Multifaceted Productivity Comparison of Off-Site Timber Manufacturing Strategies in Mainland Europe and the United Kingdom

Tsvetomila Duncheva[1] and Fiona F. Bradley[2]

Abstract: Off-site construction methods have been suggested as a necessity for improving the efficiency and productivity of the construction industry through implementation of automation and lean principles in a controlled factory environment, known as modern methods of construction (MMC). The products and the project delivery and management strategies of off-site construction were studied through a multifaceted qualitative exploration of the off-site timber management strategies of 10 manufacturers, including three UK panel, three UK volumetric, and four European (EU) volumetric timber manufacturers. A comparative productivity analysis was carried out and its sensitivities were analyzed, which led to the conclusion that the labor productivity of the surveyed UK panelized and EU volumetric manufacturers was comparable, but the UK volumetric manufacturers' productivity was lower. As a result, the level of automation and the lean and Design for risassembly (DfD) applications of the manufacturers were all explored to understand these productivity differences within the context of current market trends. **DOI: 10.1061/(ASCE)CO.1943-7862.0001641.**

Introduction

Modern methods of construction (MMC) and off-site construction have been hot topics in industry in recent years because of the need to optimize the resource efficiency of the construction industry (Chevin 2018; Hairstans and Smith 2017). This is because the UK construction industry has unfortunately been slow to adopt new construction methods (Farmer 2016) despite the proposals put forward in the Egan report, which stated that "the industry should create an integrated project process around the four key elements of product development, project implementation, partnering the supply chain and production of components" (Construction Task Force 1998).

Off-site construction is an umbrella term for construction systems which transfer a percentage of the construction process from the building site to a controlled factory environment, and numerous publicly available reports and case studies have demonstrated that off-site construction has several key advantages over traditional methods of construction (Hairstans 2015). Frequently mentioned benefits are reduced time on site, waste reduction, and improved quality, which can help alleviate the current need for housing (Goodier and Gibb 2005; Homes for Scotland 2015; Krug and Miles 2013). In the context of the UK productivity puzzle of construction stagnation, the attributes of off-site construction bring opportunities for construction productivity improvement (UK Government 2017; WPI Economics 2017). However, a historical stigma relating to off-site construction in the United Kingdom exists within the construction industry and the general public, due to negative connotations relating back to the 1960s and 1970s with the terms prefab and trailer homes (Edge et al. 2002; Miller 2015). Therefore, research is needed which demonstrates the improved practices of off-site construction in the context of increasing economic pressures in the United Kingdom.

This research study focuses on timber systems and investigated two off-site structural timber systems, namely two-dimensional (2D) panels and three-dimensional (3D) volumetric (Fig. 1). Timber was selected because it is a renewable material, sequesters carbon, and is an underutilized home-grown resource which includes multiple forests and mills, which are mainly concentrated in Scotland (Dean 2010; Forestry Commission 2014). 2D panel systems have become mainstream in UK housing construction, especially in Scotland during the last 30–40 years, where the challenging weather conditions dictate a need to reduce time on site (Hairstans 2010). However, to date, 3D volumetric timber systems are still considered innovative in the United Kingdom, whereas in Northern and Central Europe they are regarded as a mainstream product. In order to investigate these different national construction markets and economic contexts, a qualitative survey of panel and volumetric timber manufacturers was carried out between August 2015 and May 2016. Six off-site timber manufacturers from the United Kingdom and four from mainland Europe were interviewed to explore their off-site timber systems and project delivery and management strategies.

Literature Review

Economic Context

Off-Site as Part of the Solution to Pressing Economic Challenges

Research publications have suggested that off-site construction is the only viable method to alleviate what has been referred to as the housing crisis in the United Kingdom (Booth 2015; Miles and Whitehouse 2013). To mitigate the housing shortage, the off-site construction industry would need to have the capability

[1]Associate Lecturer, School of Engineering and the Built Environment, Edinburgh Napier Univ., Edinburgh EH10 5DT, UK. Email: mila.duncheva@napier.ac.uk

[2]Senior Lecturer, School of Engineering, Univ. of Glasgow, Rankine Bldg., Glasgow G12 8LT, UK (corresponding author). ORCID: https://orcid.org/0000-0003-4229-9824. Email: fiona.bradley@glasgow.ac.uk

Note. This manuscript was submitted on March 18, 2018; approved on October 2, 2018; published online on May 25, 2019. Discussion period open until October 25, 2019; separate discussions must be submitted for individual papers. This paper is part of the ***Journal of Construction Engineering and Management***, © ASCE, ISSN 0733-9364.

