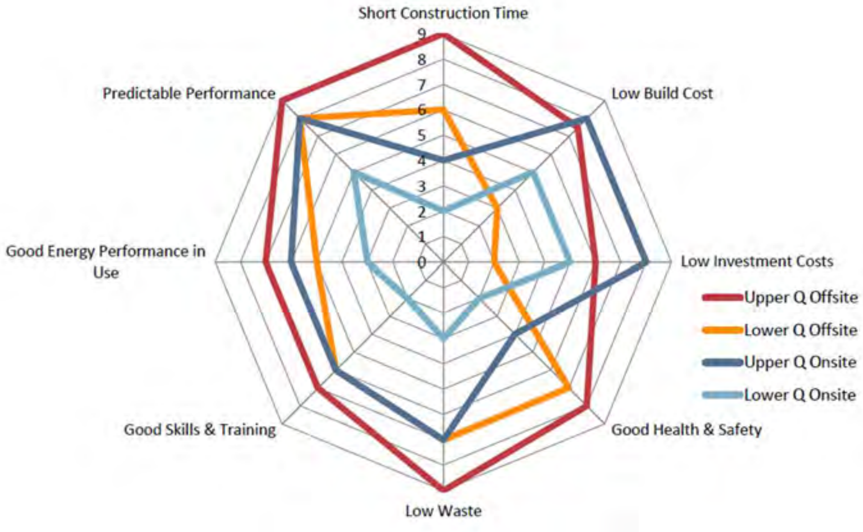


Figure 114. Spider diagram used to communicate the differences between offsite and onsite construction. Adapted from (Miles & Whitehouse, 2013).

When applied to the Offsite Timber Systems MFP index with a five-point ordinal scale according to five MFP variables, the visualisation would be as shown in **Figure 115**, using a hypothetical case. This idea can be furthered potential for expansion into an on-line tool, where users could input weighting of each variable, similar to the *Better life index*.

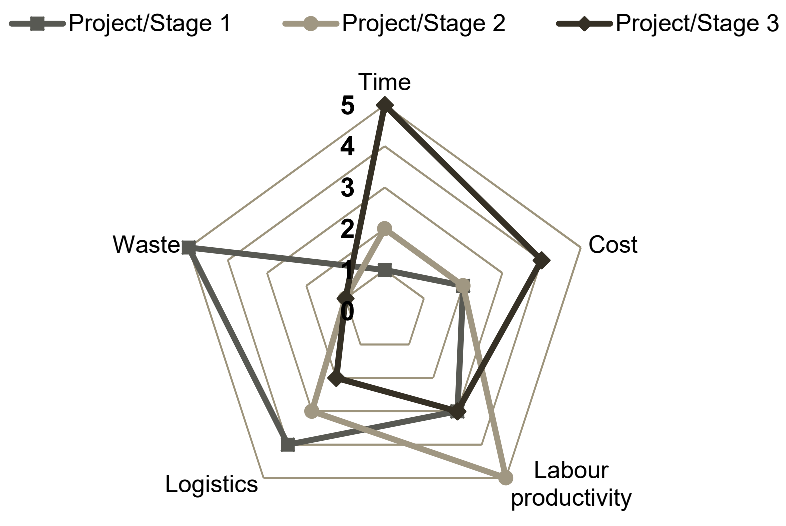


Figure 115. Proposed visualisation of Offsite timber Systems MFP index: single-project or stage, and multiple project or stages.

8.3 Offsite timber systems multivariate analysis

8.3.1 Offsite timber systems

Comparative retrospective data was available for four construction case studies, VTC (volumetric), OTP (open timber panel), CLT (cross laminated timber) and CTP (closed timber panel) from previous chapters. When these analyses were transformed to the specified ordinal values, they may be compared as shown in **Figure 116**. The score for each case study across each of the MFP variables was completed by reviewing the information from the cross-chapter summary in **Section 8.1 Multi-factor productivity analysis of offsite timber systems,** and the results reported in **Chapters 6 and 7**.

For example, in the case of the VTC case study, logistics caused significant issues to all stakeholders by limiting the frequency with which modules could be delivered to site, and this contributed to time delays for the client and unexpected costs for the developer. Time onsite delays had an impact on multiple stakeholders, including the lender, the developer, the client and the main onsite contractor. Interwoven with this were extensions to loans, and remediation costs onsite following some modules being delivered incomplete. These had a negative impact on the developer's finances. Waste materials however were low in numbers and this contributed to a cleaner site environment. Apart from the main contractor, no other stakeholder experiences benefits from this advantage. Labour productivity caused an issue for the developer during the remediation stages, when skilled labour to undertake work on the volumetric homes was challenging to source and progress was unpredictable due to snagging issues. The same approach was undertaken in allocating values on the created ordinal scale to the remaining case studies.

Although in three instances the offsite installation was rapid and efficient, other project areas especially the cladding and interior work resulted in overall project delays with impact on single or several project stakeholders. Indeed, this was the case in both innovative projects, VTC and CLT. The exception to these observations was the OTP case study, whose overall performance could be said to be neutral in all five main categories, and indeed this was originally identified as a standard-practice benchmark. In addition, both innovative case studies experienced some issues with logistics. The long CLT lead-in times had an impact on the engineering design deadlines and the panels required transport from mainland Europe, whereas in the VTC project enforcement of regulations for abnormal load transport caused challenges for the optimisation of the construction programme. With that being said, three of the case studies performed positively with regards to minimising waste materials on site, and the VTC case study was constructed to high energy standards, demonstrating environmental sustainability benefits.

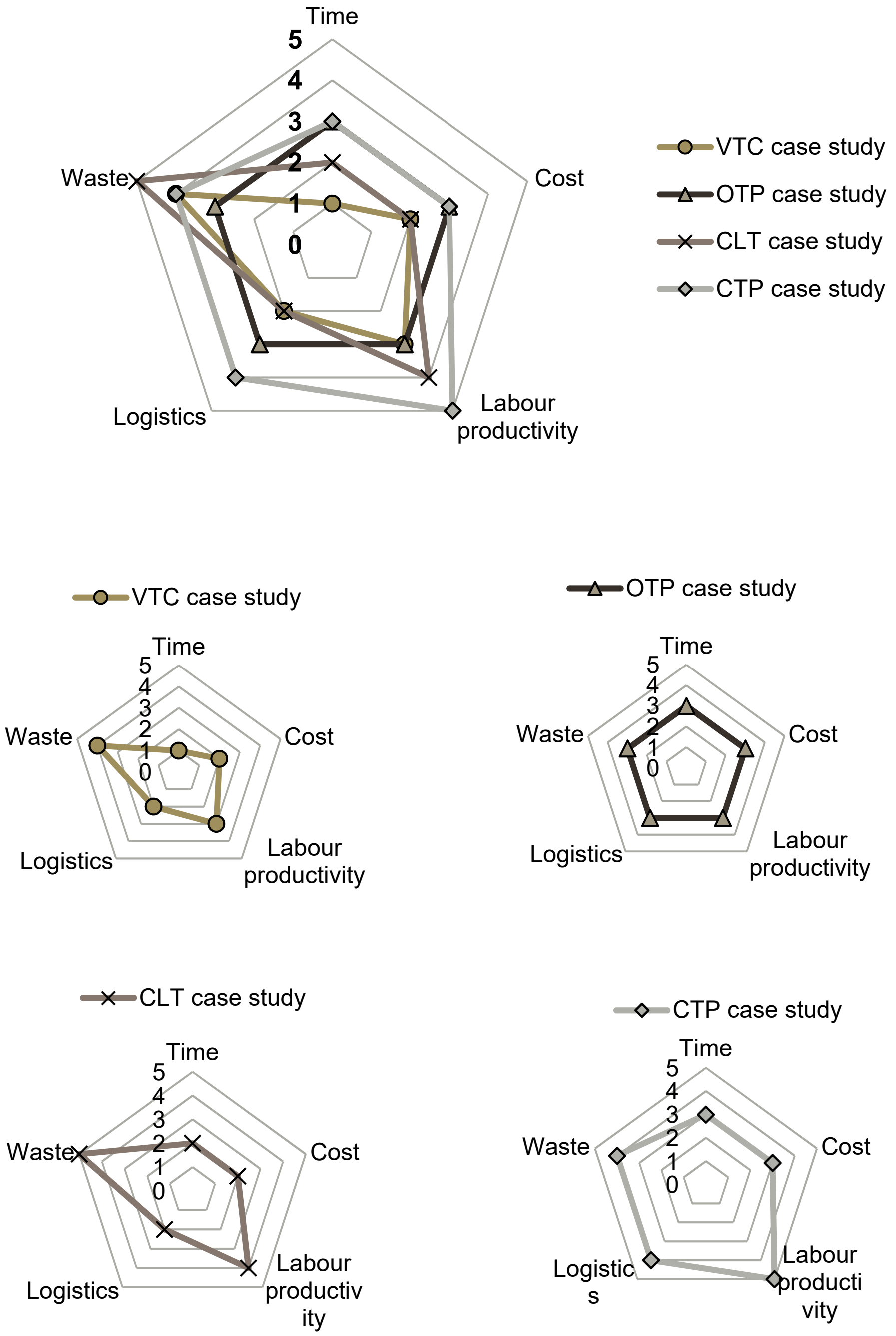


Figure 116. Comparative analysis of four construction case studies, on a project level with emphasis on the offsite system installation stage.

8.3.1 Labour-productivity analysis

To explore the future quantification through nominal variables summated in composite indicators, one of the five key variables was investigated in further detail, to examine the maximum and minimum values, as well as the potential impact of error of measurement on the comparative results and finally rank the four offsite timber systems in order of productivity performance (Murray-Smith, 2015). Because the focus of this study was productivity in the construction industry, the most critical variable, labour productivity was identified for this in-depth analysis (Gray, 2004).

Detailed labour productivity was available for the CLT and CTP full scale case studies, and was compared on a stage and task level. There were gaps in the full comparative data to this extent for the VTC and OTP case studies, however information was available for typical duration of the offsite system installation per plot, and the number of people needed to complete the work. In addition, from the frequent site observations, photographic data and clerks of works reports', informed assumptions were made on the duration, labour and productivity of the internal finishes and the external cladding. Overall these are summarised in simplified form as listed in **Table 63**, where the labour-productivity per plot was estimated by multiplication of the duration per plot by the number of people per plot, to arrive at comparative labour-hours per plot as shown in Equation 8. The error of measurement for these values could be estimated at 10% based on previous similar studies (Jarkas, 2016; Oberkampf *et al.*, 2002).

Table 63. Labour productivity analysis across four construction case studies

Variable with units/ shown in (brackets)	VTC	OTP	CLT	CTP
Offsite system installation per plot duration (hrs)	2	40	4	14
Number of people for offsite system installation (N)	6	3	8	3
Offsite system installation productivity per plot (labour-hours)	**12**	**120**	**32**	**52**
Cladding installation per plot duration average (hrs)	34	30	28	18
Cladding people per plot average (N)	6	5	18	5
Cladding productivity per plot (labour-hours)	**204**	**150**	**504**	**72**
Internal finishes per plot duration on average (hrs)	50	25	60	27
Internal finishes per plot people on average (N)	10	27	21	30
Internal finishes per plot productivity on average (labour-hours)	**500**	**675**	**1260**	**810**
Average productivity (labour-hours)	**239**	**315**	**598**	**311**

$$\frac{duration}{plot} \times \frac{labour}{plot} = labour\ productivity\ (labour - hours\ per\ plot) \quad \text{Equation 8}$$

If similar to the manufacturing survey, the differences in actual values are transformed into comparative rankings , it could be estimated that the four case studies would be ranked as shown in **Table 64**, where 1=best and 4=worst. These results suggested that VTC construction was in fact overall with highest productivity, however due to the low number of people onsite and respectively longer task durations, this was not observed as an advantage to any of the project stakeholders. The VTC labour-productivity ranking was followed closely by CTP, and OTP case studies, whereas CLT was much lower. Due to the assumptions necessary in some these data, the scientific applicability of these findings is limited to the investigated construction projects. However the ranked results can start to guide future decision-makers on the most suitable offsite timber system for their project if labour-productivity was a priority for them. With more data collected from a range of case studies, this approach can be validated and transformed into an interactive tool, where multiple prioritise criteria will be utilised to guide decisions on offsite timber systems application.

Table 64. Labour productivity analysis across four case studies: ranks

Variable with units shown in (brackets)	VTC	OTP	CLT	CTP
Offsite system installation per plot duration (hrs)	1	4	2	3
Number of people for offsite system installation (N)	2	1	2	1
Offsite system installation productivity per plot (labour-hours)	**1**	**4**	**2**	**3**
Cladding installation per plot duration average (hrs)	4	3	2	1
Cladding people per plot average (N)	2	1	3	1
Cladding productivity per plot (labour-hours)	**3**	**2**	**4**	**1**
Internal finishes per plot duration on average (hrs)	3	1	4	2
Internal finishes per plot people on average (N)	1	3	2	4
Internal finishes per plot productivity on average (labour-hours)	**1**	**2**	**4**	**3**
Total labour-productivity rank	**1**	**3**	**4**	**2**

8.4 Offsite timber systems MFP index summary

The main contribution to knowledge of this thesis was presented here, a proposal for an innovative MFP index for offsite timber systems with a five-point ordinal scale and five MFP variables: time, cost, labour productivity, logistics and waste. The proposal of this composite index was based on an in-depth multi-factor productivity analysis of offsite timber systems in literature, market, manufacturing and construction. The labour productivity was investigated in most depth and the final comparative analysis of four offsite timber systems showed that their ranking in terms of labour efficiency was as follows, in order from least to most efficient: CLT, OTP, CTP and VTC. This could be associated with the level of offsite completion in the factory of the different systems discussed in **Chapter 5**, as the systems with the higher completion in the factory tended to have higher estimated labour productivity ranking. Yet innovation was often a barrier for increased efficiency, as the innovative CLT and VTC project encountered several regulatory and supply chain issues.

Chapter 9: Conclusion

This doctoral study investigated the multi-factor productivity of offsite timber systems using a mixed methodology with six stages: a literature review, market survey targeted at designers, manufacturing survey, construction case studies and a proposal for an offsite timber systems MFP index. The staged approach with combination of qualitative and quantitative methods enabled findings from one phase to inform the research scope and analysis of the following research phase. Therefore, emerging knowledge and concepts were utilised, tested and refined throughout the research within a consistent framework of ten MFP variables to ensure the robustness of the conclusions.

Contribution to knowledge

The doctoral research provided an innovative comparative productivity analysis of volumetric timber systems in the context of three panelised timber systems. The author's contributions to knowledge have been the following:

- Unique and original comparative productivity analysis method according five main quantitative variables on an ordinal scale, and five secondary and qualitative variables
- Novel comparative detailed bottom-up labour productivity analysis of CLT and CTP case studies
- Multi-factor productivity analysis of VTC and OTP case studies with development of a new method for measurement of offsite timber labour productivity
- In-depth comparative product, process and productivity analysis of UK timber panels, UK volumetric and EU volumetric timber manufacturers; with consideration for differences in work completed in the factory
- A snapshot in time of the perceived market opportunities and challenges of VTC in the context of panelised timber systems, amongst built environment designers
- An original exploration of offsite construction literature to identification of ten MFP variables for multi-factor productivity MFP analysis of offsite timber systems

These significant contributions to knowledge were enabled by the following incremental innovations in each of the six research phases:

Market perceptions survey

- A snapshot in time of the knowledge level among designers regarding volumetric timber systems and panelised timber systems, with identification of the most effective knowledge dissemination methods (provision of technical guidance documents with strong evidence).
- An evaluation of VTC's opportunities and challenges according to their perceived importance among designers and wider stakeholder groups, where the criticality of efficiency factors relating to time, cost and build quality was revealed.
- Captured perceptions relating to the technical applicability of VTC and other offsite timber systems for several building typologies with varying requirements for design flexibility, where the importance of panelised timber systems as a means to increase design adaptability was exposed.

Manufacturing survey

- In-depth comparative product, process and management strategies analysis of UK timber panels, UK volumetric and EU volumetric timber construction.
- A novel calculation of the distribution between offsite and onsite work, to arrive at offsite completion percentages of each sampled system, benchmarked against the survey participants' estimates and findings from literature.
- Benchmarked comparative analysis of offsite timber systems manufacturing production and productivity, with consideration for varying percentages of offsite completion in the factory.
- Sensitivity and generalizability of the above analysis, which demonstrated that the surveyed UKP and EUV companies had similarly high performance within an established market, whereas that UKV companies had great potential for growth as their market matured.

Construction case studies: low-rise residential

- Explorative use of BIM tools, data collection and analysis spreadsheets and project management software for comparative offsite construction productivity measures.
- WBS for comparative productivity analysis of offsite timber systems, which built upon best-practice in the field, and was developed by cross-comparison of typical construction sequences of four different building methods.

- In-depth installation constructability analysis of the investigated volumetric system in the context of standard-practice open panel construction
- Piloted multi-factor comparative productivity analysis according to 10 MFP variables, developed throughout the course of the research and taken forward in the medium-rise case studies with use of Microsoft Project and customised site visit data collection sheets.

Construction case studies: mid-rise residential

- Constructability comparison between CLT and closed timber panel systems.
- In-depth constructability analysis of the CLT installation process with 31 observations regarding best-practice for enhanced assembly productivity.
- A CTP case study construction programme building was compiled from onsite observations, construction documents and interviews with site managers.
- Planned versus actual analysis of an innovative CLT case study building in Scotland.
- Comparative detailed bottom-up labour productivity analysis of CLT and closed timber panel systems, with estimates for labour costs.
- Causation theorised between key constructability characteristics and comparative productivity results.
- Novel qualitative multi-factor productivity analysis comparing the CLT and closed timber panel case studies.

Offsite timber systems MFP index theoretical framework

- Synergy of the findings from the previous research stages into a unique and original comparative productivity analysis method according to ten MFP variables, of which five were categories as 'main' and quantitative, and five were categorised as 'secondary' and qualitative.
- Identified radar chart visualisation for comparative productivity analysis.
- Novel MFP analysis of VTC in the context of three panelised systems according to 10 MFP variables (5 main, and 5 secondary) across the literature review, market, manufacturing and construction research.

9.1 Multi-factor productivity of offsite timber systems

The comparative multi-factor productivity analysis demonstrated that in most variables there were inconsistencies between the often positively portrayed research findings on offsite technologies, and the practical challenges observed during the construction case studies. Yet there was sufficient consistency between the findings in the literature, manufacturing and construction research phases to state that increased specification of offsite timber systems could result in improved labour productivity, waste materials, and specification & installation economic performance. These three areas are significant in the context of the UK construction productivity stagnation, the skilled labour shortage and the need to drastically reduce waste materials generated in construction within an overall drive towards a more circular construction economy. The following findings will be of interest to key built environment stakeholders such as architects, architectural technologists, engineers, local authorities, housing associations, private developers and policy-makers, regarding offsite timber systems:

1. There is great potential for **time** saving, however it is not guaranteed and innovative project management techniques can be used to optimise the programme time of offsite timber projects. In first-of-their-kind projects with ambitious programmes, programme build delays are to be expected due to unforeseen challenges.
2. VTC should be **cost**-neutral, however practical project issues in this study specifically the insolvency of the volumetric manufacturer, led to significant cost issues. The final sale price of properties was determined by the local market, rather than the offsite system.
3. The **labour productivity** of offsite system manufacturing and assembly is likely to be high due to process efficiencies from the manufacturing industry as opposed to the stagnation of productivity noted in the literature review, as was observed in Chapter 5 where one manufacturer in the EU produced to the equivalent of 11.5 apartments per week. However, the internal and external finishing works in offsite timber projects should be synchronised with the offsite activities to create an optimum interface between the offsite and the onsite work, and transfer the labour productivity efficiencies to the entire project. This issue was observed in Chapter 6 and 7, construction case studies, especially in the CLT and CTP case studies, where half of the labour-hours were utilised on the internal works.
4. **Logistics were reviewed in the literature review and were found to be** are a critical component of offsite timber projects. This was most critical in the VTC case study, whose logistics issues had an effect on all project management aspects. Logistics details should therefore be agreed as early as possible.
5. During the manufacturing and offsite installation **waste** in general was minimal, however the waste materials generation tended to increase as the synchronisation of trades onsite increased in complexity, mainly in the internal and external work periods. Opportunities

for waste materials information integration with component-based modelling for offsite construction is an avenue for future exploration in BIM-offsite studies.

6 4D **BIM** and constructability analysis seem to be the most relevant BIM tools for offsite productivity optimisation, however there seem to be untapped opportunities for BIM and VTC integration to increase project efficiencies according to KPIs, including time, environmental and cost analysis.

7 VTC is suitable for **specification** in various building typologies in the UK outside of residential developments, e.g. educational, office and retro-fit projects in the UK. CLT can also be utilised to reach higher building heights or build lightweight rooftop extensions. VTC and CLT case study **installation** processes were quantified and analysed in detail to reveal that these aspects of the build were already efficient, however from observations the completion works lacked process rigour and were less efficient.

8 It could be speculated that VTC and CLT building methods would be useful tools to achieving the increasingly stringent energy performance requirements for carbon reductions and **energy-efficiency**, which is an important driver for building method selection among clients and designers.

9 Offsite timber systems have the potential to achieve high **build quality** (low to none defects), however complex connection, detail and component specifications, as well as supply chain issues, could result in revocable build quality issues both in the offsite and onsite stages.

10 VTC and panelised offsite timber systems have inherent potential for **H&S** optimisation, however the buildability of tasks should be analysed in detail and according training provided, perhaps with the use of wearable smart PPE.

9.2 Productivity differences between offsite timber systems

Overall, the manufacturing productivity results demonstrated that the sampled volumetric timber manufacturers in the UK had lower capability, compared to UK panelised timber manufacturers, whose performance was in turn marginally lower than that of the EU volumetric timber manufacturers. This may be associated with higher application of technology in the panelised systems' manufacturing, supplemented with differences in the market maturity of the volumetric and panelised market segments in the UK and the EU. The EU volumetric timber manufacturers tended to act as sub-contractors and their systems typically included the cladding and internal finishes, with several customisation options. This was relevant in the context of the observed four construction case studies, where the cladding and internal finishes tended to have the lowest labour productivity, and whose delays tended to cause subsequent project delays with some impact on the client. The cladding system utilised in the CLT case study specifically was highly labour-intensive, as each of the brick slips was applied manually on-site on a weatherboard, and the mortar was painted afterwards.

It could therefore be deduced that with increased pre-fabrication of these elements, such as including the insulation, cladding and internal finishes, in the factory, could indeed lead to enhanced construction labour productivity. For this to be successful, supply chain integration and logistics are critical considerations, as the findings from the volumetric case study demonstrated. Indeed, open timber panel construction seemed to be familiar across the designers, manufacturing and construction operatives, and the case study's completion was the most straightforward among the surveyed systems. However, due to the low factory completion percentage, there were limited opportunities for labour productivity optimisation.