(a)

(b)

Fig. 1. Examples of off-site timber systems studied in this paper: (a) closed timber panels; and (b) volumetric timber module. (Images by Tsvetomila Duncheva.)

of producing high volumes of housing which meet the increasingly stringent energy-use regulations. This will need significant internal and external investment because at present the industry is estimated to have a maximum capacity to deliver only approximately 140,000 of the required 240,000 homes per year in England alone. In addition:

> There is evidence to suggest that the use of off-site has been reasonably successful when applied to meet the needs of significant housing developments at scale with consequential opportunities for standardisation of design details–particularly to meet the need of Government led programmes but have been more difficult to justify and to sustain in a shrinking market operating at low volumes. (Miles and Whitehouse 2013)

Furthermore, the most recent national report of the construction industry, subtitled *Modernize or Die*, highlighted that there was a need for immediate technological revolution in the construction industry to mitigate the stagnation in the construction industry labor productivity (Farmer 2016). Labor productivity may be defined with reference to the definition "the ratio of (the product's) output to (the product's) input" (Fried et al. 1993 p. 4), interpreted to provide the labor productivity calculation

$$\text{Labor productivity} = \frac{\text{Output (number of homes or monetary output)}}{\text{Labor units}} \quad (1)$$

The productivity challenge is underpinned by acute skills challenges in construction across the traditional trades and especially in new and emerging technologies such as automated production and resource optimization (Brennan and Vokes 2017). Indeed, Recommendation 8 of Farmer (2016) stated that "government should act to provide an 'initiation' stimulus to innovation in the housing sector by promoting the use of pre-manufactured solutions through policy measures." Therefore, it could be deduced that off-site systems have untapped potential to improve the productivity of the UK construction industry, but the measurement of this productivity should be considered in terms of housing outputs, labor resources, and strategies for resource optimization.

Effect of Off-Site Construction on Output Capacity and Productivity

The total value of the UK off-site construction market was evaluated at approximately £6 billion of the £131 billion construction industry output in 2006 (Mtech Group and Gibb 2007; ONS 2016b). A subsequent study from 2008 estimated the gross output value of the off-site sector to be £5.7 billion, which was approximately 7% of the UK construction industry output (Taylor 2010). Within this estimate, the output of open timber panels was £528 million, whereas closed panels had an output of only £20 million and structurally insulated panels (SIPs) only £3 million. Taylor presented data for two types of volumetric systems, permanent and temporary, without distinguishing between different structural materials. Therefore, it is not clear what percentage of the £329 million was volumetric timber systems. Overall, there appears to be a consensus among the literature that the valuation of the off-site sector is challenging because of its geographic fragmentation and its position in both manufacturing and construction; however, an estimate of 7% seems to be the accepted value of the sector across the literature, with varying growth projections (Gambin et al. 2012; UKCES 2013).

It is expected that a higher uptake of off-site construction in the United Kingdom could have a positive effect on the stagnation of construction productivity. Indeed, Eastman and Sacks (2008) proved that within the US context, the value added per employee of off-site manufacturing was 43% higher than that of onsite construction, whereas the growth of off-site construction was approximately 0.9% greater than that of onsite construction. A team of UK researchers within the context of the Heathrow expansion created a model to calculate the additional gross value added (GVA) from a conservative market share increase potential from the current estimate of 7%–25%, and found that an additional £4.3 billion GVA would be added across the United Kingdom (WPI Economics 2017).