Where productivity optimisation strategies are concerned, this research revealed the applicability of some BIM and Lean tools as more targeted to offsite timber systems productivity enhancement over others. Disappointingly, although 3-D graphic tools such as AR and project management apps were heavily advertised by software developers, their usability with the existing technology was found to require extensive training and labour input and was identified as an area for future research. In contrast, constructability analysis using familiar tools or if possible 4D time-based simulation (or visualisations) was the most critical tool to remediate some of the observed productivity challenges. This should be supplemented with early stakeholder engagement (or consultation) and where possible a federated multi-disciplinary model with reduced complexity.

9.3 Further work

The scientific limitations of this work are based firstly in the surveyed sample and secondly in the inherent methodological limitations, as is the case in most research studies on the productivity of offsite construction methods. Therefore, although great care has been taken to balance the depth and breadth of this doctoral research, the main suggestion for further work is the increase breadth of the research via an increased geographic distribution of multi-factor productivity analysis of timber offsite systems' design, manufacturing and construction across international economic contexts, to create a benchmark-able database. In addition, the size and segmentation of the UK offsite manufacturing capacity and productivity need to be clearly defined to enable increased understandings of DfMA, economic and sustainability differences between typical available systems among designers, clients, contractors and other key project stakeholders. Further work could also include business case studies for investment and business models in VTC, panelised and mass timber manufacturing facilities, which remains a gap in knowledge.

The construction tasks with the highest impact on labour utilisation were the internal works and external works, which combined accounted for approximately two-thirds of the total project labour-hours in both cases studies. Therefore, future construction work should focus on resource management optimisation in the external works and internal works, especially in the work of joiners and cladders. For instance, Location-Based Management technique can be applied to improve the flow of tasks in the internal works scheduling, and of the project overall (Seppänen, Evinger & Mouflard, 2014). Health and safety considerations such as crane usage and drilling times could be extracted from the data to optimize construction projects not only for labour and materials efficiency, but also for risk minimization in manufacturing and construction. Therefore, H&S and waste materials data could be associated with tasks (and possibly components) in BIM project construction models, to provide decision-making tools for social, environmental and economic sustainability, all of three of which can be associated with H&S and waste materials data.

Advances in automated data capture and Building Information Management (BIM) technologies can lead to increase in the accuracy of future similar research. Anonymised thumbprint technologies combined with site gear fitted with sensors have the potential to automate the data collection process and therefore enable industry-wide benchmarking of construction labour productivity. Any future such research should be done with careful consideration of the increasingly stringent Data Protection Act (Office of Public Sector Information, 1998).

The thesis findings could moreover be used as the foundation for establishment of national construction productivity measures, including the proposed Multi-Factor Productivity (MFP) index for offsite timber systems and its visualisation. This evaluation and decision-support tool can be aided by simulation models for resource flow optimisation on construction projects using offsite timber systems, synchronised with BIM models or databases, to provide estimates of the effect of different levels of prefabrication in the factory on KPIs such as time, cost, labour-productivity, energy-efficiency, waste materials, and health and safety. In further work the offsite percentage of the different systems should be estimated using data for both the manufacturing and construction phases of comparative case study projects. In addition, factors for adjustment of the MFP results according to building type, size and location could be developed. These would in turn enable the generation of a database with offsite systems' multi-factor productivity analysis without the need to ensure that case studies share similar attributes as grounds for their comparability. Critically, limiting conditions for nominal MFP variable should be defined to differentiate between the performance of different projects according to quantified performance. For example, the *time* variable can in itself be a composite variable with conditions regarding the offsite system installation, overall programme duration, and number of working days to achieve air-tight construction, cladding installation, internal finishes and snagging time. These may be measured either per plot as in this thesis, or per m^2 to enable comparison between different building typologies.

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Appendices

Appendix 4A - Market survey questionnaire

Volumetric Timber Construction Questionnaire Sample

Q1 **Thank you for your interest in our survey.**

The aim of this questionnaire is to gather information on the construction industry's perception of off-site 3D volumetric construction from home-grown timber. The survey should take you *15 to 20 minutes* to complete.

Within this survey 3D volumetric timber construction is defined as assembly in a factory environment of 3-dimensional modules, which enclose useful space (i.e. kitchen, bedroom, etc.). 3D volumetric timber modules are then transported to and installed on-site either as singular units or in horizontal and/or vertical combinations to form buildings (or parts of buildings).

Your perception of 3D volumetric timber systems as a construction professional is of great interest to our research team at the University of Strathclyde, Glasgow.

Please read the consent form and select one of the options below before proceeding.

Consent Form for Volumetric timber systems for public buildings

Name of department: Department of Architecture, University of Strathclyde
Title of the study: Volumetric timber systems for whole life zero carbon public buildings

§ I confirm that I have read and understood the information sheet for the above project and the researcher has answered any queries to my satisfaction. The information sheet can be found here: Participant Information Sheet_TD_Mar18-2015
§ I understand that my participation is voluntary and that I am free to withdraw from the project at any time, up to the point of completion, without having to give a reason and

without any consequences. If I exercise my right to withdraw and I don't want my data to be used, any data which have been collected from me will be destroyed.

§ I understand that I can withdraw from the study any personal data (i.e. data which identify me personally) at any time.

§ I understand that anonymized data (i.e. data which do not identify me personally) cannot be withdrawn once they have been included in the study.

§ I understand that any information recorded in the investigation will remain confidential and no information that identifies me will be made publicly available.

§ I consent to being a participant in the project

❍ Agree
❍ I agree and would like to be contacted further via e-mail at ____________________
❍ Disagree

General Information

Q2 What is your occupation in the construction industry?

- Architect
- Civil Engineer
- Environmental Engineer
- Manufacturer
- Local Authority
- Other ____________________

Q3 How many people does your company employ?

- 1-10
- 11-50
- 50-100
- 100+

Q4 Where are you based?

- England
- Northern Ireland
- Scotland
- Wales
- Other ____________________

Q5 What is your familiarity with 3D volumetric timber construction systems?

- Excellent
- Good
- Average
- Poor
- Very Poor

Off-site Modern Methods of Construction MMC

Q6 How would you rate your knowledge of these specific prefabricated construction systems?

	Not familiar	I have limited knowledge	I have good working knowledge	I have direct project experience
Façade panels	❍	❍	❍	❍
Structural open panels	❍	❍	❍	❍
Structural closed panels (including insulation, weather proofing, electrical and plumbing)	❍	❍	❍	❍
3D toilet pods	❍	❍	❍	❍
3D kitchen pods	❍	❍	❍	❍
3D volumetric steel	❍	❍	❍	❍
3D volumetric timber	❍	❍	❍	❍

Q7 With your knowledge, how would you rate the qualities of 3D volumetric timber construction **compared to traditional methods of construction**?

	Strong disadvantage	Disadvantage	Neutral	Advantage	Strong advantage
Design time	❍	❍	❍	❍	❍
Construction time	❍	❍	❍	❍	❍
Build quality (including air tightness)	❍	❍	❍	❍	❍
Cost	❍	❍	❍	❍	❍
Skills availability	❍	❍	❍	❍	❍
Design flexibility	❍	❍	❍	❍	❍
Recyclability	❍	❍	❍	❍	❍

Q8 How do you perceive the factors below as **opportunities** for the application of **3D volumetric construction** utilizing UK home grown timber?

	Not relevant	Limited relevance	Neutral	Relevant	Very relevant
Housing demand	❍	❍	❍	❍	❍
Public buildings demand	❍	❍	❍	❍	❍
Incorporation of low carbon technologies	❍	❍	❍	❍	❍
New timber engineered products	❍	❍	❍	❍	❍
Building Information Management (BIM) utilization	❍	❍	❍	❍	❍
Automated construction	❍	❍	❍	❍	❍
Export of 3D components to Europe	❍	❍	❍	❍	❍

Q9 How do you perceive the factors below as **restrictions** on the application of **3D volumetric timber construction**?

	Not relevant	Limited relevance	Neutral	Relevant	Very relevant
Client demand	❍	❍	❍	❍	❍
Design flexibility	❍	❍	❍	❍	❍
Cost	❍	❍	❍	❍	❍
Insufficient manufacturing facilities	❍	❍	❍	❍	❍
Cross-industry collaboration early in the design process	❍	❍	❍	❍	❍
Professional working knowledge	❍	❍	❍	❍	❍
Education and training	❍	❍	❍	❍	❍

Volumetric Timber Construction VTC

Q10 How do you perceive the factors below as potentially **increasing your application of 3D volumetric timber construction** within the UK?

	Not relevant	Limited relevance	Neutral	Relevant	Very relevant
Improved design flexibility	❍	❍	❍	❍	❍
Local manufacturing facilities	❍	❍	❍	❍	❍
Quality assurance	❍	❍	❍	❍	❍
Reduced cost	❍	❍	❍	❍	❍
Low carbon agenda	❍	❍	❍	❍	❍
Application of Building Information Management (BIM)	❍	❍	❍	❍	❍
Technical literature and guidance	❍	❍	❍	❍	❍
Greater public / client awareness	❍	❍	❍	❍	❍

Q11 How would you rate the **suitability of 3D volumetric timber construction** for these building types?

	Very unsuitable	Unsuitable	Neutral	Suitable	Very suitable
Housing (social and private)	❍	❍	❍	❍	❍
Offices	❍	❍	❍	❍	❍
Retail (commercial)	❍	❍	❍	❍	❍
Schools	❍	❍	❍	❍	❍
University buildings (including teaching facilities, accommodation and labs)	❍	❍	❍	❍	❍
Hospitals	❍	❍	❍	❍	❍
Sports and recreation	❍	❍	❍	❍	❍

Q12 Which of the following knowledge transfer mechanisms would you find **most useful** to support your specification and design of 3D volumetric timber construction (VTC)?

❍ As built VTC prototypes
❍ Digital components (i.e. BIM libraries)
❍ Best practice recommendations and technical guidance
❍ Other ____________________

Q13 Within the **next 5 years**, how would you rate **the relative importance** of these specific prefabricated construction systems in a developing building industry?

	Not relevant	Limited relevance	Neutral	Relevant	Very Relevant
Façade panels	❍	❍	❍	❍	❍
Structural open panels	❍	❍	❍	❍	❍
Structural closed panels (including insulation, weather proofing, electrical and plumbing)	❍	❍	❍	❍	❍
3D toilet pods	❍	❍	❍	❍	❍
3D kitchen pods	❍	❍	❍	❍	❍
3D volumetric steel	❍	❍	❍	❍	❍
3D volumetric timber	❍	❍	❍	❍	❍

Q14 Further to Question 13, please describe what you feel the potential influence of 3D volumetric timber construction could be **on the efficiency of construction** in a developing UK building industry.

Thank you for completing our survey.

Your opinion is greatly valued and will contribute to the development of research on off-site methods of construction at the University of Strathclyde.

Should you have any further questions or opinion, please do not hesitate to contact Mila at tsvetomila.duncheva@strath.ac.uk.

Appendix 4B - Interview questions

Section 1: Overview

1. What is your professional occupation?

2. Are you aware of Volumetric Timber Construction (VTC)? Can you briefly describe what VTC is?

Section 2: Specification & technical product information

3. Have you ever been involved in the specification of a VTC project?

   If yes, could you please give examples and any problems therein?

4. What do you think of the cost, time and procurement of a VTC project?

5. Would you consider VTC to be flexible enough to accommodate varying client design requirements?

6. Would you consider that VTC requires different project management strategies compared to traditional construction?

7. Do you consider that VTC can be successfully implemented using the RIBA project stages framework from 2013, the Building Regulations or any other codes you use?

Section 3: VTC market

8. Do you believe there are any emerging or potential markets for VTC, such as residential, private or public buildings?

9. In your opinion, what are the primary barriers to VTC use within the construction industry?

10. What about primary opportunities?

11. What would convince you as a construction professional to design and specify VTC?

Section 4: The near future and BIM

12. In what direction do you consider Government regulations will change in the upcoming years (5-10)?

13. Continuing on from the scenario you just described, would VTC systems have more advantages or disadvantages in the near future compared to the construction industry in the UK today?

    To what other factors could this be due? (i.e. technological advances such as automated construction, housing scarcity, resources depletion, energy prices, new building types)

14. Would you consider within the next 5 years BIM to be important for the development of the construction industry in the UK?

15. Would you relate the specification and design of VTC to the utilization of Building Information Modelling (and Management) BIM? In what way?

Appendix 4C - Full questionnaire responses

4C.1 Introductory section

Professional occupation

The majority of participants, 13 were from an architectural professional background. The second largest professional group were civil engineers (4), followed by manufacturers (2). Only 1 environmental engineer participated in the questionnaire. There were none participants from local authorities. A significant number of 6 participants responded ‘other’, which included "Sustainability Consultant”, “Housing Association", "Structural Engineer”, "NDPB", "director/ carpenter" and "developer". This question had 26 respondents.

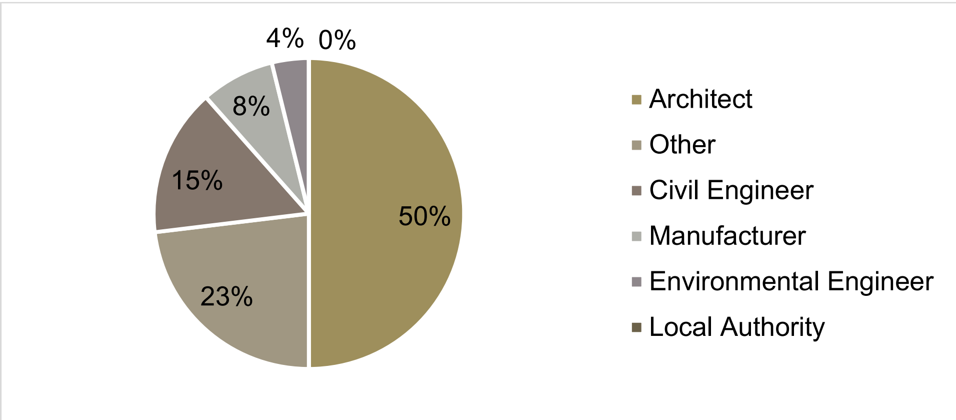


Figure 4C1 Professional occupation of questionnaire respondents

Company size

The majority of participants (11) were from small companies, or SMEs, employing up to 10 people. The second largest participant group (7) were from large companies with more than 100 employees. A similar number (6) participants were from companies with 11-50 employees. It can therefore be said that 2/3 of participants were from businesses with up to 50 staff members. There were only two participants from companies with 50-100 employees. A total of 26 participants responded to this question.

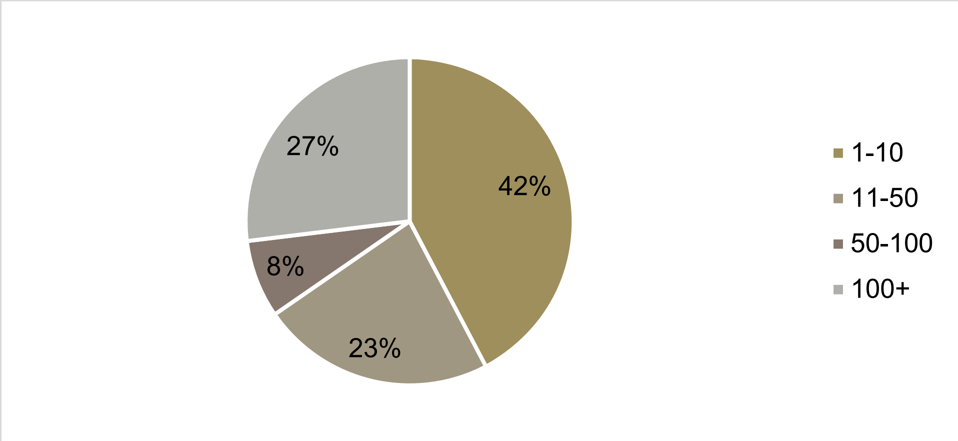


Figure 4C2 Company size of participants. N=26

Geographic location

The largest group of participants were based in Scotland, nearly 3/4 or 19 people. The second largest group were based in England (3) and there was only 1 participant from Wales. Three participants responded they were based in another location, one of whom was based in Italy and one in Germany. These two participants were known to have a good observation of and active engagement in the UK construction industry and their responses were therefore accepted. In total 26 people completed this question.

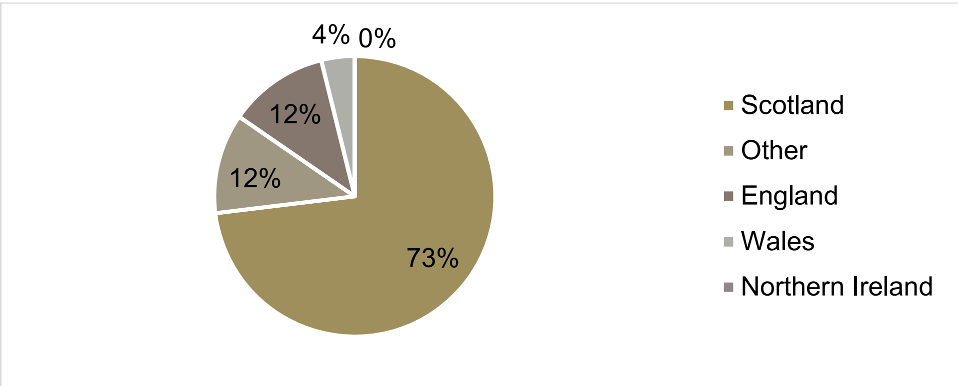


Figure 4C3 Geographic location of participant's workplace. N=26

Familiarity with volumetric timber construction

This question assessed the self-rated familiarity of the participants with VTC. It can be summarised that most of the participants (12) were not familiar with VTC, selecting either the 'poor' or 'very poor' answer option. Ten participants were familiar with VTC, selecting either the 'excellent' (2) or 'good' (10) option. Four participants provided the neutral response, self-rating their familiarity with VTC as average. A total of 26 participants completed this question. From these, 2 of the participants who selected 'very poor' and 1 who selected 'poor' did not respond to any of the following questions. It is assumed that they considered they could not contribute to this questionnaire if they were not familiar with VTC.

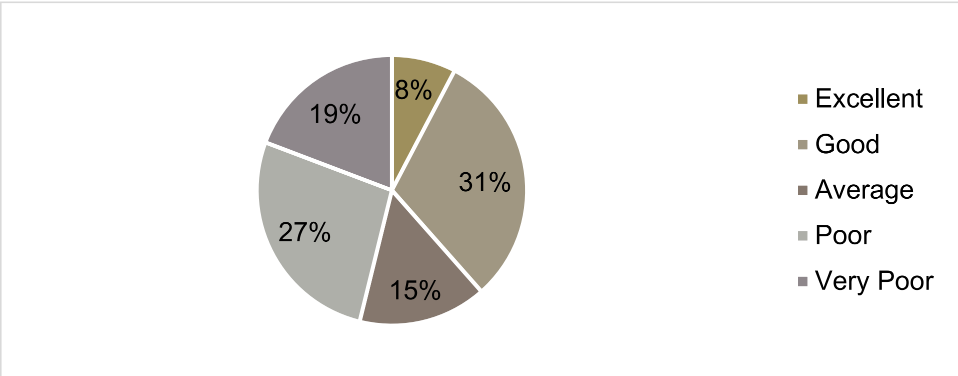


Figure 4C4 Self-rated familiarity with VTC. N=26

4C.2 Perceptions of volumetric timber construction

This section was the largest of the survey and included questions which asked about the perceived technical, market and knowledge opportunities and challenges of VTC in the UK construction industry context.

Familiarity with off-site construction

This question sought to see what the actual familiarity of the participants with different off-site technologies was. It was expected that participants would be more familiar with systems with a lower degree of prefabrication, such as façade panels and open timber panels, than with VTC. The question allowed for a co-relation between the perceived familiarity and experience of the participants was and if there we any misalignments. In total 23 people responded to this question.

In all categories of off-site construction methods the largest number of participants responded they had 'limited working knowledge'. The participants had the most practical experience with open panels (7), followed by closed panels (6). Overall 3 of the participants had worked on a 3D volumetric timber project, which was more than 3D kitchen and toilet pods and volumetric steel. Simultaneously, from the off-site construction categories, the participants were least familiar with 3D volumetric timber and steel and kitchen and toilet pods. Therefore in the graph below a line can be drawn between closed panels and 3D volumetric steel. Left of this line are the 2D systems, off which participants had more knowledge and experience with, and right of the line are the less familiar and applied in projects 3D elements.

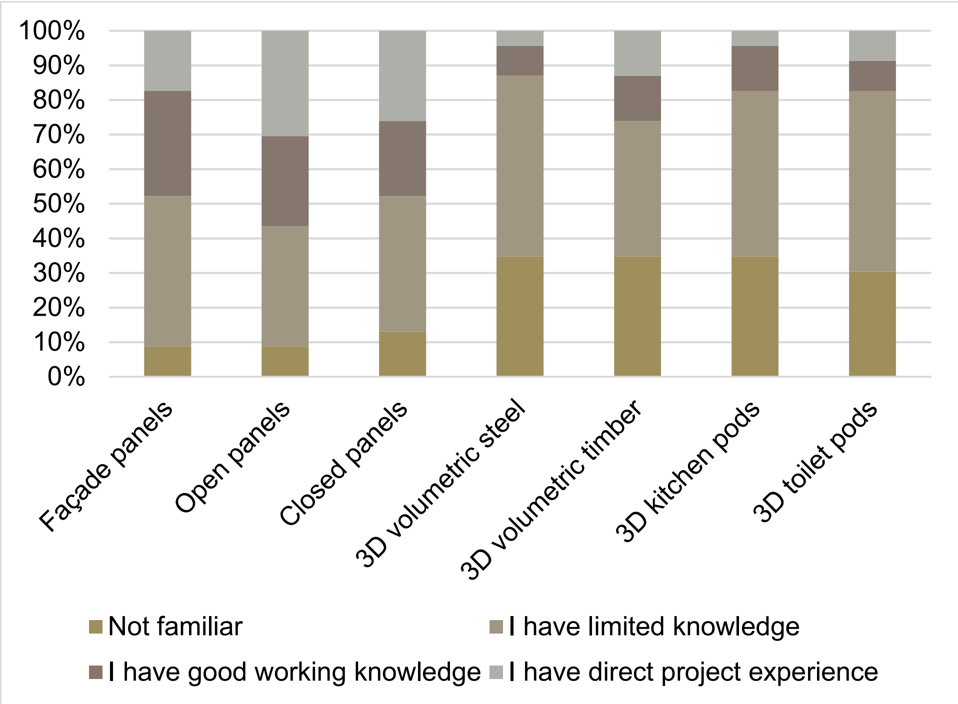


Figure 4C5 Knowledge of and experience with off-site construction systems. N=23

There were anomalies among all the categories in this question compared to the previous one. From the table below it can be seen that there was a redistribution of responses in which both extremes of knowledge increased and the middle options decreased. This could be due to participants selecting a more neutral response at first, but then changing their standpoint when asked in more detail about their working knowledge and experience.