Off-Site Systems Categorization

Off-site timber systems may be categorized as subassemblies, panelized, pods, and volumetric solutions; however, the literature on off-site methods of construction contains a plethora of classification options (Azman et al. 2010; Kamar et al. 2011). For example, the Buildoffsite *Glossary of Terms* distinguishes between component subassembly, nonvolumetric preassembly, volumetric preassembly, and complete buildings (Gibb and Pendlebury 2013); and Hairstans (2015) differentiates between four sub-categories of 2D elements with applications for walls, floors, and roofs, and 3D modules. An additional complexity of the consistency of semantics is created by geographic preferences for key terminology, such as

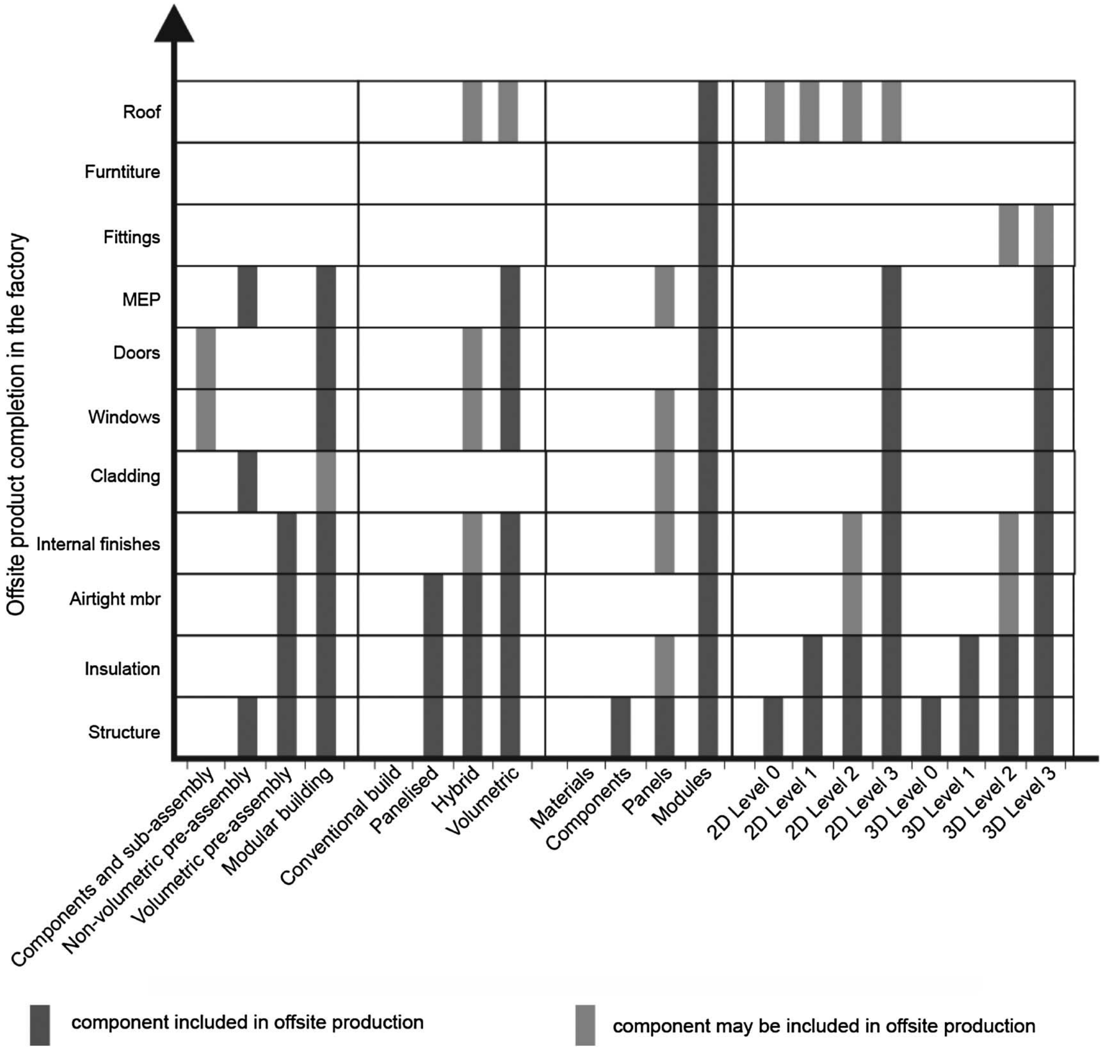


Fig. 2. Off-site systems classification comparative review according to building elements completion in the factory. (Data from Gibb and Isack 2010; Hairstans 2015; MMC Wales 2008; Oliveira et al. 2017; Smith 2011.)

industrialized building system (IBS), modular, and prefabrication (Ma et al. 2015). Further differences in off-site systems classifications are shown in Fig. 2 (Gibb and Isack 2010; Hairstans 2015; MMC Wales 2008; Oliveira et al. 2017; Smith 2011).