Table 4C1 Comparison between self-rated familiarity and working knowledge of and experience in VTC.

Familiarity with VTC		Knowledge of and experience with VTC		Difference
Very poor	5	Not familiar + Did not continues survey	8 + 3 = 11	+6
Poor + Average	7 + 4 = 11	Limited knowledge	9	-2
Good	8	Good knowledge	3	-5
Excellent	2	Direct experience	3	+1

Advantages and disadvantages

The aspect of VTC, which was most strongly perceived as an advantage was construction time, followed closely by build quality and recycle-ability. None of the participants perceived disadvantages in construction time nor in recycle-ability. Only 1 participant perceived build quality as a disadvantage. These three were therefore the main perceived advantages of VTC.

The three main perceived disadvantages were design flexibility, cost and skills availability. Of these design flexibility was the most strongly perceived disadvantage, as the negative responses in this category were more than the positive responses. Cost had the largest number of neutral responses and also an equal number of positive and negative responses. This classifies it as the second in the disadvantages ranking, although the dominant view was that of neutral VTC costs.

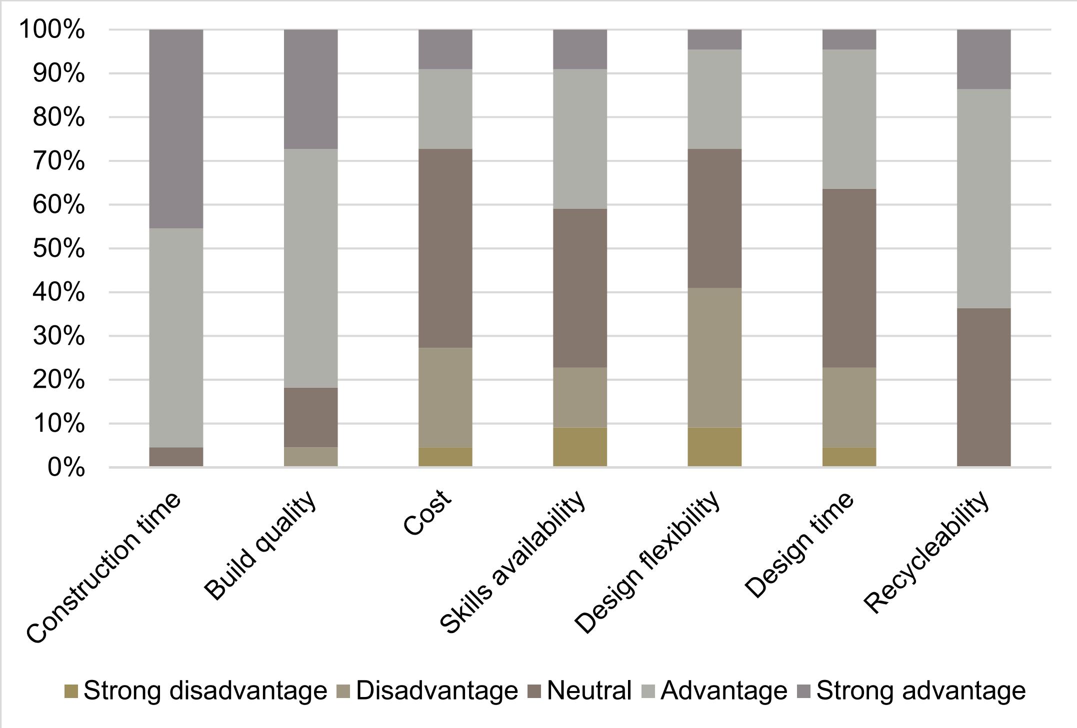


Figure 4C6 VTC advantages and disadvantages perceptions. N=22

Overall 22 respondents answered this question. The sums of the types of responses showed that the largest number of participants selected ‘Advantage’ (57), followed by ‘Neutral’ (46), which suggests that in general the perception of the participants of VTC in the listed categories was between neutral and positive.

Opportunities

The demand for housing was perceived as the most relevant opportunity for VTC. The use of new engineered timber products was the penultimate perceived opportunity. The incorporation of low carbon technologies and BIM utilization were weighed equally, ranking them third by relevance. The implementation of automated construction was also perceived as a relevant opportunity for VTC in the UK.

Overall the negative responses to this question were negligible, apart from the demand for public buildings, which was perceived by 6 participants as limited relevance, and the opportunity to export 3D components to Europe.

There were 23 responses in total to this question. The largest number of rankings selected were ‘Relevant’ (70) and ‘Very relevant’ (40) out of a total 160 rankings, suggesting that in general the listed items were perceived as significant opportunities for VTC implementation in the UK.

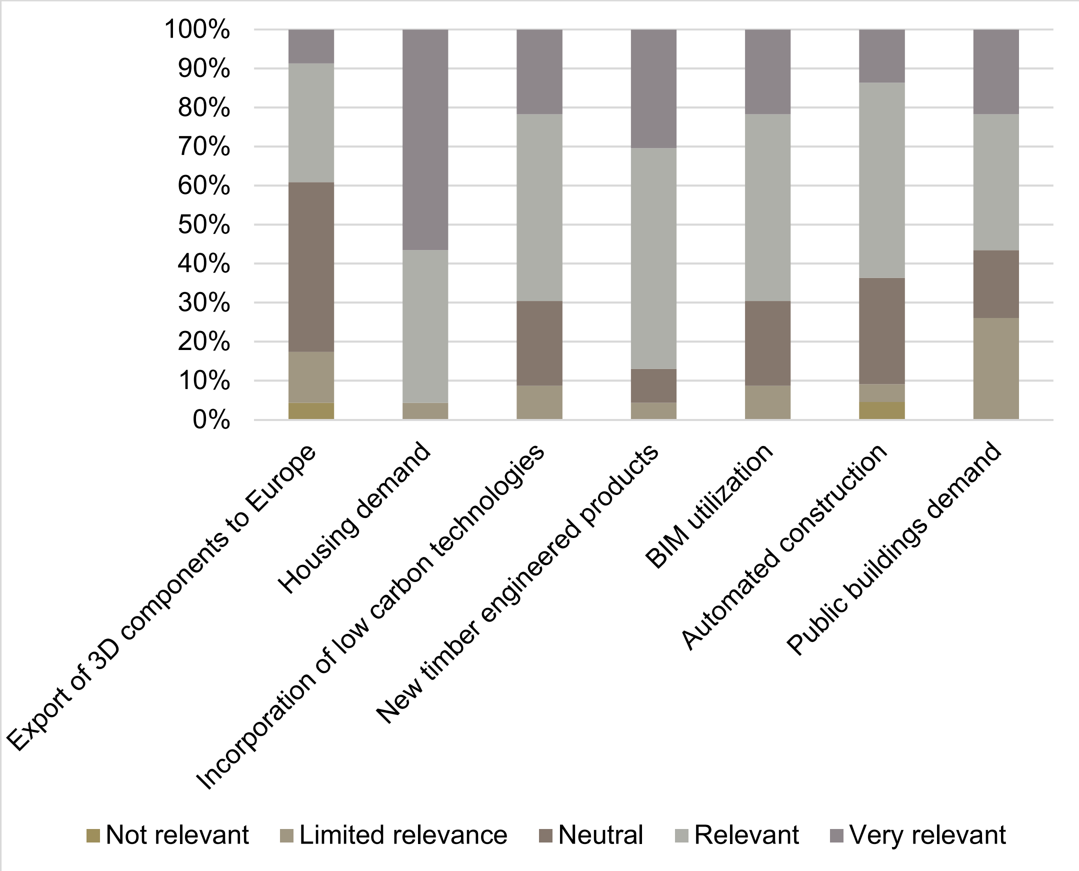


Figure 4C7 Perceived relevance of opportunities for VTC in the UK. N=23

Barriers

The most relevant barrier for VTC was perceived to be the lack of sufficient manufacturing facilities. That is, if there was a larger demand for VTC, there would a challenge in finding suppliers for the product. Professional working knowledge was the second by relevance perceived barrier, followed closely by the education and training of construction professionals. These two factors can be grouped into one category of theoretical and practical knowledge. The remaining factors all had similar perceived relevance as barriers for VTC in the UK, design flexibility, cost and collaboration early in the design process. Cost and design flexibility were the only factors which received a 'not relevant' ranking. The ranking of client demand was more varied than the other factors but shared the trend of generally positive responses.

Overall 22 people responded to this question, apart from cost, whose relevance was ranked by 23 participants. This could indicate that cost was considered the most important factor by that one additional participant. Similarly to the previous question, the responses were generally positive, suggesting that all listed items were perceived as significant barriers to VTC implementation in the UK.

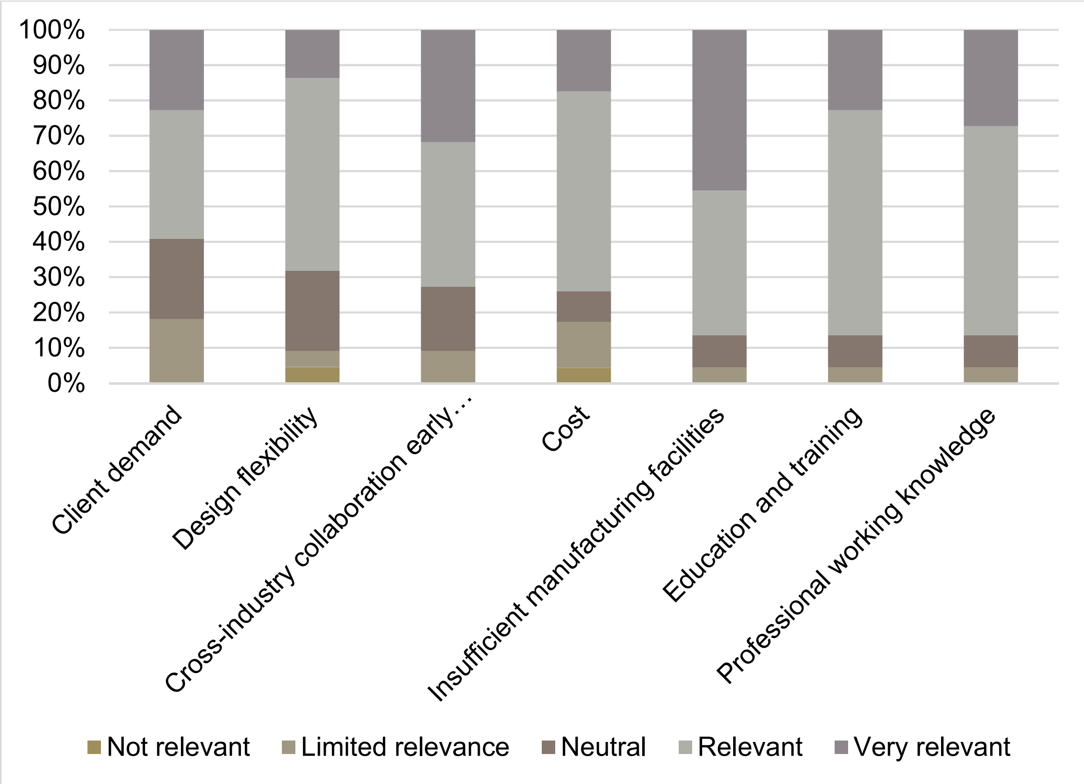


Figure 4C8 Perceived relevance of barriers for VTC in the UK. N=22

Factors which could increase the potential application of VTC

The responses to this question can be clustered into 3 groups. The most highly ranked by relevance group includes quality assurance, local manufacturing facilities and improved design flexibility in order from strongest to less significant relevance. These were all ranked as ‘Relevant’ and ‘Very relevant’ by 18 participants. The second group consists of reductions in costs and greater public or client awareness of VTC, which were both ranked as positive factors by 17 participants. From these two groups quality assurance, cost and local manufacturing facilities received the highest number of rankings as ‘very relevant’. The third group of responses were the availability of technical literature, the low carbon agenda and the application of BIM, which received some negative and comparatively fewer ‘very relevant rankings’ than the other two groups of factors.

There were 21 responses to this question, indicating that one of the participants stopped answering the survey at this point. Again, the responses were overall positive with very few neutral rankings and a negligible number of negative rankings, suggesting that a combination of all these factors could increase the application of VTC in the UK.

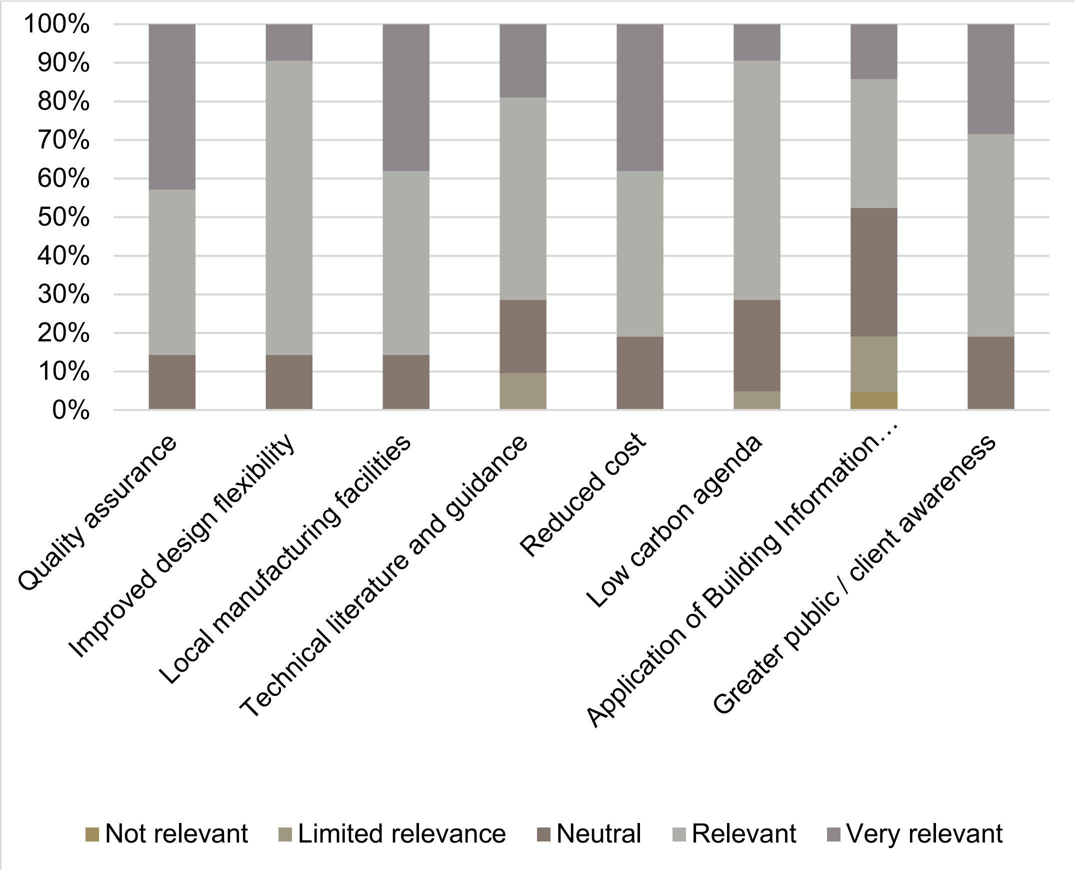


Figure 4C9 Perceived relevance of factors to increase the application of VTC. N=21

Suitable building types

Housing and offices were perceived as the most suitable building types for VTC, of which housing had a higher strength of perception. There was a second group of schools, university buildings, and sports and recreation, which were ranked positively overall, but also received a 5 negative rankings each. From this group, school buildings were perceived by the highest number of participants (6) as ‘Very suitable’, the same as offices. The third group of building types were perceived as overall unsuitable to neutral. This group consisted of hospital buildings and retail, of which retail had a much stronger negative perception of suitability.

In total 21 people responded to this question. The rankings were positive overall, but there was a much higher number of neutral and negative rankings compared to the previous question. This indicates that there was a larger variety of perceptions on the topic of building type suitability than on opportunities, barriers or factors to increase the specification of VTC.

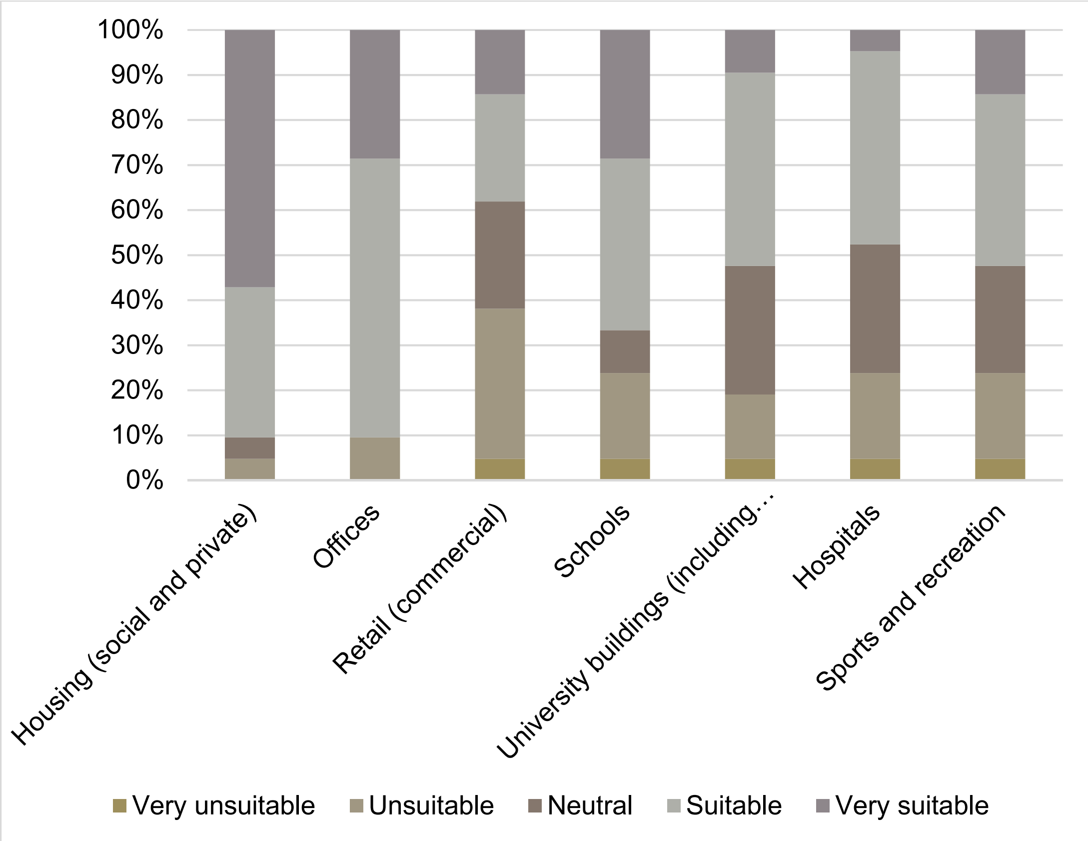


Figure 4C10 Perceived suitability of building types for VTC. N=21

Knowledge mechanisms

The majority of respondents (12) perceived that the provision of best practice recommendations and technical guidance would be the most suitable knowledge transfer mechanism for them on the topic of VTC. This was followed by the provision of as built prototypes, which was selected by 6 participants. Only 3 participants considered that digital components would be a suitable way for them to gain knowledge on VTC. Nobody selected the ‘other’ option, which suggests that these are the three main methods of suitable knowledge transfer for the surveyed construction professionals.

Of these mechanisms the provision of recommendations was most highly ranked and has the highest suitability to be produced by academia, as it should be impartial, while the remaining two options can be produced by manufacturers for their specific products. Overall 21 people answered this question.

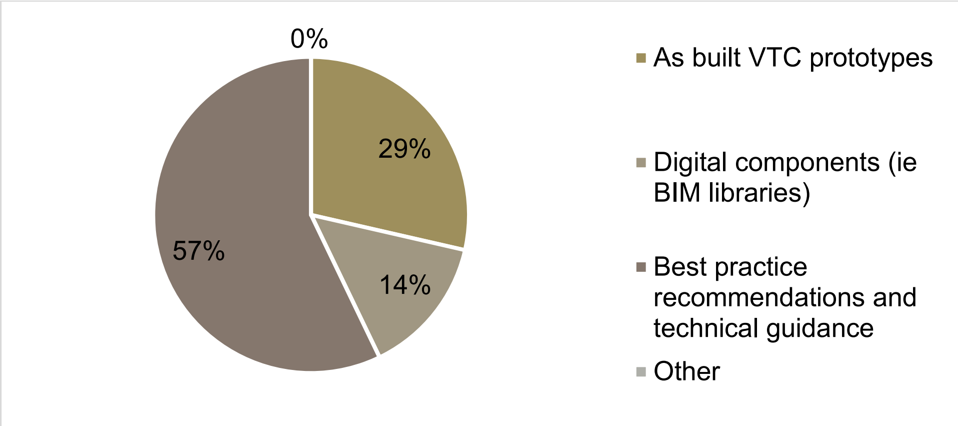


Figure 4C11 Suitability of knowledge transfer mechanisms for VTC. N=21

4C.3 The next 5-10 years

The last section enquired on the participants' vision of VTC in the near future.

Importance of off-site systems

This question built on the participants' thoughts from the previous section and was used to investigate the perceived importance of VTC compared to other off-site systems. The options were identical to the first question of the previous section to create a frame for the survey. The majority of response were neutral with very little variation towards positive or negative perceived importance. This could be interpreted as a result that all the off-site systems were perceived as similarly competitive on the UK market in the next 5-10 years, with little variation from on-site building systems.

Structural closed panels were perceived as the most important, followed by 3D volumetric timber and steel. 3D pods were perceived as having the least significance in the near future, which could be grouped as highly serviced small modules. The fact that the participants were responding to a survey about VTC could have influenced their responses to this question. The total number of participants was 21 in this question, apart from open panels (20) and 3D kitchen pods (19).

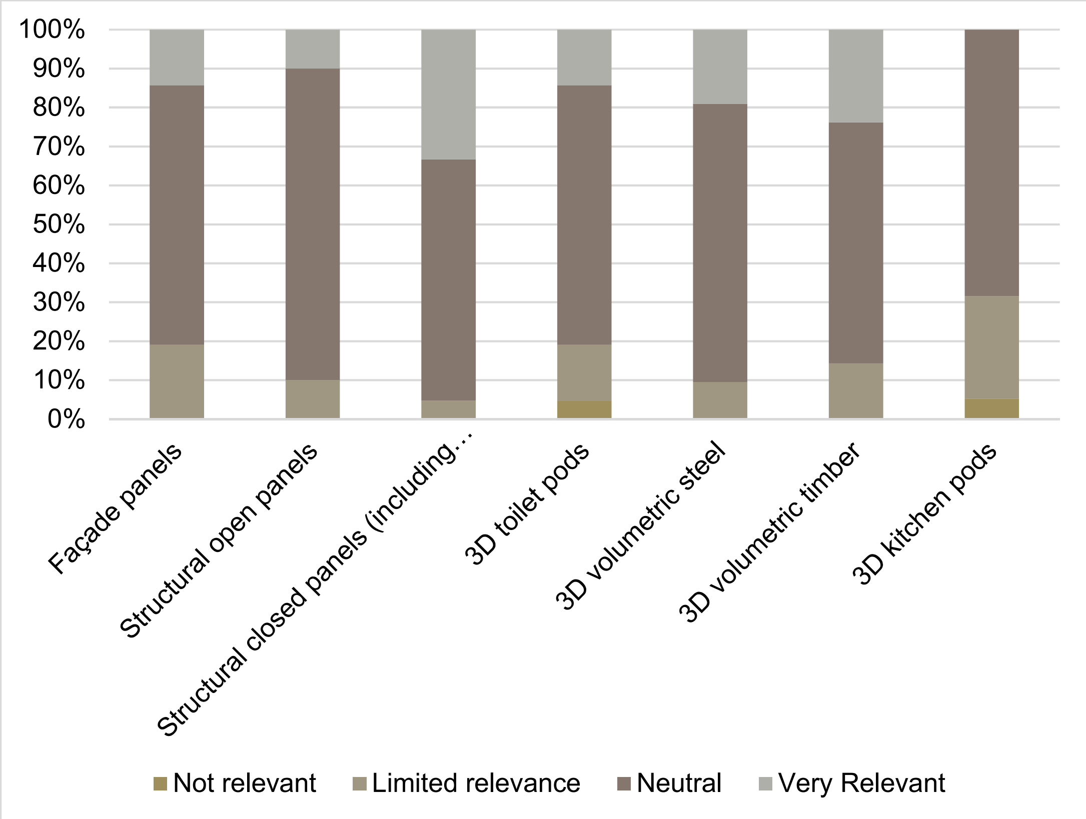


Figure 4C12 Perceived relevance of off-site systems in the next 5-10 years. N=21

VTC and the efficiency of construction

Overall 16 participants included a quantitative description of their perception of the potential impact of VTC on the efficiency of construction in the developing UK market. The most frequently mentioned topics were reduced cost, the opportunity to provide housing, improved build quality and reduced construction and production time. Other interesting points discussed the opportunity for VTC to tackle the skills shortage in construction, the use of engineered timber products and ability to achieve low energy accreditation at a lower cost. One participant emphasised on the role of the client, in whom the power to select the building system ultimately lies. Another participant admitted they were not familiar enough with VTC to provide an opinion.

The selection of quotes below elaborate on the summary of topics:

‘3D VTC decreases build time and cost. Both are critical factors in today's marketing where housing supply does not meet demand. Build time and costs will decrease further with time as processes are streamlined.’

‘3D VTC has great potential to provide consistent quality at attractive cost, using local timber but this will rely on an industry that is equipped to deliver and a suitable contractual arrangement.’

‘It should increase efficiency enormously but only where supporting and interlinked works move away from site install as well.’

Appendix 4D - Questionnaire statistical analysis

In addition to the discussion above, it was necessary to conduct some statistical test to explore the questionnaire data further, verify and validate the conclusions. The distribution of results gave insight into the dominant perceptions of the sample, but could not reveal interconnections between participants or variables. Two research questions were set for the statistical analysis:

- *Which factors are of critical importance for the (1) case study and (2) optimization process?*
- *Which factors are of secondary importance, i.e. should also be considered?*

The theoretical expectation were that a significant correlation would be found between the time, cost and carbon. From the previous results overview, it was expected that design flexibility, manufacturing facilities and client awareness would be classified as secondary factors.

4D.1 Descriptive statistics

The data from was extracted from Qualtrics into SPSS .sav format. The variables were re-ordered and renamed for analysis purposes. A decision was made to delete those cases who did not have data for variables 7 onwards, which is only responded to the questions to give consent and their familiarity with VTC. Cases who had information for variables 1-6 but answered less than 50% of variables 7-61 were also deleted. After the data clean-up 22 cases remained for statistical analysis.

The variable types were determined using descriptive statistics. Only variables with a near normal distribution should be treated as metric or scale data. The mean, skewness and kurtosis of each variable were analysed in SPSS using tables and histograms. The variables with skewness values between -1 and 1 were classified as near normally distributed and the remaining as nominal values. Exceptions were variables 1,2,3,5, 50, 58, 61 and 62, which referred to categorical rather than hierarchical information and were therefore classified as ordinal. The outcome of this stage is presented in Table 4.2 Below.

Table 4D1 Original variables number, name, label, measure and use.

N	Name	Label	Measure	Input / Output
1	ID	Anonymous ID	Nominal	Input
2	Consent	Thank you for your interest in our survey. The aim of this questionnaire is to gather information (…).	Nominal	Input
3	ProfOcup	What is your occupation in the construction industry?	Nominal	Input
4	CompSize	How many people does your company employ?	Ordinal	Input
5	Location	Where are you based?	Nominal	Input
6	VTC_fam	Familiarity with VTC	Ordinal	Input
7	Knw_fcd_pnl	Knowledge of Façade panels	Scale	Input
8	Knw_opn_pnl	Knowledge of Structural open panels	Ordinal	Input
9	Knw_cls_pnl	Knowledge of Structural closed panels	Scale	Input
10	Knw_bth_pds	Knowledge of 3D bathroom pods	Scale	Input
11	Knw_ktc_pds	Knowledge of 3D kitchen pods	Scale	Input
12	Knw_vlm_stl	Knowledge of 3D volumetric steel	Scale	Input
13	Knw_vlm_tmb	Knowledge of 3D volumetric timber	Scale	Input
14	Qlt_dsg_tme	VTC quality vs conventional construction - Design time	Scale	Both
15	Qlt_cns_tme	VTC quality vs conventional construction - Construction time	Scale	Both
16	Qlt_bld_qlt	VTC quality vs conventional construction - Build quality (incl. air tightness)	Scale	Both
17	Qlt_cst	VTC quality vs conventional construction - Cost	Scale	Both
18	Qlt_skills	VTC quality vs conventional construction - Skills availability	Scale	Both
19	Qlt_dsg_flx	VTC quality vs conventional construction - Design flexibility	Ordinal	Both
20	Opp_recycle	Opportunity perception - Recycle-ability	Scale	Both
21	Opp_hsn_dmn	Opportunity perception - Housing demand	Ordinal	Both
22	Opp_pbl_dmn	Opportunity perception - Public buildings demand	Scale	Both
23	Opp_low_crb	Opportunity perception - Incorporation of low carbon technologies	Scale	Both

N	Name	Label	Measure	Input / Output
24	Opp_tmr_eng	Opportunity perception - New timber engineered products	Scale	Both
25	Opp_BIM	Opportunity perception - Building Information Management (BIM) utilization	Scale	Both
26	Opp_aut_cns	Opportunity perception - Automated construction	Ordinal	Both
27	Opp_exp_EU	Opportunity perception - Export of 3D components to Europe	Scale	Both
28	Res_client	Restriction perception - Client demand	Scale	Both
29	Res_dsg_flx	Restriction perception - Design flexibility	Ordinal	Both
30	Res_cst	Restriction perception - Cost	Ordinal	Both
31	Res_mnf_fcl	Restriction perception - Insufficient manufacturing facilities	Ordinal	Both
32	Res_collab	Restriction perception - Cross-industry collaboration early in the design process	Scale	Both
33	Res_wrk_knw	Restriction perception - Professional working knowledge	Scale	Both
34	Res_edc_trn	Restriction perception - Education and training	Scale	Both
35	Inc_dsg_flx	Increase potential - Improved design flexibility	Scale	Both
36	Inc_mnf_fcl	Increase potential - Local manufacturing facilities	Scale	Both
37	Inc_qlt_ssr	Increase potential - Quality assurance	Scale	Both
38	Inc_rdc_cst	Increase potential - Reduced cost	Scale	Both
39	Inc_low_crb	Increase potential - Low carbon agenda	Scale	Both
40	Inc_BIM	Increase potential - Application of Building Information Management (BIM)	Scale	Both
41	Inc_tch_ltr	Increase potential - Technical literature and guidance	Scale	Both
42	Inc_client	Increase potential - Greater public / client awareness	Scale	Both
43	Bld_hsn	Suitable building type - Housing (social and private)	Ordinal	Both
44	Bld_off	Suitable building type - Offices	Ordinal	Both
45	Bld_ret	Suitable building type - Retail (commercial)	Scale	Both

N	Name	Label	Measure	Input / Output
46	Bld_sch	Suitable building type - Schools	Scale	Both
47	Bld_uni	Suitable building type - University buildings	Ordinal	Both
48	Bld_hsp	Suitable building type - Hospitals	Ordinal	Both
49	Bld_sprt	Suitable building type - Sports and recreation	Ordinal	Both
50	Knw_trnsfr	Preferred knowledge transfer mechanism	Nominal	Both
51	Yr5_fcd_pnl	Importance in the next 5 years - Façade panels	Scale	Target
52	Yr5_opn_pnl	Importance in the next 5 years - Structural open panels	Scale	Target
53	Yr5_cls_pnl	Importance in the next 5 years - Structural closed panels	Scale	Target
54	Yr5_bth_pod	Importance in the next 5 years - 3D bathroom pods	Scale	Target
55	Yr5_ktc_pod	Importance in the next 5 years - 3D kitchen pods	Ordinal	Target
56	Yr5_vlm_stl	Importance in the next 5 years - 3D volumetric steel	Scale	Target
57	Yr5_vlm_tmb	Importance in the next 5 years - 3D volumetric timber	Scale	Target
58	VTC_efficiency	Influence of VTC on efficiency in the next 5 years	Nominal	Target
59	StartDate	Start Date	Scale	Input
60	EndDate	End Date	Scale	Input

The table shows that the majority of variables could be treated as metric and therefore manipulated using mathematics. There were, however, 14 ordinal variables with abnormal distribution, that is skewed and/or with an even distribution. The variables above are ordered according to the question number they were part of, but it is difficult from the lengthy list to distinguish conceptually similar variables. It was therefore necessary to group the variable into theoretical categories prior to further analysis to better understand the data.

4D.2 Theoretical categories

The established principle of creating summated scales was most appropriate for this survey, as several questions asked participants about their perceptions on one element. In the explanations cost will be used as an example, but the principles were applied to all variables.

Cost appeared in three questions:

- asking about the cost quality of VTC compared to conventional construction,
- about the perception of cost as a restriction to VTC implementation and
- the relevance of cost in increasing VTC specification.

All these variables were ranked using a 5-point Likert scale and the summated Cost scales was established. The process was repeated for all variables and14 categories listed below were established.

Initial category list

1. Expertise category VTC = (VTC_fam + Knw_vlm_tmb)/2
2. Cost category = (Qlt_cst + Res_cst + Inc_rdc_cst)/3
3. BIM category = (Opp_BIM + Inc_BIM)/2
4. Manufacturing category = (Qlt_skills + Res_mnf_fcl + Inc_mnf_fcl + Opp_aut_cns)/4
5. Time category = (Qlt_dsg_tme + Qlt_cns_tme)/2
6. Design category = (Res_dsg_flx + Inc_dsg_flx)/2
7. Client category = (Res_client + Inc_client)/2
8. Low carbon category = (Opp_recycle + Opp_low_crb + Inc_low_crb)/3
9. Housing category = (Opp_hsn_dmn + Bld_hsn)/2
10. Public building category = (Opp_pbl_dmn + Bld_off + Bld_sch)/3
11. Quality category = (Qlt_bld_qlt + Inc_qlt_ssr)/2
12. Knowledge category = (Res_wrk_knw + Res_edc_trn + Inc_tch_ltr)/3
13. Timber panels = (Knw_cls_pnl + Opp_tmr_eng + Yr5_cls_pnl)/3
14. 3D future = (Yr5_bth_pod + Yr5_ktc_pod + Yr5_vlm_stl + Yr5_vlm_tmb)/4

The categories were calculated as new variables in SPSS and their descriptive statistics were extracted. From the distribution graphs and mean values, the variables were classified for their perceived importance using the rules:

1. Primary category criteria: positive, very positive, negative or very negative peak of 1 value with a difference greater than 1 frequency AND 2.5 <= mean >= 3.5
2. Secondary category criteria: positive, very positive, negative or very negative peak of 2 or 3 values with a difference greater than 1 frequency AND 2.5 <= mean >= 3.5
3. Excluded category criteria: no peak OR 2.5 > mean < 3.5

In other words, the importance of a category was decided to be ranked by the dominance of the opinion in the category, if the category was non-neutral. The logic employed was that if most of the participants thought cost was either positive or negative, this was an important finding which should be considered in the next research stages.

The example cost category had the following results, from which the conclusion was drawn that cost was an important category with a dominantly positive participant perception.

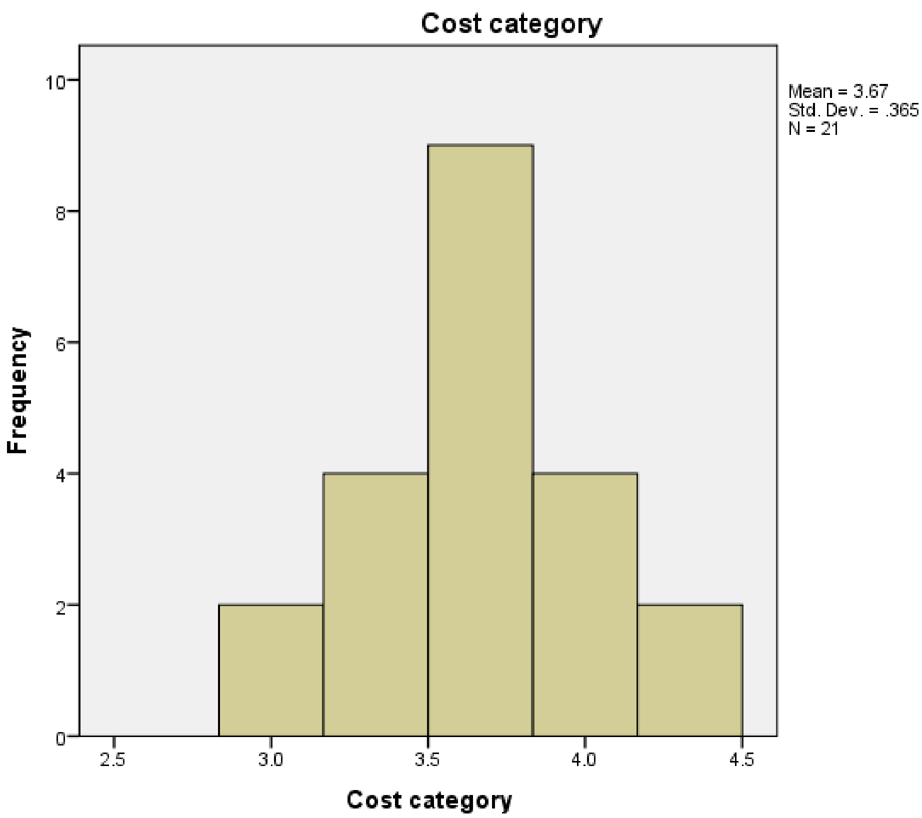


Figure 4D1. Distribution of cost category

From these tables the <u>primary categories were defined as follows</u>:

Primary	**Secondary**	**Excluded**
Cost	BIM	Expertise VTC
Time	Manufacturing	Public buildings
Design	Client	Timber panels
Housing	Low carbon	Future of 3D
	Quality	
	Knowledge	

However, on inspection of the categories and their results it became evident that the logical combination of two 5-point Likert scales (Strong disadvantage-Strong advantage and Not relevant-Very relevant) was incorrect when evaluating the perceived importance of a category. In some cases of mixed scales the distributions observed were flat and segmented, rather than normally distributed. The correlations of variables within each category were also extracted and the analysis summarised below revealed that only categories 1,9,12 and 14 had variables with significantly correlated variables (0.865-0.475). It was hypothesised that creating a separate category for overall perceived quality of VTC could remedy the illogical combination and none to partial correlations of variables within the categories. New corrected categories are summarised in the list below.

Table 4D2 Hypothetical categories bivariate correlation.

Number	**Category**	**Mixed Likert Scales**	**Full**	**Partial**
1	Expertise VTC	Y	F	-
2	Cost	Y	-	P
3	BIM	N	-	-
4	Manufacturing	Y	-	-
5	Time	Y	-	-
6	Design	N	-	-
7	Client	N	-	-

Number	Category	Mixed Likert Scales	Full	Partial
8	Low carbon	N	-	P
9	Housing category	Y	F	-
10	Public building category	Y	-	P
11	Quality category	Y	-	-
12	Knowledge category	N	F	-
13	Timber panels	Y	-	P
14	3D future	N	F	-

Table 4D2 Continued.

<u>Corrected final category list</u>

1. Offsite knowledge = (VTC_fam + Knw_fcd_pnl + Knw_opn_pnl + Knw_cls_pnl + Knw_bth_pds + Knw_ktc_pds + Knw_vlm_stl + Knw_vlm_tmb)/8
2. VTC quality perception = (Qlt_dsg_tme + Qlt_cns_tme + Qlt_bld_qlt + Qlt_cst + Qlt_skills + Qlt_dsg_flx)/6
3. Cost category 2 = (Res_cst + Inc_rdc_cst)/2
4. BIM category = (Opp_BIM + Inc_BIM)/2
5. Manufacturing and Construction = (Res_mnf_fcl + Inc_mnf_fcl + Opp_aut_cns + Inc_qlt_ssr)/4
6. Design category = (Res_dsg_flx + Inc_dsg_flx)/2
7. Client category = (Res_client + Inc_client)/2
8. Low carbon category = (Opp_recycle + Opp_low_crb + Inc_low_crb)/3
9. Housing category = (Opp_hsn_dmn + Bld_hsn)/2
10. Public building category 2 = (Opp_pbl_dmn + Bld_off + Bld_sch + Bld_hsp)/4
11. Knowledge category = (Res_wrk_knw + Res_edc_trn + Inc_tch_ltr)/3
12. 3D future = (Yr5_bth_pod + Yr5_ktc_pod + Yr5_vlm_stl + Yr5_vlm_tmb)/4
13. 2D future = (Yr5_fcd_pnl + Yr5_opn_pnl + Yr5_cls_pnl)/3

Descriptive statistics and bivariate correlation were also conducted for the newly created categories or summated scales. The results showed that 8 summated scales were normally distributed and 6 were either skewed had a too high kurtosis. This list was used in the final questionnaire analyses.

The distribution of the summated scales was also extracted from SPSS as histograms, which are shown in Figs. 4.13 and 4.14 below. The value ranges for the summated scales are meaningful, because identical or similar Likert scale-measured variables are included in each category. For example, the VTC quality category summates different qualities of VTC perceived as 1 = ‘strong disadvantage’ through 3 = ‘neutral’ to 5 = ‘strong advantage’. The results demonstrate that if all qualities of design time, construction time, build quality, skills availability and design flexibility are considered with equal weight, VTC was perceived as being slightly advantageous by the participants overall, with a mean of 3.44 and a peak on the chart at the 3.5 point on the X axis. A more difficult to interpret chart is for example the public building category, which combines the perceived relevance of public buildings as an opportunity for VTC with the perceived suitability of VTC for schools, retail and healthcare buildings. In both measures 1 represents a very negative (not relevant/ unsuitable) answer, 3 is neutral and 5 is a very positive (relevant/suitable) answer. The distribution histogram shows that there was not a dominant opinion, but that overall there were more positive (greater than 3) than negative perceptions (less than 3, which were the views of 5 respondents).

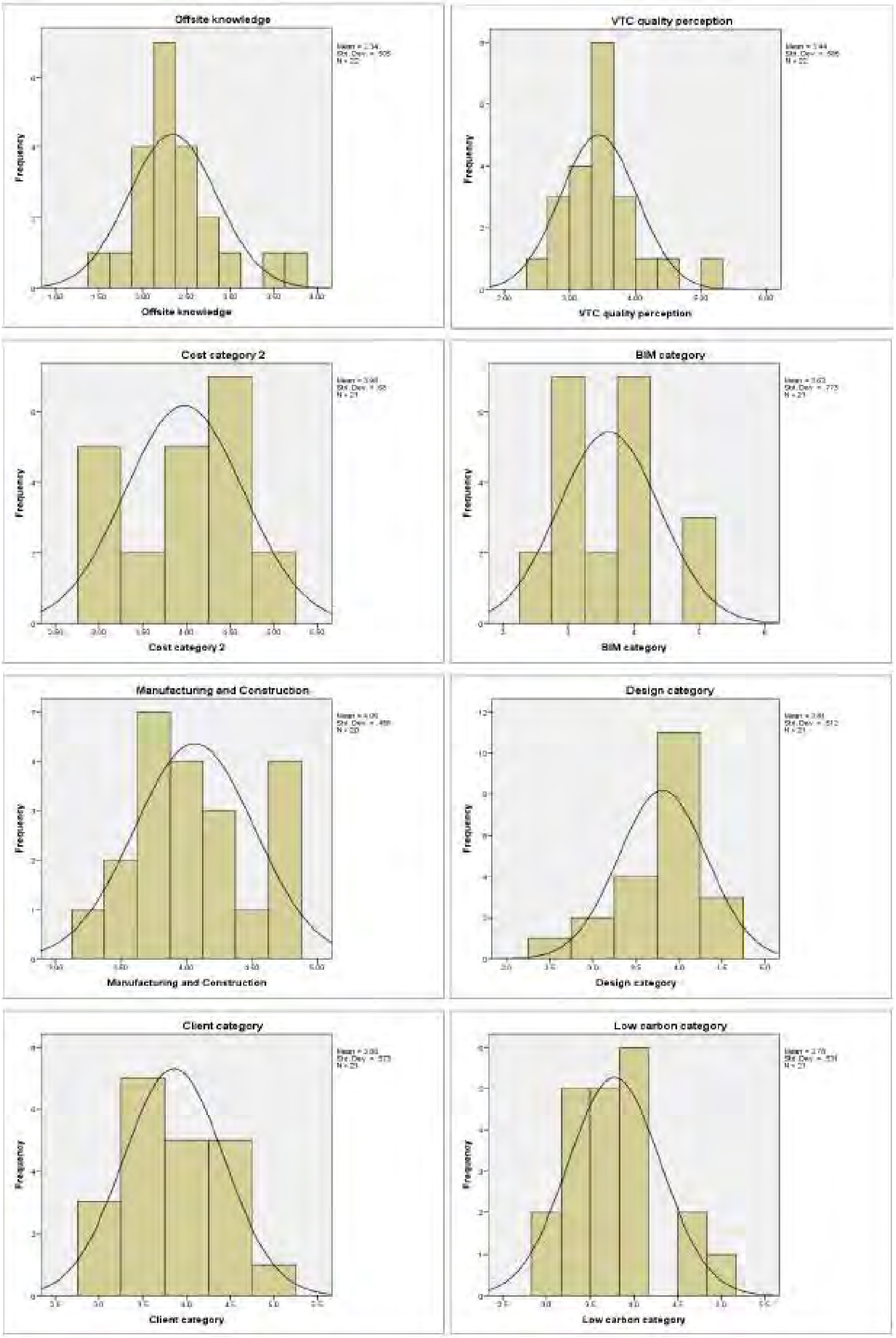


Figure 4D2 Distribution of summated scales (categories) 1 to 8.