A common theme among the off-site categorization 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 on-site and off-site work. To communicate this basis for differentiation, estimated percentages of off-site completion are often used, which increase incrementally with the increasing value added in the factory during the off-site systems production. However, discrepancies exist in the literature regarding the factory completion percentages of each off-site level, which may be correlated with the differences in off-site semantics and classifications outlined previously. Specifically, in the reporting of volumetric solutions level of off-site completion, the estimates vary between 70% and more than 95%, whereas panelized solutions tend to be grouped and attributed approximately 25% of off-site completion without regard for incorporation of insulation, sheeting, windows, and so on (Lawson et al. 2014; Smith 2011). The level of off-site product completion in the factory may be correlated with strategies applied by off-site 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 and Rudberg 2014).

Volumetric Timber Systems Characterization

The main drivers for off-site timber construction uptake in the United Kingdom are connected with the mitigation of the construction industry's most critical challenges—productivity stagnation, skills shortage and house completions—as outlined in the Introduction. The attributes of volumetric timber construction are often shared with off-site timber construction characteristics but with increased values due to the higher off-site completion level (up to 95% is cited in the literature) (Smith 2016). The volumetric timber attributes which make the systems instrumental in mitigating the aforementioned industry challenges are summarized in Table 1. These topics are relevant to the identification of key variables as well as measurement and analysis methods for analysis of volumetric timber construction productivity.

Volumetric Timber Labor Productivity

Productivity is measured internationally because it is the unit of measurement associated with quality of life; namely the more a nation can produce in products and services with its given

Table 1. Main 10 attributes of volumetric construction

Type	Variable	Economic challenge mitigation potential	References
Opportunity	Time	Housing demand and supply through increased time predictability and time efficiency	Lawson et al. (2014) and NAO (2005)
Opportunity and challenge	Cost	Housing demand and supply through increased predictability and improved cash flow; initial investment can be a barrier	Lawson et al. (2014), NAO (2005), Pan and Sidwell (2011), and Polat et al. (2007)
Opportunity	Labor productivity	Productivity stagnation and skills shortage through new technical roles and increased process efficiencies (for example, through Lean or automation)	Mankiw and Taylor (2010), Koszerek et al. (2007), O'Mahony and Timmer (2009), and ONS (2007)
Opportunity	BIM	Advances in BIM and smart construction methods such as volumetric timber manufacturing are closely interconnected	Vernikos et al. (2013), Goulding and Arif (2013), Babič et al. (2010), and Tulenheimo (2015)
Opportunity	Waste	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.	WRAP (2009, 2014a, b), Goulding and Arif (2013), Hairstans (2011), Smith (2011), Quale et al. (2012), and Li et al. (2014)
Opportunity and challenge	Logistics	Road transport legislation limits the size of modules in different contexts; however, the number and carbon footprint of people and materials transport is reduced with volumetric timber systems	Krug and Miles (2013), Goulding and Arif (2013), Quale et al. (2012), and Dainty and Brooke (2004)
Opportunity	Low-carbon construction	The climate change impact potential of volumetric timber systems is much lower than that of traditional methods, but other forms of engineered timber may be superior	Monahan and Powell (2011), Jaillon and Poon (2014), Lehmann (2013), Hairstans (2018), Quale et al. (2012), and Dodoo et al. (2014)
Challenge	Specification guidelines	There is no single technical guideline resource for designers and specifiers of volumetric timber in the United Kingdom	Lawson et al. (2014), SINTEF (2013), and Rupnik (2017)
Opportunity	Build quality	Targets the low-carbon agenda, wasteful snagging processes reduction, and resource efficiency through automation and quality management system (QMS) application	Dodoo et al. (2014), Bayliss (n.d.), Krug and Miles (2013), Pan et al. (2008), and Johnsson and Meiling (2009)
Opportunity	Health and Safety	Improved conditions due to a controlled factory process and equipment use can help mitigate the construction skills shortage	Goulding and Arif (2013), Lawson et al. (2014), Hairstans (2015), and Court et al. (2009)