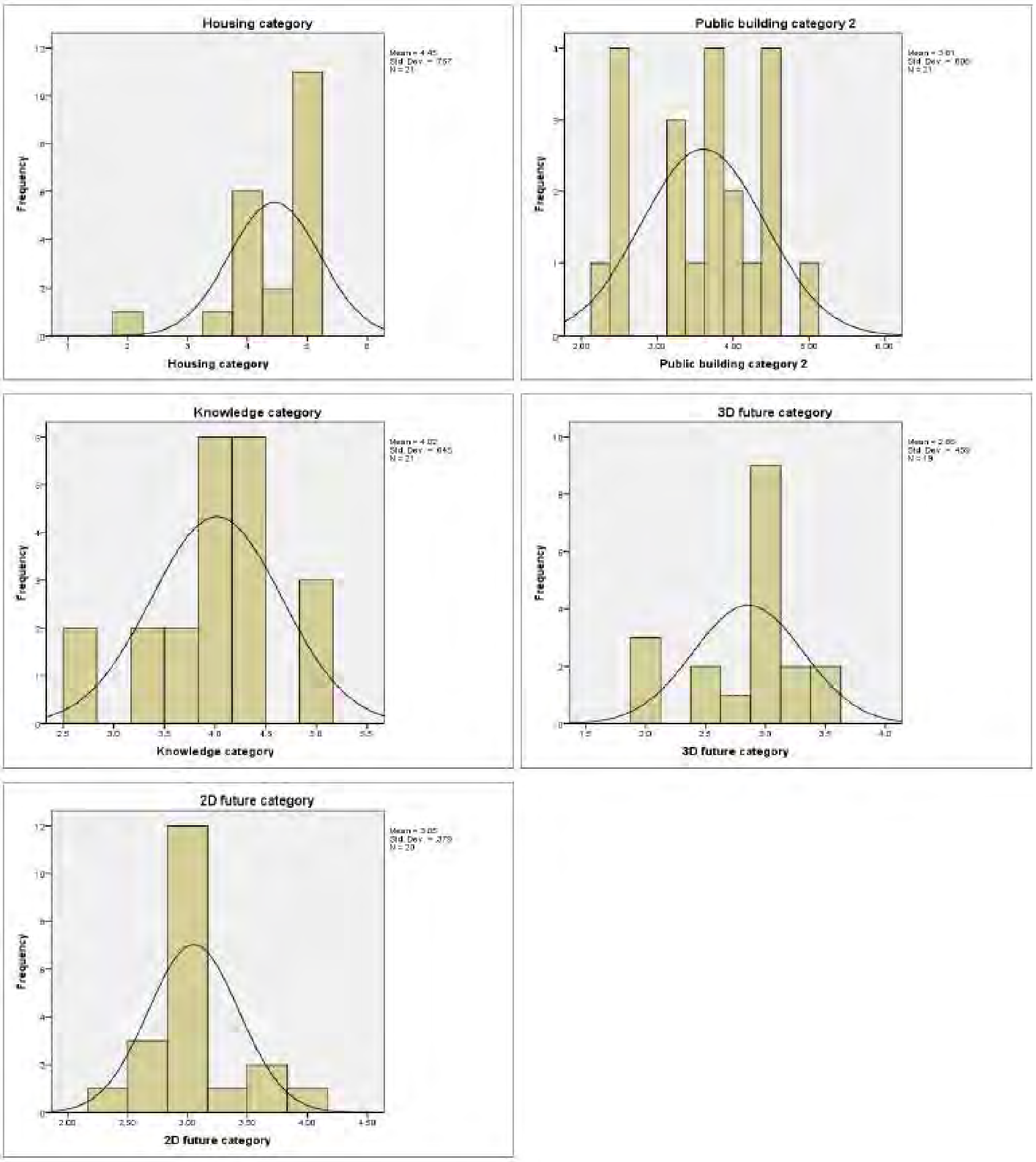


Figure 4D3 Distribution of summated scales (categories) 9 to 13.

4D.3 Correlation analysis

The variables were analysed for bivariate correlation between each other, but this was too complex to make meaningful clusters and conclusions. As mitigation, a bivariate spearman rho correlation analysis was run for the initial categories. After observations on the inconsistency of results explained above, finally a bivariate spearman rho analysis was run between the corrected categories. The analysis process was iterative with three refinement stages.

The results from the final correlational analysis are summarised in the table below. The most significant correlations per valuable were considered in the analysis and are extracted in the table. Two groups of categories were formed, which were named according to the meaning of the contained categories. The main group was named the 'VTC summary group' as it seemed to reveal the most important characteristics connected to the overall perception of VTC. The secondary group had only 3 categories and suggested that these were connected to the future more advanced implementation of VTC. The 'Design category' correlation was kept with a negative sign instead of inversing the category to maintain meaningful results. As the aim was only to group the summated scales (categories), the negative sign would not affect further statistical analysis.

Table 4D3. Correlation group 1.

VTC summary group		**BIM category**	**Design category**	**Low carbon category**	**Housing category**	**3D future category**
VTC quality perception	Correlation Coefficient	.434*	-.467*	.456*	.516*	.512*
	Sig. (2-tailed)	.049	.033	.038	.017	.025
	N	21	21	21	21	19

Table 4D4. Correlation group 2.

Advances group		**Public building category 2**	**Knowledge category**
Manufacturing and Construction	Correlation Coefficient	.488*	.735**
	Sig. (2-tailed)	.029	.000
	N	20	20

4D.4 Factor analysis

To conduct a factor analysis it is recommended to have a sample of minimum 50 cases (Krzanowski & Marriott, 1994**)**. However, this questionnaire had only 22 cases and therefore the factor analysis alone could not be trusted. The factor analysis was used as a method to explore the correlations between the variables to make summated scales, and subsequently mainly as a tool for refinement of the identified correlated summated scaled above. In the settings dialogue no rotation of the variables was set. Orthogonal and oblique rotation are conventional next steps in the analysis to provide more meaningful results, as stated by (Krzanowski & Marriott, 1994) but neither could be calculated for the original variables by IBM SPSS.

The results of the factor analysis all the variables in the survey generated 15 factors with an eigenvalue greater than 1. Of these only 7 had statistically meaningful correlations, as listed below. In grouping, each variable was assigned to the factor with which it had the highest correlation. Meaningful names were assigned to each factor based on the contained variables.

Table 4D5. Factor 1: 3D Timber construction overview

Variable	Correlation
Familiarity with VTC	-.572
Knowledge of 3D bathroom pods	.720
Knowledge of 3D kitchen pods	.752
Knowledge of 3D volumetric steel	.813
Knowledge of 3D volumetric timber	.754
VTC quality vs conventional construction - Design time	.617
VTC quality vs conventional construction - Build quality (incl. air tightness)	.538
VTC quality vs conventional construction - Design flexibility	.584
Opportunity perception - Public buildings demand	.599
Increase potential - Application of Building Information Management (BIM)	.487
Suitable building type - Offices	.525
Suitable building type - Retail (commercial)	.707
Suitable building type - Hospitals	.594
Suitable building type - Sports and recreation	.645

Variable	Correlation
Importance in the next 5 years - 3D bathroom pods	.686
Importance in the next 5 years - 3D volumetric steel	.740
Importance in the next 5 years - 3D volumetric timber	.806

Table 4D6. Factor 2: Panel competition

Variable	Correlation
Where are you based?	.502
Knowledge of Façade panels	.565
Knowledge of Structural open panels	.676
Knowledge of Structural closed panels	.711
Opportunity perception - Automated construction	-.508
Restriction perception - Cost	.476
Restriction perception - Cross-industry collaboration early in the design process	.456
Importance in the next 5 years - Structural open panels	.576
Importance in the next 5 years - Structural closed panels	.624

Table 4D7. Factor 3: Knowledge

Variable	Correlation
Restriction perception - Client demand	-.456
Restriction perception - Professional working knowledge	.654
Restriction perception - Education and training	.705
Increase potential - Local manufacturing facilities	.700
Increase potential - Quality assurance	.638
Increase potential - Technical literature and guidance	.695
Increase potential - Greater public / client awareness	.532

Table 4D8. Factor 4: Future development drivers

Variable	Correlation
Opportunity perception - Recycle-ability	.688
Opportunity perception - New timber engineered products	.638
Opportunity perception - Building Information Management (BIM) utilization	.720
Increase potential - Low carbon agenda	.554
VTC quality vs conventional construction - Skills availability	.420

Table 4D9. Factor 5: Critical elements

Variable	Correlation
VTC quality vs conventional construction - Construction time	.445
VTC quality vs conventional construction - Cost	.532
Opportunity perception - Housing demand	.494
Opportunity perception - Incorporation of low carbon technologies	.601
Opportunity perception - Export of 3D components to Europe	-.556
Increase potential - Improved design flexibility	-.471
Suitable building type - Housing (social and private)	.546

Table 4D10. Factor 6: Larger scale application elements

Variable	Correlation
Restriction perception - Insufficient manufacturing facilities	.562
Increase potential - Reduced cost	.487
Suitable building type - Schools	.661
Suitable building type - University buildings	.610

Table 4D11. Factor 7: Research target audience output

Variable	Correlation
What is your occupation in the construction industry?	.627
Preferred knowledge transfer mechanism	.617

At this stage of the analysis, these factors were too complex to analyse meaningfully and use as input in the case study and optimisation methodologies. A subsequent factor analysis was performed of the finalised categories, whose correlation was analysed in the previous section. The results of the factor analysis both confirmed and enhanced the bivariate correlational analysis. Out of the 5 generated factors, 4 were identified as meaningful and are summarised in the tables below. In reading the tables, the reader should be informed that correlations above 0.4 are considered statistically significant (at the 0.05 level of 2-tailed significance) and correlations above 0.6 are statistically very significant (at the 0.01 level of 2-tailed significance). A positive correlation shows a positive to positive or negative to positive correlation between the categories and the factor. A negative correlation shows a positive to negative or negative to positive correlation. The factors were analysed using pairwise exception, which makes the most use of the data, which is it includes all data fields in the calculations, even if the participant did not complete the questionnaire. Because of the small sample size this was the most applicable data exclusion method.

Table 4D12. VTC overview correlation

VTC overview factor

VTC quality perception	.836
Cost category 2	-.629
Design category	-.749

Table 4D13. Growth correlation

Growth factor

BIM category	.493
Manufacturing and Construction	.850
Public building category 2	.676
Knowledge category	.651

Table 4D14. Projects correlation

Projects factor	
Client category	.582
Low carbon category	.630
Housing category	.757

Table 4D15. Prospects correlation

Prospects factor	
Offsite knowledge	.692
3D future category	.466
2D future category	.445

4D.5 Groups

The correlation and factor analysis were used in combination to draw conclusions on the final factor groups. After the exploratory analysis described above the findings were combined with the distribution of the most dominantly perceived variables for each question. The variable number was therefore reduced by considering only the top 3 answers per questions and a bivariate Pearson rho analysis was conducted for these 'top' variables. The groups that emerged had many communalities with the categories creation, bivariate correlation and factor analyses. The created Groups 1-3 are summarised in the tables below with highlighted correlation data. The areas in grey should be ignored, as they duplicate the non-greyed out data or represent a correlation of a variable with itself.

Table 4D16. Group 1 correlation

Group 1: Timely application factors		Qlt_cns_tme	Qlt_bld_qlt	Opp_hsn_dmn	Inc_qlt_ssr	Bld_hsn	Bld_off	Bld_sch	Yr5_cls_pnl
Qlt_cns_tme	Correlation Coefficient	1.000	.613**	.651**	.375	.567**	.234	.257	.600**
	Sig. (2-tailed)		.002	.001	.094	.007	.307	.261	.004
	N	22	22	22	21	21	21	21	21
Qlt_bld_qlt	Correlation Coefficient	.613**	1.000	.523*	.182	.505*	.221	.589**	.463*
	Sig. (2-tailed)	.002		.013	.431	.019	.335	.005	.035
	N	22	22	22	21	21	21	21	21
Group 1:		Qlt_cns_tme	Qlt_bld_qlt	Opp_hsn_dmn	Inc_qlt_ssr	Bld_hsn	Bld_off	Bld_sch	Yr5_cls_pnl
Opp_hsn_dmn	Correlation Coefficient	.651**	.523*	1.000	.553**	.828**	.457*	.331	.618**
	Sig. (2-tailed)	.001	.013		.009	.000	.037	.142	.003
	N	22	22	22	21	21	21	21	21
Inc_qlt_ssr	Correlation Coefficient	.375	.182	.553**	1.000	.549**	.570**	.271	.503*
	Sig. (2-tailed)	.094	.431	.009		.010	.007	.235	.020
	N	21	21	21	21	21	21	21	21
Bld_hsn	Correlation Coefficient	.567**	.505*	.828**	.549**	1.000	.567**	.190	.440*
	Sig. (2-tailed)	.007	.019	.000	.010		.007	.408	.046
	N	21	21	21	21	21	21	21	21
Bld_off	Correlation Coefficient	.234	.221	.457*	.570**	.567**	1.000	.438*	.073
	Sig. (2-tailed)	.307	.335	.037	.007	.007		.047	.752
	N	21	21	21	21	21	21	21	21
Bld_sch	Correlation Coefficient	.257	.589**	.331	.271	.190	.438*	1.000	.217
	Sig. (2-tailed)	.261	.005	.142	.235	.408	.047		.344
	N	21	21	21	21	21	21	21	21
Yr5_cls_pnl	Correlation Coefficient	.600**	.463*	.618**	.503*	.440*	.073	.217	1.000
	Sig. (2-tailed)	.004	.035	.003	.020	.046	.752	.344	
	N	21	21	21	21	21	21	21	21

**. Correlation is significant at the 0.01 level (2-tailed). *. Correlation is significant at the 0.05 level (2-tailed).

Table 4D17. Group 2 correlation

Group 2: Technology		Qlt_skills	Qlt_dsg_flx	Opp_recycle	Opp_low_crb	Opp_tmr_eng
Qlt_skills	Correlation Coefficient	1.000	.321	.509*	.408	.263
	Sig. (2-tailed)		.145	.016	.060	.238
	N	22	22	22	22	22
Qlt_dsg_flx	Correlation Coefficient	.321	1.000	.623**	.310	.265
	Sig. (2-tailed)	.145		.002	.161	.234
	N	22	22	22	22	22
Opp_recycle	Correlation Coefficient	.509*	.623**	1.000	.496*	.507*
	Sig. (2-tailed)	.016	.002		.019	.016
	N	22	22	22	22	22
Opp_low_crb	Correlation Coefficient	.408	.310	.496*	1.000	.444*
	Sig. (2-tailed)	.060	.161	.019		.039
	N	22	22	22	22	22
Opp_tmr_eng	Correlation Coefficient	.263	.265	.507*	.444*	1.000
	Sig. (2-tailed)	.238	.234	.016	.039	
	N	22	22	22	22	22

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

Table 4D18. Group 3 correlation.

Group 3: Future development		Res_ edc_trn	Res_wrk_knw	Inc_dsg_flx	Inc_mnf_fcl	Yr5_vlm_tmb
Res_edc_trn	Correlation Coefficient	1.000	.554**	.033	.627**	.252
	Sig. (2-tailed)		.007	.887	.002	.271
	N	22	22	21	21	21
Res_wrk_knw	Correlation Coefficient	.554**	1.000	.216	.748**	.225
	Sig. (2-tailed)	.007		.348	.000	.327
	N	22	22	21	21	21
Inc_dsg_flx	Correlation Coefficient	.033	.216	1.000	-.070	.644**
	Sig. (2-tailed)	.887	.348		.763	.002
	N	21	21	21	21	21
Inc_mnf_fcl	Correlation Coefficient	.627**	.748**	-.070	1.000	-.034
	Sig. (2-tailed)	.002	.000	.763		.882
	N	21	21	21	21	21
Yr5_vlm_tmb	Correlation Coefficient	.252	.225	.644**	-.034	1.000
	Sig. (2-tailed)	.271	.327	.002	.882	
	N	21	21	21	21	21

**. Correlation is significant at the 0.01 level (2-tailed).
*. Correlation is significant at the 0.05 level (2-tailed).

4D.6 Interpretation

The extracted most important groups of variables need to be compared and enhanced with the interview data to determine the most crucial factors for subsequent optimisations of VTC. From the questionnaire analysis the factors in Group 1 can be selected as the most important in the next research phase. The correlation was highest in Group 1 among variables related to housing, which can be interpreted as a guideline for case study selection in the subsequent research phases. Group 2 suggests the technology-related factors, which are also connected with the topic of sustainability – environmental, social and economic. The expressed interest of the participants in these factors as a separate entity demonstrates that sustainable technology incorporation is important for the successful application of VTC. The final Group 3 provides the tools and methods by which the research could conduct and communicate the optimisations to enable VTC specification in the next 5 years: professional education materials, demonstration of design flexibility through case studies and evaluation studies of local manufacturing facilities establishment. These groups of factors and specific topics if fully developed will provide an in-depth efficiently communicated investigation into VTC. However, due to the practical restriction of PhD research the groups need to be further narrowed down and prioritised.

4D.7 Validation

The descriptive statistics (mean, skewness, kurtosis and variance) of the initial and corrected categories were also analysed to extract normally distributed and meaningful summated scales. On categories including only scale variables Pearson correlation was used and in categories including a mix of scale and ordinal categories the Spearman rho was used.

Table 4D19. Validation

	N Valid	Mean	Skewness	Std. Error of Skewness	Kurtosis	Std. Error of Kurtosis	Normal distribution
Offsite knowledge	22	2.3409	1.016	.491	1.245	.953	N
VTC quality perception	22	3.4394	**.805**	.491	1.079	.953	N
Cost category 2	21	3.9762	**-.302**	.501	-1.176	.972	N
BIM category	21	3.62	**.457**	.501	**-.630**	.972	**Y**
Manufacturing and Construction	20	4.0625	**.218**	.512	**-.882**	.992	**Y**
Design category	21	3.81	**-.974**	.501	**.955**	.972	**Y**
Client category	21	3.86	**.184**	.501	**-.822**	.972	**Y**
Low carbon category	21	3.78	**.707**	.501	**.261**	.972	**Y**
Housing category	21	4.45	-1.832	.501	4.367	.972	N
Public building category 2	21	3.6071	**-.222**	.501	**-.982**	.972	**Y**
Knowledge category	21	4.02	**-.531**	.501	**.374**	.972	**Y**
3D future category	19	2.86	**-.824**	.524	**-.009**	1.014	**Y**
2D future category	20	3.0500	**.871**	.512	1.504	.992	N

The suggested group structure was validated against the original variables correlation matrix. The created groups of summated scales were indeed correlated within, although in many cases on examining only the variable correlation more than one grouping was possible.

4D.8 Limitations

The most significant limitation of the questionnaire was the small sample size. The 21 fully completed respondents were not a representative sample of the design and construction professionals in the UK. However, diversity rather than representativeness was the aim of the questionnaire survey. The questionnaire results provide a snapshot in time of the perceptions of SME architects and other construction professionals, who were sufficiently interested in the research topic to complete the questionnaire. The challenge in gathering responses was a finding in itself, many approached people were not familiar with VTC and were therefore reluctant to provide their opinions. The questionnaire results did not provide a complete non-arguable list of variables for subsequent analysis, but did provide a starting point for explorations in the interview analysis and the identification of factors for the case study and optimisation research phases.

A cluster analysis was not performed because of the aforementioned inadequate sample size (a sample size of more than 100 is typically recommended). The aim of the questionnaire results statistical analysis was to group variables in meaningful groups and determine the critical elements to be used in the subsequent research phases. The descriptive statistics, summative scales, correlational and factor analyses were sufficient to make conclusions on the most important and conceptually related variables, combined in summated scales and finally in inter-connected groups.

Appendix 5A - Questions for interviews with factory tours of volumetric/panelised timber manufacturers

Please note that the original was formatted to fit on a single side of an A4 page.

Topics of interest for volumetric timber (VT) (/panelised timber) factories visits 2015-2016

1) Manufacturing line main stages
    a. Number of manufacturing line stages and their function.
    b. Type of equipment used at each stage (function, name)
        i. Use of CNC and any other automated production equipment (cranes, nail bridges)?
    c. How is waste minimised?
        i. How and what waste is recycled?
        ii. And how much waste is produced from a standard project?
    d. Production rate (houses per year, or modules per day)?
    e. With how many production staff, on what shift patterns?

2) Building elements
    a. Materials used and any options available
    b. Standard element sizes (especially timber + its grade + is it home-grown?)
    c. Types and sizes of connectors used in module production
    d. Types and sizes of connectors used in building construction
    e. Do these connectors allow for re-use / recycling of the modules or their elements?

3) Modules / panels
    a. Maximum module (/panels) size and weight
    b. Level of offsite production (windows, doors, services (plumbing, electrical, ventilation, heating), furniture (kitchen/bathroom), wall, floor and ceiling finishes, cladding?)
    c. Transportation restrictions and their impact on module (/panel) size.
    d. What are the transportation costs per module (/panel)?
    e. Number of repetitive modules needed to make volumetric timber cost-efficient?
    f. Potential cost and time savings of using VT (/panelised timber) compared to conventional construction?

4) Process
    a. What are the steps you would take in a project, from idea to completion?
        i. Working with the client – how are they involved and when?
        ii. How and when are architects involved? (what are their responsibilities)
        iii. How and when are engineers involved? (what are their responsibilities)
    b. How do you estimate the project time from design to completion?
    c. Use of BIM – what is your attitude towards BIM?
        i. What is your preferred software platform?
        ii. How is it integrated with the production process?
        iii. How is it integrated with the construction process?
        iv. Are printed drawings read manually or are 3D models exchanged?
        v. Do you produce schedules for modules / building elements from BIM models?
        vi. How do you convert BIM / CAD to CNC information?

5) Projects
    a. Are there any height restrictions due to the structural stability of the module system?
    b. What air tightness values can be achieved? Insulation values?
    c. How are fire and noise transmission regulations met?
    d. How is quality assurance executed? What is inspected and certified?
    e. Do you also carry out the on-site foundations work and construction?
    f. Do you calculate the carbon footprints of projects? Only on request?
    g. Apart from residential buildings, do you think see potential in other building types?

6) Volumetric timber in the next 5 years
    a. What is your companies' vision and goals for the next 5 years?
    b. What do you see as the main opportunities for your company and VT in Europe in general?
    c. What do you see as the main challenges for your company and VT in Europe in general?

Appendix 6A - Data availability low-rise case studies

Table 6A1. Data availability: Volumetric Timber Case Study

Document	Availability
1. General information	
1.1. Architectural drawings	Yes
1.2. Engineer drawings	Yes
1.3. Specifications	Yes
1.4. Crane procedures	Yes
1.5. Waste reports	Yes
1.6. Deliveries	
1.6.1. Deliveries reports and source or estimated mileage for general materials	Yes
1.6.2. Offsite system delivery route, vehicle type, estimated mileage and any special route considerations.	Yes
1.7. Contractor's progress reports	
1.7.1. List of sub-contractors	Yes
1.7.2. Register of crew times (labour-hours) on site	Yes
1.7.3. Plant use on site, including type and hours used or days rent	Yes
2. Labour Productivity	
2.1. Construction programme	Yes
2.2. Clerk of works reports	Yes
2.3. Health and safety procedures	Yes
2.4. Just-in-time or other lean processes utilised?	Yes
2.5. Procurement route used and roles of each stakeholder (general information)	Yes
2.6. Interviews on project progress	Yes

Table 6A2. Data availability: Open Timber Panel case study

Document	Availability
1. General information	
1.1. Architectural drawings	Yes, access to onsite printed drawings & from bid
1.2. Engineer drawings	Yes, from project bid
1.3. Specifications	Yes
1.4. Crane procedures	partial
1.5. Waste reports	Yes
1.6. Deliveries	
1.6.1. Deliveries reports and source or estimated mileage for general materials	Yes, partial
1.6.2. Offsite system delivery route, vehicle type, estimated mileage and any special route considerations.	Yes, estimate
1.7. Contractor's progress reports	
1.7.1. List of sub-contractors	Yes, partial
1.7.2. Register of crew times (labour-hours) on site	Yes, high level
1.7.3. Plant use on site, including type and hours used or days rent	Yes, high level
2. Labour Productivity	
2.1. Construction programme	Yes
2.2. Clerk of works reports	Yes, snagging
2.3. Health and safety procedures	Yes
2.4. Just-in-time or other lean processes utilised?	Yes
2.5. Procurement route used and roles of each stakeholder (general information)	Yes
2.6. Interviews on project progress	

Appendix 6B - Data collection and analysis method development process

Data collection sheet v1

p.3

N	Plot	Module	Task	Start	Finish	Duration	Resource	Predecessor
29	42/43	2	truck manoeuvred into place		09:45 / 09:50	5 min	4 men	
30	42/43	2	hooking crew: module attached to crane		9:50 / 10:00	10 min	hand drill, 1 man	
31	"	"	module detached from truck		9:52 / 10:00	8 min		
32	"	2	crane chains straightened, ladder removed		10:00 / 10:02	2 min	2 men	
33	"	2	craning of the module, had to be repositioned in the air several times,		10:05	15 min	4 men	
			then lowered but there was a small issue near the end, tilted module		10:20			
34	42/43	truck	during the lift the cables and steel strops beams put away		10:05 / 10:20	15 min	2 men	
35	42/43	2	module lifted on one side - tilted, then lowered down		10:20 / 10:25	5 min		
36	42/43	2	crane chains lowered and then lifted back up to a straight position		10:25	10 min	3 men and blocks to measure	
			to lift and re-position the modules.		10:35		the distance between the modules	
37	42/43	2	distances measured horizontally and vertically		10:35 / 10:37	2 min	measure tape, 2 men	
38	42/43	2	module lifted and re-positioned again and again x 5		10:37 / 10:58	20 min		
39	42/43	2	2 chains removed and only the back ~~end of the module~~		10:59			
			lifted, because it did not lift up					
40	42/43	3+4	modules driven onto site on trucks		11:00 / 11:15	15 min		

this was challenge for the crew!

Figure 6B1. Sample from a 4-page anonymised example record from a 1-day observation. Data collection sheet v2

Site name										
Date		Weekday			Hrs		Weather	°C	Wind km/h	RH
Factor N	1	2	3	4	5	6	7	8	9	10
Factor name	Time	Cost / Man-hours	Waste	Quality	Health and Safety	Installation process	Logistics	Interface offsite / onsite	Contract	General
Notes										

Factor N	Location	Task	Stakeholder	Measure	Other

Figure 6B1. Data collection sheet final version 2.0

Lean and BIM productivity improvement analysis variables

The variables in this table were used to analyse the low-rise case studies activities according to lean and BIM efficiency improvement potential.

Table 6B1. Lean and BIM productivity improvement analysis variables

Variable	Values range	Definition reference
Activity type	VA	Value-Adding Activity. (O’Connor & Swain, 2013)
Activity type	ENVA	Essential No-Value Adding Activity. (O’Connor & Swain 2013).
Activity type	W	Waste or 'Muda'. (O’Connor & Swain 2013).
Lean Waste 'muda'	M_Tran	Transportation. (Womack & Jones, 2003)
Lean Waste 'muda'	M_Inv	Inventory. (Womack & Jones 2003)
Lean Waste 'muda'	M_Mot	Motion. (Womack & Jones 2003)
Lean Waste 'muda'	M_Wait	Waiting. (Womack & Jones 2003)
Lean Waste 'muda'	M_Ov_Prod	Over-production. (Womack & Jones 2003)
Lean Waste 'muda'	M_Ov_Proc	Over-processing. (Womack & Jones 2003)
Lean Waste 'muda'	M_Def	Defects. (Womack & Jones 2003).
Lean Waste 'muda'	M_Skill	Skills misuse. (Corfe *et al.*, 2013)
Lean principle	LP_Val	Value (O’Connor & Swain, 2013; Womack & Jones, 2003).
Lean principle	LP_Val_Str	Value Stream. (O’Connor & Swain, 2013; Womack & Jones, 2003).
Lean principle	LP_Flow	Flow. (O’Connor & Swain, 2013; Womack & Jones, 2003).
Lean principle	LP_Pull	Pull from customers. (O’Connor & Swain, 2013; Womack & Jones, 2003).
Lean principle	LP_Perf	Perfection. (O’Connor & Swain, 2013; Womack & Jones, 2003).
Lean tool	LT_Vision_HK	Hoshin Kanri – vision. (O’Connor & Swain, 2013)
Lean tool	LT_Collab_Plan	Collaborative planning and project management. (O'Connor and Swain, 2013)
Lean tool	LT_Str_Prb_Slv	Structured problem solving. (O’Connor & Swain, 2013)
Lean tool	LT_5S	5S workplace management. (O’Connor & Swain, 2013)
Lean tool	LT_Vis_Mngmnt	Visual management. (O’Connor & Swain, 2013)
Lean tool	LT_Prcss_Impr	Process improvement. (O’Connor & Swain, 2013)
Lean tool	LT_Oprtns_Impr	Operations improvement. (O’Connor & Swain, 2013).

Variable	Values range	Definition reference
Lean tool	LT_Dir_Obsrv	Direct observation of work. (O'Connor & Swain, 2013)
Lean tool	LT_Stndrd_Op	Standard operations. (O'Connor & Swain, 2013)
Lean tool	LT_Logistics	Lean Logistics. (O'Connor & Swain, 2013)
BIM Principle	BIM_Erl_Stkhdr	Early involvement of stakeholders (Sanchez, Hampson & Vaux, 2016)
BIM Principle	BIM_Rev_Meet	Review meetings (Sanchez, Hampson & Vaux, 2016)
BIM Principle	BIM_OnlnCollab	Online collaboration and project management (Sanchez, Hampson & Vaux, 2016)
BIM Principle	BIM_IntOperblt	Interoperability and data formats (Sanchez, Hampson & Vaux, 2016)
BIM Principle	BIM_Dat_Sta	Data standards (Sanchez, Hampson & Vaux, 2016)
BIM Principle	BIM_POE	Asset performance assessment, modelling and displays (Sanchez, Hampson & Vaux, 2016)
BIM Principle	BIM_Asset_Man	Asset management and maintenance scheduling (Sanchez, Hampson & Vaux, 2016)
BIM Principle	BIM_Cnstr_An	Constructability analysis (Sanchez, Hampson & Vaux, 2016)
BIM Principle	BIM_FrontPlann	Front-end planning (Sanchez, Hampson & Vaux, 2016)
BIM Principle	BIM_LCC	Life-cycle costing (Sanchez, Hampson & Vaux, 2016)
BIM Principle	BIM_Logistics	Streamlined logistics (Sanchez, Hampson & Vaux, 2016)
BIM Tool	BIM_Obj_Lib	Object libraries creation. (Sanchez, Hampson & Vaux, 2016)
BIM Tool	BIM_Sync_Doc	Synchronised model and documents. (Sanchez, Hampson & Vaux, 2016)
BIM Tool	BIM_Obj_Mod	3D Object-based modelling. (Sanchez, Hampson & Vaux, 2016)
BIM Tool	BIM_Vis	3D Visualisations. (Sanchez, Hampson & Vaux, 2016)
BIM Tool	BIM_Laser	3D Laser Scan. (Sanchez, Hampson & Vaux, 2016)
BIM Tool	BIM_Aug_Rea	3D Augmented reality. (Sanchez, Hampson & Vaux, 2016)
BIM Tool	BIM_Tim	4D Time simulation in 3D. (Sanchez, Hampson & Vaux, 2016)
BIM Tool	BIM_Cos	5D Cost estimation. (Sanchez, Hampson & Vaux, 2016)
BIM Tool	BIM_Qant_T-o	5D Quantity take-off. (Sanchez, Hampson & Vaux, 2016)

Variable	Values range	Definition reference
BIM Tool	BIM_Clash	6D Clash detection. (Sanchez, Hampson & Vaux, 2016)
BIM Tool	BIM_Rul_Check	6D Automated rule checking. (Sanchez, Hampson & Vaux, 2016)
BIM Tool	BIM_Ene_Sim	7D Energy simulation. (Sanchez, Hampson & Vaux, 2016)
BIM Tool	BIM_CO2_Calc	7D Carbon calculation. (Sanchez, Hampson & Vaux, 2016)
BIM Tool	BIM_Fed_Mod	Federated model. (Sanchez, Hampson & Vaux, 2016)
BIM Tool	BIM_Virt_Colab	Real-time virtual model collaboration. (Sanchez, Hampson & Vaux, 2016)
BIM Tool	BIM_Cobie	Cobie Information exchanges. (Sanchez, Hampson & Vaux, 2016)
BIM Tool	BIM_Share_Fold	Project share folder. (Sanchez, Hampson & Vaux, 2016)
BIM Tool	BIM_Prog_Tra	Progress tracking on site + automatic report generation. (Sanchez, Hampson & Vaux, 2016)
BIM Tool	BIM_Doc_Site	Onsite design and documents review. (Sanchez, Hampson & Vaux, 2016)

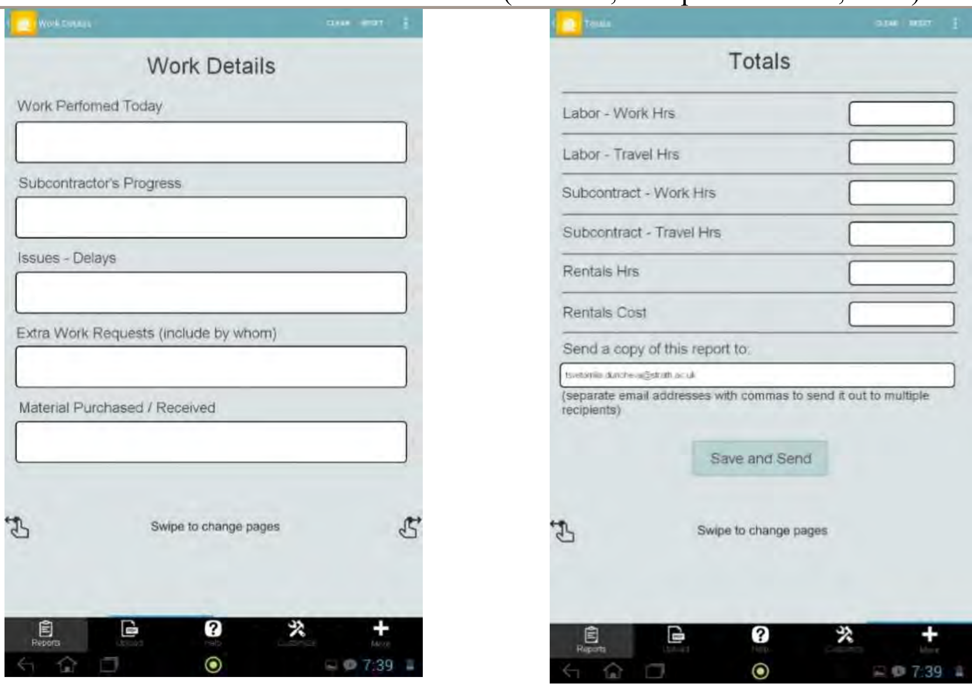


Figure 6B3. Simplified digitised data collection tool tested in the pilot case studies, two sample pages from an iPAD mini 4-enabled spreadsheet tool for project managers.

MS Excel spreadsheets and data storage

This table lists the Excel spreadsheet and their contents, used during the initial data collection and analysis stage of the low-rise case studies.

Table 6B2. Data entry Excel spreadsheets developed during the explorative pilot case studies, based on the identified productivity inputs, where R (rank) 0= necessary admin, 1=useful and quantitative, 2 useful and qualitative 3=not useful.

Sheet name	Key columns	Function	Notes on use	R
Data collection form	Information type, Date asked for availability, Enquired, Received	Systematically collect data across case study projects and record receipt of data.	Continuous and useful to communicate data requests to the stakeholders	**0**
Data plan	Data source, measurement and units	Establish framework for data collection, data entry and analysis	Very useful at the start of the case study. Developed using knowledge from first two PhD projects. Also used during data entry to identify data sources.	**0**
Data collection sheet	Site name, date and time, weather conditions; Factor N, Location, Task, Stakeholder, Notes	Record data on site systematically, according to pre-defined variables and categories.	Spreadsheet used printed on site to note site observation and interview data. Attempted iPad use but was not practical in poor weather conditions.	**0**
Variable codes	Date added, full name, description, abbreviation, reference	Systematic comparison of onsite activities according to pre-defined referenced variables	Essential for Data Validation settings of labour productivity data entry data entry.	**0**
Entry codes	Code, Date, Description, Time, Labour-hours, etc.	Assign unique code to each data collection task (e.g. each site visit, interview) and identify which spreadsheets need to be completed with data from the task.	Very useful from the start to the middle of the project, however in the later stages when the frequency of site visits decreased, not relevant. The unique code in format ABC123 can be used to trace back data sources and data collection timing.	**2**
1 Time	Date, Location, Planned start, Planned end, Actual start, Actual end, Actual duration, Delay	Measure construction progress and most importantly, the duration of each activity.	This worksheet was transformed during the course of the research to reflect planning methods used by contractors. At the end it was substituted with MS Project software.	**1**

Sheet name	Key columns	Function	Notes on use	R
2 Labour-hours	Activity, N labour-hours, Labour type, Activity type, Source	Measure the number of labour hours per activity, trade and week.	The most used spreadsheet. Data entry is labour-intensive and prone to human error. Substituted with MS Project software.	**1**
2 Cost	Item, location, unit, price per unit, cost	Measure economic cost of the project in GBP.	Not used.	**3**
3 Waste materials	Material, weight	Measure waste materials	Used in previous studies but not yet at CLT and CTP case studies. Use should be continued.	**2**
4 Quality	Component, Impact,	Measure re-work	Useful record of re-work and high quality do-it-right-first-time observations. Needs to be adapted to include labour hours of re-work.	**2**
5 H&S	Activity, Duration (hrs), People N, Risk Level, Stakeholder	Measure health and safety issues such as high-risk activities and best practice risk minimisation.	Used at the start, however health and safety observations were not critical in this study. An additional BIM-study on Health and Safety was conducted.	**2**
6 Installation process	Start, End, Duration, Labour-hours	Measure the installation process and its labour productivity in higher level of detail (minutes and hours)	Very important spreadsheet, used in the constructability analysis of different offsite systems.	**1**
7 Logistics	Travel Date, Start Point, End Point, 1 or 2 Way, Distance (km), Mode of Transport	Measure offsite logistics in distance and numbers of travels	Systematically used at first, however the key distance was simply multiplied by the number of trips.	**2**
8 Interface onsite - offsite	Activity, Lessons learnt, Stakeholder	Highlight the connection between onsite and offsite activities and how one impacts the other	Useful points on the causal effects between the onsite and offsite processes. Used until March 2017.	**2**
9 Contract	Activity, Lessons learnt, Stakeholder	Observation and interview data on the contract general type and specific which effect the project progress.	Useful addition to the qualitative data, however with hindsight this could have been a case-study specific issue.	**2**

In some cases, one issue could be included in several sheets. For example, the connections are part of the installation process, however their utilization will also impact the productivity and the health and safety aspects. In future work on constructability and productivity it is recommended to reduce the spreadsheet number by two-thirds, to 5.

The following are suggested as the key data collection sheets:

- programme time,
- labour-hours,
- installation constructability,
- logistics, and
- waste materials.

These spreadsheets contain quantitative data and have been identified as the key parameters for construction productivity analysis. The remaining 5 spreadsheets containing qualitative information should be recorded in separate qualitative data files and analysed using qualitative data tools, to explain the quantitative data. Therefore, differences in digitisation use, health and safety, and build quality could be rigorously analysed and use to explain differences in the quantitative measures.

A sample of data entry regarding time and labour is shown in the table below. These early data entries were transformed from project progress meeting hand-written notes and were kept with intentions to analyse them for project time and labour productivity. However, the use of an established project management tool with data inputs as captured in this table, namely Microsoft Project, was used as a more accurate record and analysis of project management data.

Table 6B3. Sample entries in *Time* spreadsheet, D=duration (hours), Pe=people (number of).

Activity	Start	End	D	Pe	Plant
Scottish water have approved the connection on one of the adjacent streets	22/08/2016	26/08/2016	40	5	-
Some leaks were discovered when the draw line for BT and Skye had been changed and the seal was not resealed, so the seals have to be redone	06/09/2016	06/09/2016	4	1	Handheld tools
Phase 2 brick and blockwork and PV today installed	27/07/2016	31/08/2016	200	-	Various on site - fork lifts, hand-held tools

Activity	Start	End	D	Pe	Plant
Phase 3 blockwork started	08/08/2016	19/08/2016	80	-	Various on site - fork lifts, hand-held tools
The contractor has to process the new schedule proposal	31/08/2016	02/08/2016	24	3	-
A new schedule was discussed and proposed this morning at the site meeting before the progress meeting	31/08/2016	31/08/2016	2	10	-
A second production line will be opened in the factory to increase output to at least 1, if possible 2 deliveries per week	01/09/2016	08/09/2016	80	5	Heavy-duty
Police escorts come to meet the modules at [border town] 1-2 hours after the modules are parked there. They do not depart until the trucks are parked at [border town].	n/a	n/a	2	4	4 trucks

The developed system for data collection and data entry needs to be combined with a robust files storage system. In this research study the following folder system was used: 01-General information, 02-Architectural drawings, 03-Engineer drawings, 04-Specification, 05-Health & Safety, 06-Minutes, 07- Contractor reports, 08-Site visits, and 09-Data.

Comparative offsite timber MS Project template settings

Table 6B4. WBS created in this thesis for offsite timber systems productivity comparison

Group	Code	Full name
C1 - Ground	C11_Grnd_Wrk	Foundations and ground-works
C1 - Ground	C12_Flr_Slb	Floor slab
C2 - Superstructure	C21_Reinforcement	Steel reinforcement or beams
C2 - Superstructure	C22_Sl_Plts	Sole plates
C2 - Superstructure	C23_Off_Sstm	Offsite system installation
C2 - Superstructure	C24_Other_Sstm	Other offsite system such as staircases
C2 - Superstructure	C25_Srvcs_Cnct	Connection of offsite system services
C2 - Superstructure	C26_Off_Sng	Offsite system inspection and remediation (snagging)
C2 - Superstructure	C27_Off_Hndvr	Offsite system handover to main contractor
C3 - Roof	C31_Rf_Trss	Roof trusses erection
C3 - Roof	C32_Rf_Sht	Roof sheeting and felting
C3 - Roof	C33_Rf_Til	Roof tiling
C3 - Roof	C34_Roof_PV	Installation of solar photo-voltaic panels
C4 – Seal and insulate	C41_Wndws	Windows installation
C4 – Seal and insulate	C42_Drs	Doors installation
C4 – Seal and insulate	C43_Mmbrns	Membranes (damp-proof, breather)
C4 – Seal and insulate	C44_Insltn	Insulation
C5 - External	C51_Brck	Brickwork
C5 - External	C52_Blck	Blockwork
C5 - External	C53_Clddng	Cladding
C5 - External	C54_Rndr	Render
C5 - External	C55_Ext_Str_Srf	External structures and surfaces
C6 - Internal	C61_Jnr1	Electrical first fix
C6 - Internal	C62_Plmb1	Plumbing first fix
C6 - Internal	C63_Electrc1	Joinery first fix
C6 - Internal	C64_Jnr2	Electrical second fix
C6 - Internal	C65_Plmb2	Plumbing second fix
C6 - Internal	C66_ Electrc2	Joinery second fix
C6 - Internal	C67_ Jnr3	Electrical third fix
C6 - Internal	C68_Plmb3	Plumbing third fix
C6 - Internal	C69_ Electrc3	Joinery third fix
C6 - Internal	C60_Dcrtr	Decoration
C7 - Handover	C71_Bldg_Sng	Building inspection and snagging
C7 - Handover	C72_Bldg_Rmd	Building remediation
C7 - Handover	C73_Hbttn	Habitation
C8 - Key plant	C81_Scffld_Up	Scaffold erection
C8 - Key plant	C82_Scffld_Dn	Scaffold strip
C8 - Key plant	C83_Crn_Rnt	Crane rental

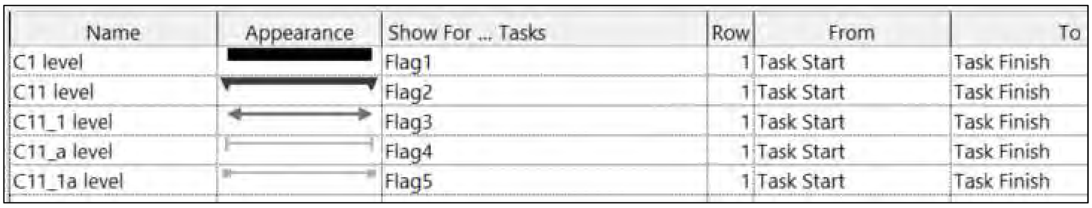
Group	Code	Full name
C8 - Key plant	C84_Lift_Instll	Install lift(s)
C9 - Management	C91_Mngmnt	Daily management
C9 - Management	C92_Delay	Delay
C9 - Management	C93_Delay_Mtg	Mitigated delay

Table 6B5. Project file template settings type and justification

Entry or setting	Template / custom	Justification
WBS	Template	Identical task codes and names to be used across all projects. See Table 8
WBS Sub-tasks	Custom	Tasks with _a, _2 and _2a suffixes are project-specific entries for recording of different trades or locations
Task duration	Custom	Data
Task start	Custom	Data
Task finish	Custom	Data
% Complete	Custom	Data
Actual work	Custom	Results
Resource Names (Task Column)	Custom	Data
Resource sheet	Template	Identical labour codes to be used across all projects. See Fig. 60
Resource calendar workhours	Custom	Data
Resource excluded workdays	Template	National holidays and winter break valid across regions. See Fig. 61
Project calendar	Custom	Data
Flag fields	Template	Flag values to be used across projects
Bar visualisations	Template	Identical visualisations to be used across projects, linked to flag values. See Fig. 62

Table 6B6. Labour resources codes linked to main construction task used in this thesis, adopted based on project progress reports

Code	Full resource description
L91 Smngr	Site manager
L11 Grndw	Ground-worker
L12 Flrsb	Floor slab worker
L23 Offrct	Offsite erector
L83 Crnop	Crane operator
L31 Rfrct	Roof erector
L33 Rftlr	Roof tiler
L24 Brckl	Bricklayer
L63 Elctr	Electrician
L62 Plmbr	Plumber
L61 Joinr	Joiner
L34 SlrPV	Solar PV installer
L60 Dcrtr	Decorator
L81 Scfld	Scaffolder
L55 Lndsc	Landscaper
L71 EngIn	Engineer or Inspector
L00 Glbrr	General labourer



Name	Appearance	Show For ... Tasks	Row	From	To
C1 level		Flag1	1	Task Start	Task Finish
C11 level		Flag2	1	Task Start	Task Finish
C11_1 level		Flag3	1	Task Start	Task Finish
C11_a level		Flag4	1	Task Start	Task Finish
C11_1a level		Flag5	1	Task Start	Task Finish

Figure 6B4. Template Settings. Visual Bar Styles properties linked to Flag data.