resources, the greater is their quality of life (Mankiw and Taylor 2010). In statistical data sets, productivity output is mostly measured in either total output, gross value added, or gross domestic product (GDP); input units can be either materials or labor (ONS 2007). National productivity is most prevalently measured in GDP per person, a type of labor productivity measurement, and this may be increased by upskilling staff, new technologies, or improved management techniques. Other methods of productivity measurement are materials, energy, or multifactor productivity measurements, in which only the output growth due to increased efficiencies is measured. The two dominant multifactory productivity measures are labor-capital value added, in which an increase in GVA is mapped to increases in labor and capital; and capital, labor, energy, materials, and business services (KLEMS) total output productivity (O'Mahony and Timmer 2009). More detailed multifactor analyses are typically applied to evaluate the development of specific sectors.

In construction, productivity measurements can range from a high-level analysis of the entire industry to very specific processes such as the installation of a floor cassette on site (Kenley 2014). Four levels of construction productivity measurement have been theorized (Table 2). Kenley proposed that future research should improve each productivity level via an established methodology, such as lean production or location-based management.

In volumetric timber construction, productivity is most often measured as production of modules per labor unit and number of people required on site (Hager 2014; Kamali and Hewage 2016; Yu et al. 2013). With volumetric building, the on-site labor

Table 2. Construction productivity improvement methods proposed by Kenley (2014)

Level	Reference	Productivity	Knowledge gap
Industry	Nasir et al. (2013) and Vilasini et al. (2014)	Comparison of construction productivity of different countries can be used for benchmarking.	Challenge in gathering data due to segments of construction being part of the manufacturing sector, such as off-site systems.
Firm	Van der Vlist et al. (2014)	Investment in information and communication technology can be used to increase the competitivity of a company in the market.	Connection between the technological investment in a company and their profitability.
Project	Isaac and Navon (2014)	Automated data collection and transformation of the data into efficiency estimation calculations.	Challenge to improve productivity due to difficulty of manually collecting data from construction sites.
Activity	Kenley (2014)	Measuring physiological indicators such as heartrate established a connection between strain and productivity.	The relationship between physical strain and activity productivity.

can be reduced by approximately two-thirds compared with traditional construction methods (Lawson et al. 2014; NAO 2005). Moreover, according to the cited studies, a building can be made watertight and windtight in one-fifth the time required by traditional methods, whereas panelized systems require one-half the time of traditional methods. However, the authors noted that the productivity improvements in volumetric manufacturing are challenging to evaluate, and only provided an estimate that the factory processes could be twice as efficient as on-site processes. Lawson et al. (2014) estimated that this could result in approximately 10% cost reductions in volumetric unit production processes versus traditional construction. In the context of the United States, it has been estimated that approximately 250 labor-hours are required to produce one module with an area of approximately 55 m^2, equivalent to 5 labor-hours per unit area (Mullens 2011).

Management Strategies

Different off-site construction management strategies have been investigated by previous research studies, with an emphasis on enablers and barriers. For example, Nadim and Goulding (2011) conducted a qualitative survey with interview data from European off-site company representatives and concluded that a combination of five parameters would be needed to address industry-wide challenges: business process, market, people, product, and technology. Three specific factors were identified as particularly challenging: (1) the need for a sustainable market demand, (2) a reduction in public prejudice toward off-construction site from historic events, and (3) a balance between replicable and bespoke production strategies. Furthermore, they identified that logistics regulations and changing building regulations created barriers for off-site construction. Other researchers have investigated the actual and apparent cost challenges to the industry in the United Kingdom (Pan and Sidwell 2011) and the quality assurance advantages in volumetric timber construction (Johnsson and Meiling 2009). In addition, findings from a workshop with UK industry representatives suggested that in future construction research, the design and management strategies of off-site manufacturers should have a higher priority than manufacturing strategies (Goulding et al. 2012, 2014).