Resource Name	Type	Initials	Max. Units	Std. Rate	Accrue At	Base Calendar
L91 Smngr	Work	L91	1,000%	£25.00/hr	Prorated	Mon-Sat 48 hrs
L11 Grndw	Work	L11	1,000%	£11.21/hr	Prorated	Mon-Fri 40 hrs
L12 Flrsb	Work	L12	1,000%	£11.81/hr	Prorated	Mon-Fri 40 hrs
L23 Offrct	Work	L23	1,000%	£12.64/hr	Prorated	Mon-Fri 40 hrs
L83 Crnop	Work	L83	1,000%	£11.81/hr	Prorated	Mon-Fri 40 hrs
L31 Rfrct	Work	L31	1,000%	£12.64/hr	Prorated	Mon-Fri 40 hrs
L33 Rftlr	Work	L33	1,000%	£13.82/hr	Prorated	Mon-Fri 40 hrs
L24 Brckl	Work	L24	1,000%	£13.82/hr	Prorated	Mon-Sat 48 hrs
L63 Elctr	Work	L63	1,000%	£10.97/hr	Prorated	Mon-Sat 48 hrs
L62 Plmbr	Work	L62	1,000%	£10.97/hr	Prorated	Mon-Sat 48 hrs
L61 Joinr	Work	L61	1,000%	£13.82/hr	Prorated	Mon-Sat 48 hrs
L34 SlrPV	Work	L34	1,000%	£13.14/hr	Prorated	Mon-Fri 40 hrs
L60 Dcrtr	Work	L60	1,000%	£13.82/hr	Prorated	Mon-Sat 48 hrs
L81 Scfld 48hrs	Work	L81	1,000%	£13.82/hr	Prorated	Mon-Sat 48 hrs
L55 Lndsc	Work	L55	1,000%	£13.14/hr	Prorated	Mon-Sat 48 hrs
L71 EngIn	Work	L71	1,000%	£30.00/hr	Prorated	Mon-Fri 40 hrs
L00 Glbrr 40hrs	Work	L00	1,000%	£7.80/hr	Prorated	Mon-Fri 40 hrs

Figure 6B5. Template Settings. Resource sheet. Cost Data source: (AECOM, 2017).

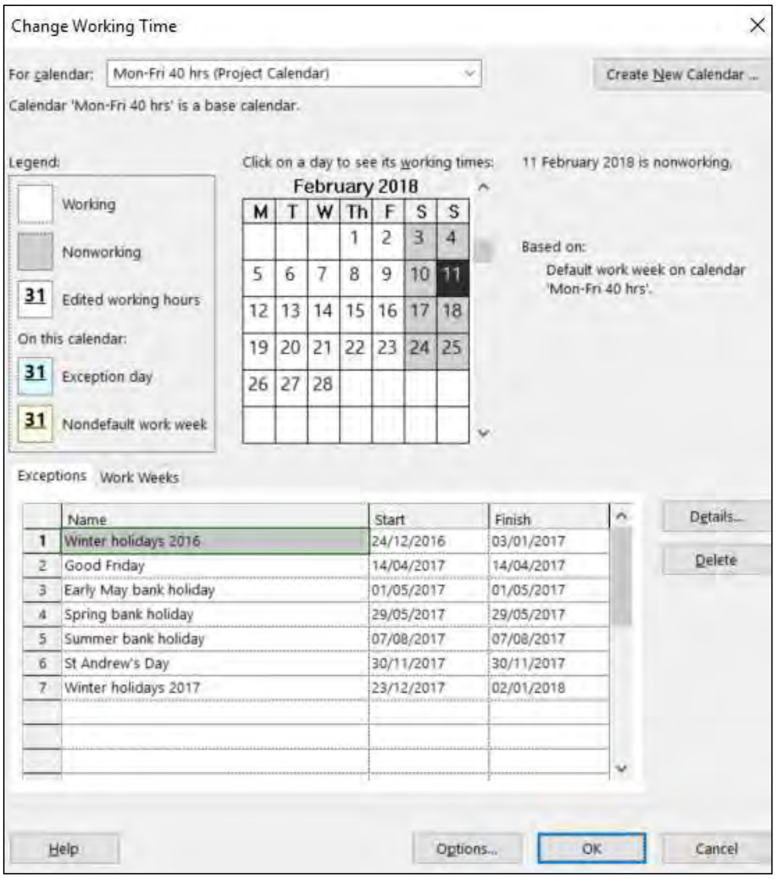


Figure 6B6. Template Settings. Calendar, excludes local holidays, which are project-specific.

Appendix 6C - Constructability results and analysis

The connection between constructability and productivity of offsite construction systems was discussed in **Chapter 2**. The pilot case studies were explorative in nature, and therefore the emphasis in this chapter was placed on the multi-factor comparative productivity method development. The following results are presented for a limited sample of typical house type instances in each of the case study projects, semi-detached houses. Due to the fragmented nature of the data collection resulting from the trial of several data collection and analysis methods, retrospective quantitative results extraction and analysis was judged to be unreliable and instead qualitative summaries on each of the identified main research themes were extracted from the case studies field and intermediate analysis notes.

Constructability results

The results from the first pilot studies were collected using a standardised spreadsheet and hand-written notes supplemented with audio-visual materials: photographs with time meta-data and videos. The transformation of this data into a structured constructability comparative analysis was piloted, listed below and shown in and Figure 6C1. The results were reported with reference to a robust database of 513 photographs and 1 video file with duration 19:15 minutes capturing the complete truck to connected process of the fourth and last for the day module installation, all taken on 11/05/2016 during the installation of plots 42 and 43 within Phase 1.

a) crane set up

b) Prepare services connections

c) lift module

d) install moduel

Figure 6C1. Constructability images VTC case study pilot. 11/05/2016.

Task definition

Action

1) Prepare floor slab and sole plates: clean, check levels, level screw/nail heads with the timber, level the cut profile of water pipes,
2) (Simultaneous with 1 & 3): Set up the crane: manoeuvre to pre-agreed position, ensure the crane is securely grounded.
3) (Simultaneous with 1 & 2): Truck with module 1 relocates to pre-agreed position near the crane and driver(s) remove the straps.
4) The crane is connected to the module using lifting hooks.
5) The crane lifts and moves the module to location above the soleplate.
6) The module is slowly lowered, guided by module installers to fit on the pin connections and water/electricity mains connections. In some case the module may require minor relocation.
7) The module is released from the crane and the crane starts preparing for the following module.
8) Excess DPM is stapled to the module walls.

9) The top access area for the staircase is removed (marked with spray-paint), if the module is on the ground floor.
10) (if the module is on the first or above floors) The services are connected from the inside of the top module to the one below.
11) Tools removed from the plot and re-located to the next installation plot.

Tools

1) Broom, circular saw, hammer, cordless drill, spirit level,
2) Portable crane
3) Truck
4) Hooks and chains, spanner
5) Crane and visual gesture communication between crane crew and offsite installers
6) Crane and visual gesture communication between crane crew and offsite installers
7) Spanner and ladder
8) Stapler
9) Stanley knife
10) Various hand-held tools
11) All hand-held

Number of people

1) 1
2) 4 (of whom 1 crane driver)
3) 1(+1) truck drivers
4) 1
5) 4 (of whom 1 crane driver)
6) 3
7) 2
8) 1
9) 1
10) 2

Approximate time

1) 1 hour
2) 15 minutes
3) 3 minutes
4) 15 to 30 minutes
5) 5 minutes
6) 5 to 30minutes
7) 5 minutes
8) 3 minutes
9) 5 minutes
10) 2 minutes

10-minute break between pods

VTC vs OTP

Similarities

[1] In both the volumetric and the open panel systems typical non-specialist hand-held tools were used for the installation of the offsite components.

[2] The installation teams were similar in size, however the VTC system also required a crane operations team.

[3] In both cases materials were stored on site exposed to the elements. In the VTC case study a tools container was also used.

Differences

[4] The volumetric timber systems installation required a crane, whereas the open timber panels were installed manually.

[5] The logistics were more complex considered in the volumetric timber case study.

[6] The OTP process required four weeks to get the building air and water tight, whereas with the VTC process this was completed after the modules per plot were completely installed, usually in one day.

Comments

Good practice

[7] The crane area in the VTC case study was outlined using tape to prevent people entering the high-risk zone.

[8] The teams were co-ordinated in the VTC case study and improved their installation process buildability with small tweaks over time.

Be aware

[9] PPE was worn by most people on site in the OTP case study, however in some instances workers needed reminding to wear safety hats.

[10] The VTC system installation require the use of ladders, which could be substituted with lower-risk access platforms in future projects.

Warning

[11] Spacers should be used when connecting the modules to the sole plates or the module below, to avoid hands getting trapped below the module. This was introduced after a near-miss incident.

[12] Staircase modules for the apartments had to be rotated from horizontal to vertical position and at one point the installer operative was inside the module while the module was above ground still, to open a problematic access hatch. This was considered a high-risk activity and the site manager requested that it was not repeated.

[13] Sudden rain when staircase access hatches of modules are opened resulted in one instance in water flooding inside the module. This was remediated as soon as possible, however higher care was taken not to repeat this in the following installations.

Cause and effect

[14] The completion of the volumetric units was originally scheduled with duration of three days, which was later increased to a week, however in reality the module completions in the later phases required extensive remediation to achieve sustainability Key Performance Indicators (KPIs) and lasted approximately 6 weeks. In contrast, in *Phase 1* of the VTC case study, the volumetric units were installed as scheduled.

[15] Additional pressures were put on the VTC project by police escort resources reduced availability, leading to volumetric units deliveries waiting up to 5 hours for police officers near the Scottish border.

[16] At the start of the project there were intentions to increase VTC module deliveries to two per week, equalling 8 modules installed per week, however this was not possible due to offsite manufacturer's capacity and productivity issues and police escort resources reduced availability.

[17] The OTP case study had only minor disruptions to the programme, due to drawings inconsistency and the trades were effectively synchronised according to an established sequencing of construction activities.

Constructability improvement potential

In accordance with the developed productivity improvement analysis spread-sheet based method, the seventeen observations from **Table 6C1** results were inserted as separate entries and categories according to their typology (similarities, differences, good practice, be aware, warning and cause & effect). The analysis for those observations categorised as *Lean wastes* is shown in **Table 6C1**.

From the analysis it can be hypothesised that lean logistics tools, visual management, process improvement and collaborative planning could be utilised in future similar projects to increase the constructability and subsequently the productivity of volumetric timber and open timber panel projects. In addition, BIM-based construction analysis using 4D Time simulations of the buildability could be used to optimise the health and safety and materials handling in future similar volumetric timber units installation, whereas a single digital federated model source of information could be of most use in future similar open timber panel projects.

Table 6C1. Productivity improvement potential analysis, pilot case studies. For variable references see Appendix 6B.

Construct-ability observation reference	Waste 'Muda' Type	Lean Principle Potential	Lean Tool Potential	BIM Principle Potential	BIM Tool Potential
[3] Similarities	M_Inv	LP_Val_Str	LT_Logistics	BIM_Cnstr_An	BIM_Tim
[5] Differences	M_Mot	LP_Val_Str	LT_Logistics	BIM_Logistics	BIM_Virt_Colab
[9] Be aware	M_Skill	LP_Perf	LT_Vis_Mngmnt		
[11] Warning	M_Skill	LP_Perf	LT_Prcss_Impr	BIM_Cnstr_An	BIM_Tim
[13] Warning	M_Def	LP_Val_Str	LT_Prcss_Impr	BIM_Cnstr_An	BIM_Tim
[14] Cause & effect	M_Def	LP_Val_Str	LT_Oprtns_Impr	BIM_Rev_Meet	BIM_Virt_Colab
[15] Cause & effect	M_Wait			BIM_Erl_Stkhdr	BIM_Vis
[16] Cause & effect	M_Skill	LP_Val_Str	LT_Collab_Plan	BIM_Erl_Stkhdr	BIM_Vis
[17] Cause & effect	M_Ov_Prod	LP_Perf			BIM_Fed_Mod

Appendix 7A - Data availability mid-rise case studies

Table 7A1. Data availability: Cross laminated timber case study

Document	Availability
1. General information	
1.1. Architectural drawings	Yes
1.2. Engineer drawings	Yes
1.3. Specifications	Yes
1.4. Crane procedures	Yes
1.5. Waste reports	Yes
1.6. Deliveries	
1.6.1. Deliveries reports and source or estimated mileage for general materials	No
1.6.2. Offsite system delivery route, vehicle type, estimated mileage and any special route considerations.	Yes
1.7. Contractor's progress reports	*No*
1.7.1. List of sub-contractors	*No*
1.7.2. Register of crew times (labour-hours) on site	via interviews
1.7.3. Plant use on site, including type and hours used or days rent	Yes
2. Labour Productivity	
2.1. Construction programme	Yes
2.2. Clerk of works reports	No
2.3. Health and safety procedures	Yes
2.4. Just-in-time or other lean processes utilised?	Yes
2.5. Procurement route used and roles of each stakeholder (general information)	Yes
2.6. Interviews on project progress	Yes

Table 7A2. Data availability: Closed timber panel case study

Document	Availability
1. General information	
1.1. Architectural drawings	Yes
1.2. Engineer drawings	No
1.3. Specifications	Yes
1.4. Crane procedures	Yes
1.5. Waste reports	Yes
1.6. Deliveries	
1.6.1. Deliveries reports and source or estimated mileage for general materials (if available)	No
1.6.2. Offsite system delivery route, vehicle type, estimated mileage and any special route considerations.	Yes
1.7. Contractor's progress reports	Partial
1.7.1. List of sub-contractors	No
1.7.2. Register of crew times (labour-hours) on site	Via interviews
1.7.3. Plant use on site, including type and hours used or days rent	Yes
2. Labour Productivity	
2.1. Construction programme	block-specific for offsite; General site pattern for internal works; Remaining via interviews
2.2. Clerk of works reports	No
2.3. Health and safety procedures	Yes
2.4. Just-in-time or other lean processes utilised?	Yes
2.5. Procurement route used and roles of each stakeholder (general information)	Yes
2.6. Informal interviews on project progress	Yes

Appendix 7B – CLT and CTP case studies constructability results

CLT constructability results

CLT ground floor slab pour

Action

Typical floor slab actions: formwork, reinforcement, & concrete pour. Because of the CLT tolerance power-floating was also required.

Tools

Concrete pour equipment, manual concrete spreaders and level tools, power floater

Figure 7B1. CLT floor slab.

Tolerances

The ground floor slab was poured in accordance with the grid which corresponded to the wall centre lines. Although, pouring slabs is standard practice in construction, with CLT there was a need for precision in both dimensions and levels. The levels could not be above +10mm or below -20mm of the set slab level, nor could it be at both extremes of the tolerance. For example, -17 and +7 differences would have been unacceptable, whilst -1 and +10 differences would have been acceptable.

Number of people

Concrete pour = 1 crew depending on sub-contractor decision. Seven people worked on the ground floor slab, as follows:

- 1 = concrete pour
- 3 = concrete spread with manual tools
- 1= slab thickness check and concrete spread
- 2 = concrete power floating for a level surface

Approximate time

Slab pour = 2 days; Slab cure = 5 days

CLT ground floor brackets

Action

The grid of the floor slab were checked and the grid lines were set out using string and/or paint. String enabled more precise alignment of the brackets to the line. DPC paint was applied along the panel location lines. The ground floor brackets were installed using two bolts and a filler. The brackets were installed along one side of the CLT panel position.

Figure 7B2. CLT ground floor brackets.

Tools

- DPC paint and roller
- Drill
- Dust blower
- Silicone gun
- Hammer

Number of people

Brackets fitting = 4

DPC paint = 2

Approximate time

1) Lay down grid for the building with spray-paint = 3 hrs
2) Mark areas for DPC paint beneath the walls. = 2 hrs
3) Paint on DPC. = All day
4) Mark one side of the walls with nails and string = 1 hr
5) Mark the locations of each bracket at 1000mm centres along one side of the walls. = 1 min per bracket
6) Drill 2 openings per bracket. = 2-3 min per bracket
7) Remove the dust from the holes. = 1 min per bracket
8) Add adhesive to the hole. = 1 min per bracket
9) Attach the bracket to the concrete with two screws. = 1m per bracket
10) Adjust the position of the bracket with a hammer. = 1m per bracket
11) Attach bitumen DPC around the perimeter of the slab. = 4 hrs – done by main contractor, not CLT, installers

Ground floor CLT wall panels

Action, number of people and approximate time in minutes (min)

Figure 7B3. CLT wall panels.

1) Clear the space around the location of the panel = 1 min

2) Attach lifting straps to the CLT panel (2 people) = 1 min
3) Lift CLT panel crane into place along the brackets (3 people on the ground guide the CLT panel) = 1-3 mins
4) Measure if the panel is level horizontally (1 person) = 30 s
5) If necessary, move the panel slightly so that it is square (1 person +mallet) = 30 secs
6) Attach the CLT panel to the brackets using screws (1 person) = 1 min (simultaneously with 7 and 8)
7) Attach 1 temporary prop to the CLT using screws (1 person) = 1 min (simultaneously as 6 and 8)
8) Measure if the panel is level vertically, next to the temporary prop (1 person) = 1 min (simultaneously with 6 and 7)
9) Attach 2nd temporary prop to the CLT using screws (1 person) = 1 min (simultaneously with 10)
10) Measure if the panel is level vertically, next to the temporary prop (1 person) = 1 min (simultaneously with 9)
11) Release lifting straps from the crane and the CLT panel (2 people) = 1 min (simultaneously with action 12)
12) Remove excess material from the top of the panel near the location of the lifting straps (1 person) = 1 min (simultaneously with 11)

Tolerances

The panels were assembled with a +/-5 mm tolerance.

Team division

1 crane operator
Truck = 1 person
On site = 5 people as follows:

<u>Panel hoisting:</u>
Supervision = 1 person
Guide panel = 3 people
Retrieve connectors = 1 person

<u>Panel connection:</u>
Bracket connections = 1 person
Angled steel connection = 1 person
Level measurement = 1 person
Detach panel = 2 people

Tools

Spirit level, Mallet, Lifting straps, Cordless drill

Upper floors CLT wall and CLT floor panels

Action, number of people and approximate time

Wall panels:
1) Unload panel from truck either to the exact construction location or to an intermediate location on the construction level. (3 people) = 2-20 minutes depending on number of re-locations
2) Locate panel alongside pre-installed brackets. (3 people)
3) Measure the vertical level of the panel (1 person) = 1 min simultaneously with 4 and 5
4) If adjoining perpendicular wall measure and mark screws line and install 2-3 screws. (1 person) = 1 min simultaneously with 3 and 5
If not adjoining perpendicular wall connect to temporary prop using screws. (1 person) = 1 min simultaneously with 3 and 5
5) Retrieve next panel from panels stack and attach to crane.

Floor panels:
1) Unload from truck into intermediate or final position
2) Connect to the wall panels below using screws as per construction drawings

Note: observation of CLT floor panels' installation was limited

The CLT team were typically be split into two halves, one more experienced group installing the panels with temporary fixings and the less experienced team following to complete the taping and fixing.

Team

- 1 crane operator
- 4 people on the upper level working on CLT panels hoisting
- 2+ people below ground working on connections

Tools

- Spirit level
- Mallet
- Lifting straps
- Cordless drills
- Cordless nail guns


Figure 7B4. Floor panel CLT installation.


Figure 7B5. Floor panel CLT connection.

CLT internal works

Tools

Various hand-held tools typical for the involved trades.

Action

Electricals 1st fix, erect metal stud partitions, plumber 1st fix, joiner 1st fix, lay floors; (these combined = 1st fix)
Erect non-loadbearing partitions, fire ceilings, airtightness check, MVHR, lowered ceiling, ames tape, plumber fit out, electrical fit out, plumber snag; (these combined = 2nd fix)
Joiner finishing, kitchen, wet wall and tiling, pre-decoration snag, decoration, joiner 3rd fix, external inspection, contractor inspection, contractor clean, client inspection, client remedial work, client final inspection, floor finish and blinds, handover; (these combined = 3rd fix)

Number of people

Varied per task and trade. Between 1 and 18. The highest numbers of people tasks were 'Erect metal stud partitions' (18), 'joiners first fix' (18), and the 'lowered ceiling' (10).