Automation

Volumetric manufacturing systems which utilize automation through a combination of computer-aided design (CAD) and computer-aided manufacturing (CAM) can benefit from standardized product quality and reduction of rework as a result from human error (Gibb 1999). Although manufacturing tends to be unique to each company, there are three key components to volumetric assembly lines: framing stations, working tables, and turning tables (Lawson et al. 2014). Volumetric timber manufacturing strategies can be categorized as

1. manual, in which traditional building methods are transferred to an enclosure;
2. those with some CAM applications (e.g., nailing bridge and/or optimizing saw); and
3. technologically extreme, in which automated digital manufacturing techniques and resource efficiencies are transplanted from the automotive industry to the off-site manufacturing process.

Automation levels currently 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, whereas in the United Kingdom more moderate automation of off-site systems is observed (Buntrock 2017; Dalgarno 2015; Hairstans 2015). Automation may furthermore be linked to increased opportunities for digitalization of construction through building information management for an integrated whole-life-cycle approach to resource efficiency (Sinclair 2013; Vernikos et al. 2013).

Lean

Recent publications have investigated the effects of lean strategies on off-site manufacturing. Lean process improvements aim to reduce *muda* [Japanese for waste (Womack and Jones 2003)] within manufacturing, management, and the supply chain process, and these include eight key muda types: "transportation, inventory, motion, waiting, over-production, over-processing, defects and skills misuse" (Corfe 2013). Meiling et al. (2015), who 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. However, the research discovered differences in the perceptions of management and production staff regarding the production processes, which suggested that clarification and communication is needed between management and production personnel. Moreover, a case study of a Canadian volumetric manufacturer revealed that companies that originated as on-site traditional contractors and subsequently transferred to or branched out to off-site manufacturing tended to implement on-site 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 a simultaneous reduction in labor-hours.

DfMA and DfD

Design for Manufacture and Assembly (DfMA) is a recent strategy for materials and labor optimization, and its principles are generally applied by off-site manufacturers in the United Kingdom (Hairstans 2015). In accordance with DfMA, products are designed for optimum cost efficiency in the manufacture and assembly processes, and the optimization can include a reduction of part numbers, the use of standard parts, or the reduction of the 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 function change, upgrade, and optimum reuse of their components at the end of the products' life cycles. DfD in combination with DfMA can therefore be used to implement circular economy principles in the construction industry. A circular economy is a concept in which products and materials are reused, repaired, or recycled before disposal, thereby reducing waste and improving resource efficiency (Sinclair et al. 2013). DfD is a familiar technique in the automotive industry, which is often used as a comparator for off-site construction. (Bogue 2007), There still, however, seems to be a gap in DfD application in the technical design of buildings, because it is currently limited to theoretical life-cycle assessment (LCA) and carbon recovery methods (Crowther 1999; Thormark 2001). Overall, these principles could be implemented through production strategies to increase the whole-life-cycle resource efficiency of off-site timber systems.

Gap in Knowledge

In summary, the preceding research studies discussed either generalized industrywide trends or management strategies of one to two off-site companies. Moreover, in the current literature, off-site systems tend to be grouped together, which does not reflect the incremental levels of off-site completion for the different off-site systems, namely subassemblies, panelized, pods, and volumetric. Therefore, this research study builds upon previous work by analyzing different product, process, and management strategies among panelized and volumetric timber manufacturers. The results are discussed in the context of the pressing labor productivity challenges, with consideration of the different levels of off-site completion between systems and generalized DfMA strategies which may improve resource efficiency.

Methodology

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

A multifaceted in-depth qualitative survey method was therefore applied in this research study to explore the products and processes of volumetric (and panelized) timber manufacturers using semi-structured interviews (Reason 1994). This study explored different approaches to the management of off-site timber systems in the United Kingdom and in Central and Northern Europe. The discussion topics for the interviews contained 36 questions overall, grouped in 6 general topics: (1) manufacturing line stages, (2) building elements, (3) modules/panels, (4) process, (5) projects, and (6) volumetric timber. The context was the next 5 years, and a complete list is given in Appendix S1. In addition, nonscheduled exploratory questions were asked for companies that had a specific area of expertise (Reason 1994). The length of the interviews was between 3 and 8 h, and the interviews with 8-h duration took place over 2 days. Some interviews were preceded by a presentation by the company representative about their strategy and projects, and some were followed by building visits. All interviews included a factory tour, during which the manufacturing process was discussed step-by-step, and most interviews ended with site visits to completed buildings delivered by the manufacturers.