Approximate time

Approximately 5 to 6 plots per week were completed per trade, 26 subsequent activities.
Overall start 24th April 2017 (ground floor electricals whilst CLT was being completed);
Overall end 2nd February 2018 (on 26/01/2018 only the final decorator's work was pending).
Overall duration 41 weeks, including holidays; 38 weeks, excluding 2 weeks festive holiday and 1 week public holiday.

Figure 7B6. Electrical services installation at CLT case study. 30/06/17.

Figure 7B7. CLT plumbing routing detail. 13/10/2017.

CLT external works

Tools

Various hand-held tools were used for brick-laying, cladding panel installation and brick-slips installation.

Action

Lay ground floor brickwork courses, install brackets, install breather membrane, install insulation, install cladding battens, install cladding board, apply mortar adhesive layer (where applicable), install brick slips (where applicable).

Number of people

25 for cladding panels
8 for the brick-slips, 2 of whom apprentices

Approximate time

Overall from 24/04/2017 to 02/02/2018. Overall duration 41 weeks, including holidays;

Figure 7B8. Cladding support system: insulation, brackets and battens. 13/10/2017.

Figure 7B9. Brick-slips cladding. 13/10/2017

CLT health and safety observations

Site traffic and materials storage indicated practice in the CLT case study which translated into low hazards from plant and efficient retrieval of components.

Moreover, the steel staircases were installed in a matter of hours and could be used straight away, shown in **Figure 7B7**. This resulted in highly reduced hazardous conditions, because the internal staircases were less risk-inherent than scaffold staircases. According to the site manager approximately seven weeks of work were saved compared to conventional construction.

The gas mains were a challenge, because of perceived risks by the gas suppliers in connection with disproportionate collapse. This was the first CLT construction project in the world to have gas utilities, which were separate for each apartment block. According to the site manager in future projects a central gas main with a distribution system to the apartments should be used.

Harnesses and Personal Protection Equipment (PPE) were generally used as prescribed by the crews indicating good health and safety techniques, as on some construction sites parts of PPE can be often neglected. In addition, during the CLT installation the activities with higher hazard levels had to do with working with heights, mainly during the floor panel installation due to the risk of falling off the panel edge during fixing. Moreover, when using cranes there was a slight but potentially high-impact chance of mechanical malfunction outside the operator’s control. The CLT installers responsible for doing the fixing may have had an increased chance of feeling symptoms of hand-arm vibration syndrome due to prolonged use of power drills. Although vibration dampeners in modern hand-held tools should mitigate most of the effects, this area needs further investigation for best-practice connection detail specification with health and safety in mind.

Figure 7B10. Staircase at CLT case study. 17/03/2017 DSC00616.

CLT waste observations

There was little to no waste during the CLT installation. The start of the first internal fixes was also done with observation of best practice site cleanliness. These points are exemplified in **Figure 7B8**. During the CLT installation approximately 9 tonnes of active waste were collected from site, or 200 kg per plot. No timber waste was collected for recycling, and the CLT off-cuts were upcycled for use as separators or for other general construction purposes. During the internal and external works, the external site area was maintained in clean order, however some untidiness was observed during the later stages of the internal works. The higher quantities of waste materials and less orderly tool storage during work can be explained by pressures to expedite work when behind schedule.

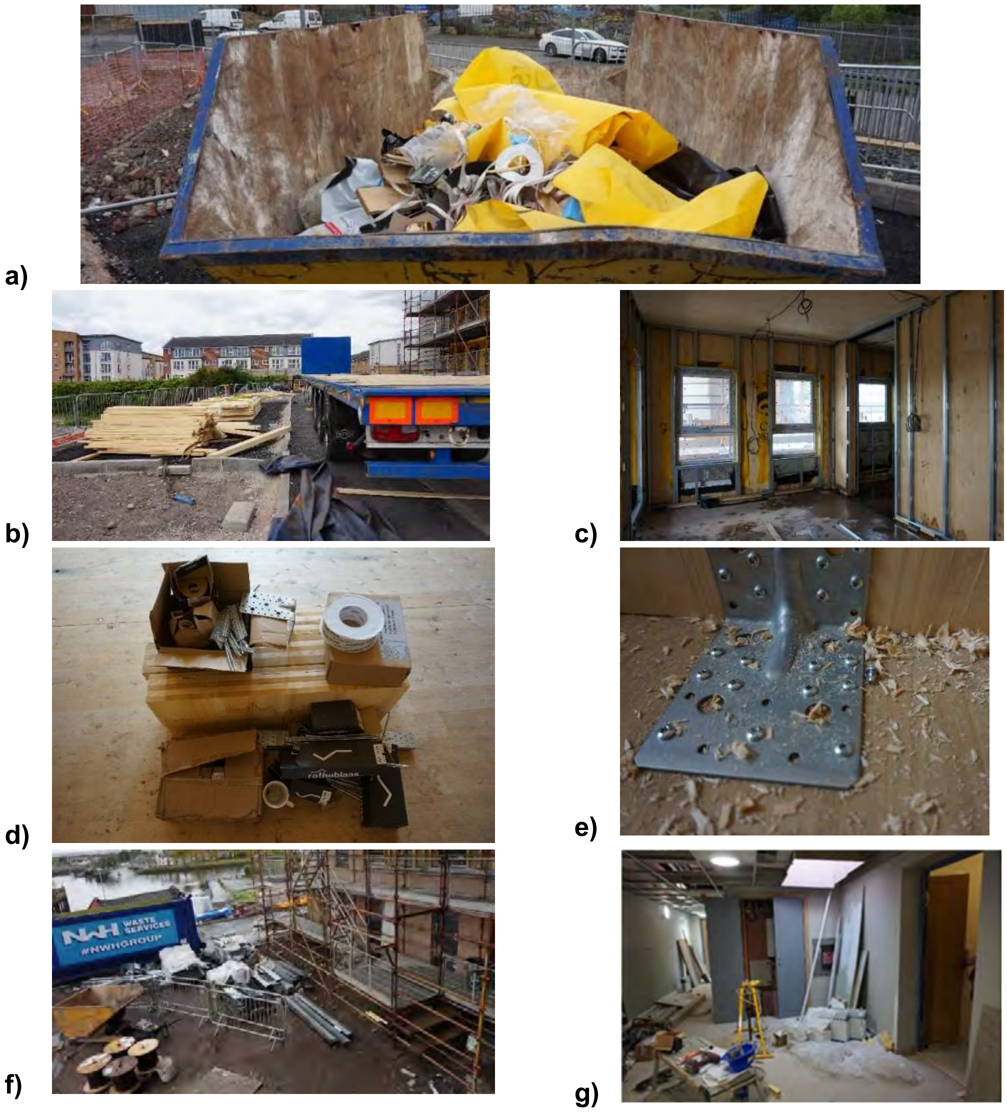


Figure 7B11. Waste observations. a) CLT installation waste; b) CLT panels stacked; c) clean internal environment; d) CLT waste; e) CLT woodchips; f) external works and g) internal works waste observations.

CLT qualitative data validation

The constructability results were reviewed by the project's engineer and BIM manager during a results face-validation interview and overall, they were considered to be an accurate and relevant representation of the CLT installation process. Some changes were suggested by the BIM manager to highlight how the buildability observed at the CLT case study related to typical CLT projects. The results of the constructability interview validation are shown in the table below.

Table 7B1. Constructability results validation changes.

Action	Validation changes made
CLT installation ground floor. Brackets	Clarified that 1 min is the duration per bracket alignment, not for the overall task
CLT installation ground floor. Brackets	Adhesive (or resin) application and dust removal from the holes is not typically necessary in all the brackets. Typically, two types of brackets are specified, uplift and basic. The uplift brackets have resin application, whereas the basic brackets have a mechanical anchor and only need one hit with a hammer, which triggers the expanding anchor.
CLT installation ground floor. Brackets	The bitumen is applied by the contractor not by the CLT installers, that is best practice
CLT installation ground floor. Brackets	Added 'Organize lorry loading for efficient installation of the panels off the lorry.' This is important because the panels need to be organized in a certain order to increase the buildability of the task.
CLT installation ground floor. Brackets	Added 'It is best practice to use string to mark panel locations and to ensure the string is tight'
Constructability. CLT installation ground floor. CLT wall panels	Expanded comment to specify team division into two groups – more and less experienced Added note on targeted dimensions Added note on the importance of tolerances in the ground floor CLT installation
Constructability. CLT installation upper floors. CLT wall and floor panels	Added note on a top-down time per panel calculation Added note on team division into two groups – installers (more experienced) and fixers (less experienced) Added note that if the panels are smaller in size, two people can do the panel installation. Substituted 'attach angled steel column' with 'connect temporary prop' Substituted 'detach from crane' with 'remove lifting slings'
Constructability. CLT installation upper floors. CLT wall and floor panels	Added note on the importance to differentiate between the CLT panels installation (on critical path) and the fixings (not on the critical path)
Constructability. CLT installation upper floors. CLT wall and floor panels	Added notes on the use of fencing as a best practice injury prevention method for floor installation.

CTP constructability results

The CTP constructability results are broken down step-by-step in the figures below, and the collected labour and equipment data is shown for each step of the process in the tables below. Please note that the wall and floor panels' installation was scheduled in two simultaneous sections, each with a dedicated crane and installation crew. These results were validated during an interview with the site manager, where the results were presented, and the site manager provided information to fill data gaps and suggested some minor amendments.

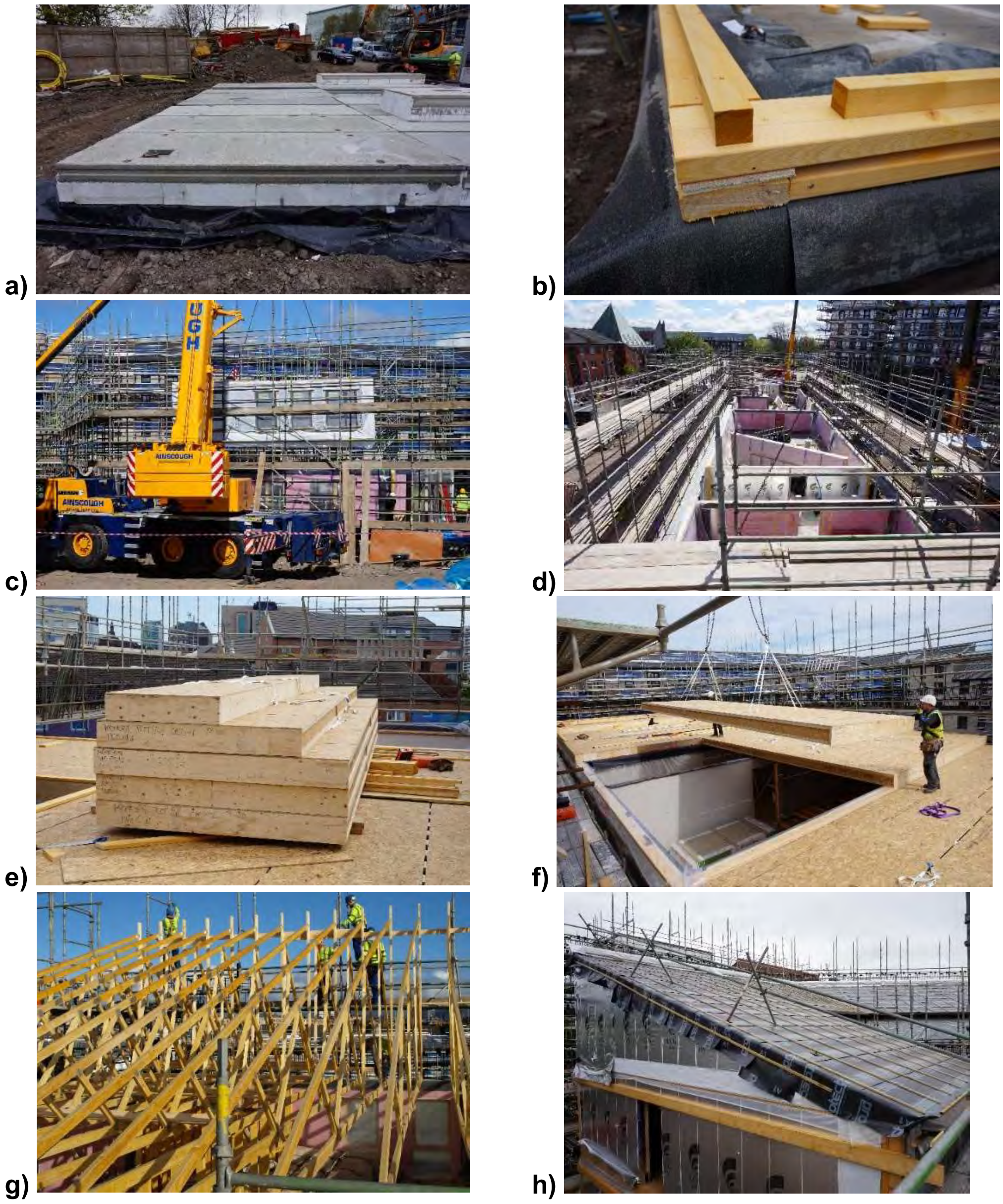


Figure 7B12. Offsite timber systems construction sequence at CTP case study: a) precast floor slabs, b) sole plates, c) and d) wall panels, d) and f) floor cassettes, g) roof trusses, and h) roof finish works – tiling battens installed and to be tiled.

Table 7B2. CTP ground floor slab constructability results

Process in sequential order	Labour and plant
Foundations Section 1	
Foundations excavation	2
Underbuild masonry	2
Solumn works (drainage, ducts, membranes)	3
Ground floor prefab slab	3 + crane
Foundations Section 2	
Foundations excavation	2
Underbuild masonry	2
Solumn works (drainage, ducts, membranes, insulation)	3
Ground floor prefab slab	3 + crane
Slab survey	2
Scaffold up *	5 to 6
Soleplate	2 x 3 =6

Table 7B3. CTP wall panels and floor cassettes constructability results

Process in sequential order (in 2 sections)	Labour and plant
Ground floor closed timber panels	3 + crane
Pre-loading sheets	2
Bean bag install	1
1st floor closed timber cassettes	2 + crane
1st floor closed timber panels	3 + crane
Pre-loading sheets	2
Bean bag install	1
2nd floor closed timber cassettes	2 + crane
2nd floor closed timber panels	3 + crane
Pre-loading sheets	2
Bean bag install	1
3rd floor closed timber cassettes	2 + crane
3rd floor closed timber panels	3 + crane
Pre-loading sheets	2
Bean bag install	1
Roof trusses construction	7
Internal finishing works CTP	2
External works CTP	2

Table 7B4. CTP blockwork common areas constructability results

Process in sequential order	Labour and plant
GF blockwork	3 x 3 = 9
GF stairs	3 + crane
1st floor blockwork	3 x 3 = 9
1st floor stairs	3 + crane
2nd floor blockwork	3 x 3 = 9
2nd floor stairs	3 + crane
3rd floor blockwork	3 x 3 = 9
3rd floor stairs	3 + crane
Common areas roof construction	2

a) b)

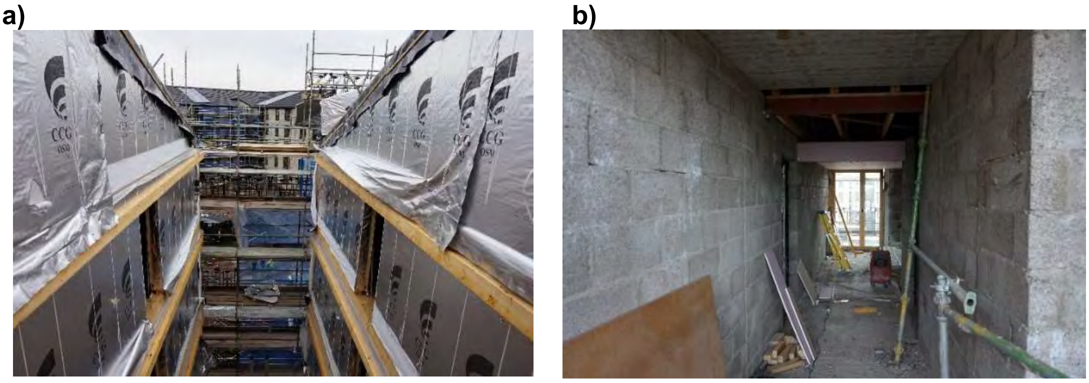


Figure 7B13. Blockwork utilisation for common circulation areas: a) ground floor to roof void following offsite timber systems installation, and b) a blockwork common area under construction.

CTP internal works

a) b)

Figure 7B14. CTP case study internal works: a) CTP apartments, and b) blockwork common areas

Table 7B5. CTP internal works constructability results

Process in sequential order	Labour and plant
CTP apartments	
Joiner 1st fix	7
Plumber 1st fix	6
Electrician 1st fix	3
Joiner 2nd fix	3
Plumber 2nd fix	3
Pocket door installation	2
Fitted kitchen	3
Electrician 2nd fix	3
Ceramic tiling	3
Plumber sanitary ware	3
Electrician 3rd fix	3
Decoration	6
Joiner 3rd fix	1

Table 7B5. Contd. Process in sequential order	Labour and plant
Blockwork common areas	
Joiner	9
Windows	6
Plaster	15
Screed	15
Stair balustrade	6
Skirting	9
Door frames	3
Lifts install	6
Decorate	9
Hang doors	3
Ironmongery	3
Balustrade paint	3

Table 7B6. CTP external works constructability results

Process in sequential order	Labour and plant
Façade and roof works	
Roof solar PV	3
Windowsills and doors	2
Roof tiling	3
Brickwork flats	11
Cladding closes	3
Rainwaters	1
Scaffold drop	7
Hard landscaping	7 + diggers, etc. plant
Parking bays	1
Soft landscaping	4

CTP health and safety observations

The following main health and safety observations were made:

- All seen workers wore appropriate PPE, with some minor exceptions which were noted by the site manager during walk-arounds.
- The unloading of plasterboard sheets included team work and manoeuvring at the edge of the scaffold with restricted vision. This demonstrated best-practice handling of a high-risk activity.
- The operational area of the crane was always separated with a white and red marker line.

CTP waste observations

Although some materials such as nails were sometimes found discarded on scaffolds, in general the CTP case study demonstrated good materials storage techniques as shown in **Figure 7B12**. Plasterboard was stored indoors in packaged batches, insulation was stored outside exposed to the elements, but packaged ordered for ease of retrieval, and materials to be discarded were set aside orderly. The offsite timber system was delivered just-in-time and were erected directly after their delivery to site. Any packaging from the offsite systems was returned to the factory, to be sent to recycling.

Figure 7B15. CTP case study materials waste and storage observations: a) plasterboard, b) insulation, c) packaging, d) just-in-time panels delivery.

CLT constructability compared to CTP

Floor Slab

- The CLT panels could not overhang the concrete slab, at minimum they had to be flush with the slab edge, at best with an extra 30mm. This differed from CTP construction, where a small overhang (e.g. 30mm) was allowed.
- A detailed floor slab measurement and check were needed in the CLT project. But not in the CTP project.

Ground floor connectors

- The CTP project used sole plates and differences in the level of the slab were compensated for during the sole plate construction by using plywood sheets to elevate the sole plates, see **Figure 7B13**.
- Sole plates may also be specified with CLT, however in this project the engineers specified bracket connections as shown in **Figure 7B13**.

- Both the brackets and the sole plates required drilling into concrete, which can be taxing on the worker because of vibrations.

a) b)

Figure 7B16. Differences in ground floor connectors: a) CTP and b) CLT project.

Secondary structure

- The steel beams in the CLT project were required for structural stability and was constructed during the offsite timber system assembly.
- In the CTP project the blockwork was required in the common areas due to fire regulations and was constructed after the offsite timber system.

Ground floor wall panels

- Both CLT and CTP systems required hoisting via a crane and a skilled team to complete the task safely and efficiently.
- The tools used to install both types of panels were similar.
- The CTPs were stored vertically and hoisted within a steel lifting frame to the level of construction and were then relocated one by one.
- The CLT panels were stored horizontally and were ideally hoisted from the truck directly into the construction location.
- The CTPs were firstly all unloaded from the truck on to the relevant storage location and the trucks left the site immediately, whereas with CLT the truck was left on site and the panels were gradually unloaded.
- Sacrificial elements in the window openings were used during the CLT transportation and lifting and required to be cut after panel assembly. Instead, the CTPs had pre-fitted windows.
- The CTPs were hoisted and constructed with a protective membrane, whereas the CLT panels were constructed exposed to the elements and this did not impact their moisture content above the standard.

- The CTPs were manufactured, transported and hoisted in sets of two or three smaller panels connected during the manufacturing for greater efficiency of handling, and only separated on-site using a manual saw, as shown in **Figure 7B14**. In contrast, the CLT panels were manufactured, transported, hoisted and constructed separately.

Figure 7B17. Two-in-one transporting and lifting system used in CTP project.

Upper floors offsite system installation

- The processes of CLT floor panels and CTP floor cassettes installation were similar.
- The common areas in the CTP building could not be constructed using a combustible material and therefore the staircases were constructed using prefabricated concrete stairs and landings and concrete blockwork for the walls.
- The floor cassettes used in the CTP project were programmed as a separate installation day, whereas the floor CLT panels were programmed along with wall panels' installation.
- Sole plates were installed directly after the floor cassettes installation.

Internal works

- In both building systems the internal works were scheduled separated into the traditional trades of electricians, plumbers, decorators in several subsequent fixes.
- In both projects a six-day working week was required for the internal works to keep the project schedule.
- The CTPs included the plasterboard and windows pre-fitted in the factory within the external wall panels.
- The CLT system required a specialist acoustic detail solution, which was changed during construction and could have caused delays in the internal works.

- The internal works for the apartments and common areas were not specifically scheduled for the CTP project. Because the studied apartment building was the last one to be constructed within a larger development, a pattern of operation had been established in the previous blocks and was followed in the CTP project without a strictly timed schedule. In contrast, the internal work for the CLT project were scheduled in high level of detail.
- The CTP internal works for the apartments included 13 activities, whereas the internal works for the CLT included 26 activities, which was a significant difference.

External works

- Both buildings used a combination of cladding boards and brick-type material. In both cases the cladding materials were constructed using traditional trades.
- In both projects a six-day working week was required for the façade works to keep the project schedule.
- In the CLT project brick-slips were specified, which caused a significant delay in the completion of the external work. Metal panels were also specified as cladding. In the CTP project bricks and zinc panels were specified. – see **Figure 7B15**.
- The variance in cladding panels labour was high between the two projects – 25 people (CLT) vs. 3 people (CTP) for the cladding panels. This can be explained by the different linear metres of cladding panels on the two projects.
- The variance was lower for the brick-type materials labour utilisation – 8 people (CLT) vs. 11 people (CTP)

a) **b)**

Figure 7B18. Different brick-type cladding: a) brick-slips (CLT) and b) brick (CTP).