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 off-site timber panel manufacturers were selected in the United Kingdom, three off-site volumetric timber manufacturers were selected in the United Kingdom, and four volumetric timber manufacturers were selected in Central and Northern Europe. This sampling strategy was informed by previous research findings that timber panels are mainstream methods of construction in the United Kingdom, whereas the volumetric timber market is more mature in mainland Europe than in the United Kingdom (Meiling et al. 2015; Taylor 2010; Venables and Courtney 2004).

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 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 (Bjertnæs and Malo 2014; Fern 2014). As a starting point, the available literature on volumetric timber and panelized timber manufacturers was collected and synthesized (Modularize 2015). From the created database, 12 off-site timber manufacturers were contacted across the United Kingdom and mainland Europe via email and follow-up telephone conversations to arrange face-to-face interviews. Ten of these manufacturers were sampled for this research study based on data availability; more details are given in the "Limitations" section. The 15 interviewees were representative of a variety of occupations, including architects, production managers, and directors (Fig. 3).

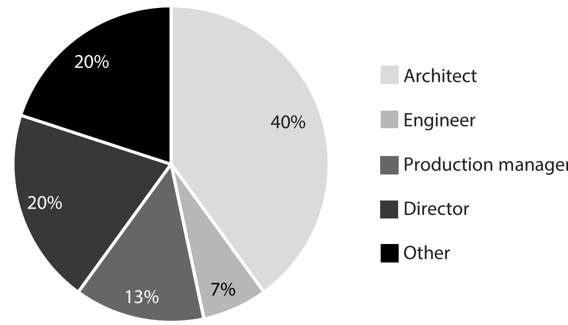


Fig. 3. Total survey sampling by profession.

The 10 manufacturers varied between family-run and international businesses, recently and long-established companies, and those with either a single or several manufacturing facilities; and represented 5 countries in Europe. 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. The sampling strategy of this survey therefore covered a large variety of business models and stakeholders from off-site timber manufacturing companies in Europe.

Data Collection and Analysis Methods

The data collection was conducted between August 2015 and May 2016, followed by analysis until November 2016. The UK interviews were recorded with prior consent and were transcribed with the aid of hand-written notes to emphasize important points. The EU participants did not consent to interview recordings and therefore hand-written notes were the data sources; to ensure accuracy, the notes were written during and within 24 h 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.

In qualitative data analysis, the data would typically be explored at this stage through coding of repeat themes and cases in a software package such as NVivo version 11 (Bazeley 2013). Indeed, this approach was trialed with the manufacturers, for each of whom a report was produced with section titles corresponding to the interview questions and selected images from the factory tours inserted with captions and dates. This allowed comparison of instances of responses within NVivo, which was useful for analysis of automation, lean, Design for Disassembly, and other quantifiable qualitative survey explorations. In addition, the results were exported to a concise Excel spreadsheet, in which each of the survey question responses was transformed into ultimately 230 rows of data organized in 6 main themes to create a database for the survey (Hesse-Biber 2010). This allowed identification of patterns in survey responses and categorization of reported opportunities and challenges according to five main themes: production, market, design, building information modeling (BIM), and carbon. The production outputs were unfortunately reported using different units, and their transformation to a normalized comparative unit of measurement was therefore only possible through quantitative secondary manipulations of the data (further details of the measurement units transformation are given in the "Analysis and Discussion" section). 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 and the numeric-coded shared attributes according to productivity levels. This facilitated insightful and meaningful conclusions (Creswell and Clark 2007).

This rigorous data collection, analysis, and conclusions approach was developed based on previous research studies in industrialized construction (Hairstans and Smith 2017; Nadim and Goulding 2011; Succar 2009). For example, Hairstans and Smith applied a method of semistructured 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 United Kingdom) using open-ended questions with emphasis on the variety of responses as opposed to instances of responses in an exploratory research study.

Limitations

The qualitative multifaceted in-depth nature of this study represents a compromise between breadth and depth of research investigation. This study explored the variety of production and project strategies from a carefully selected sample of off-site manufacturers. This contrasts with a quantitative survey, in which breadth would be favored over depth and the aim would be to collect responses on limited topics from a large sample across the globe which would be representative of off-site timber manufacturers in contrasting economic contexts. Therefore, the conclusions drawn from this study may not applicable to all off-site systems, because of the large variety of manufacturing systems in the international market. However, through data analysis triangulation and detailed benchmarks against previous studies, the validity of the conclusions was demonstrated.

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 therefore operational yet, and another company announced bankruptcy hours prior to the scheduled interview and as a result the interview did not take place. These examples demonstrate the practical limitations of conducting fieldwork in the dynamic economic context of off-site timber construction.

Assumptions made in the units transformation of this survey are clearly stated in the "Analysis and Discussion" section, and care was taken that these were based on rigorously collected data and findings from previous research. 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 of this research study are of relevance to architects, engineers, housing associations, local authorities, and developers, to name a few, the analysis of their role in off-site timber projects was outside the scope of this study. However, further information about the perceptions of built environment designers and comparative analysis of off-site construction projects are available in the lead author's doctoral thesis and subsequent journal publications. Although cost factors are important in business models, this survey avoided collection of sensitive cost data, and therefore items such as investment in research and development (R&D), new equipment, training, software, and so on were excluded from the scope of the research.

Results

Off-Site System Results

Product Type

Three UK companies manufactured open- or closed-panel systems. The open-panel systems prefabricate the frame with either oriented strand board (OSB) or plasterboard (gypsum) on one side, and the closed-panel systems further include insulation, board on both sides, and service cavity battens with thicknesses varying between 90 and 240 mm. The six volumetric companies prefabricated modules, but two of them also offered panels to their clients if transportation or design requirements made a full volumetric solution unsuitable. Most often, bespoke open plan or double height spaces in the building were provided because panels and the other spaces were provided as modules. The most common construction method was the traditional timber stud frame at 600-mm on center (Fig. 4).

(a)

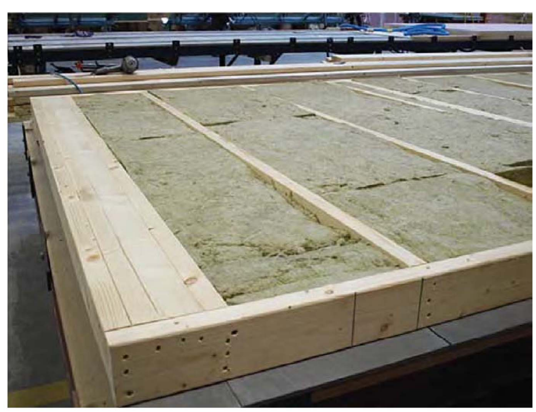

(b)

Fig. 4. Timber frame with 600-mm on center closed panel at the insulation fitting stage: (a) UKP; and (b) EUV. (Images by Tsvetomila Duncheva.)

Table 3. Factory comparison based on product type and timber system

Type	UKP1	UKP2	UKP3	UKV1	UKV2	UKV3	EUV1	EUV2	EUV3	EUV4
Panel	Y	Y	Y	—	—	—	Y	—	—	Y
Volumetric	—	—	—	Y	Y	Y	Y	Y	Y	Y
Stud	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
CLT	—	—	—	—	Y	—	—	Y	—	—
SIP	—	Y	—	—	—	Y	—	—	—	—

Note: Y = Yes.

Table 4. Factory comparison based on maximum product size and average weight

Dimension	UKP1	UKP2	UKP3	UKV1	UKV2	UKV3	EUV1	EUV2	EUV3	EUV4
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	0.32	0.35	5	15–20	12	8	16	24	10

Note: The specified dimensions are for standard manufacturing line only; larger products can be assembled manually.

All manufacturers included a timber stud frame in their products, even if it was limited to the internal service wall areas. Two volumetric manufacturers (UKV2 and EUV2) used cross-laminated timber (CLT) as their main structural component, and UKP2 and UKV3 used SIPs to construct the external walls of their modules. These companies added value to the engineered timber products in their factories by fitting stud frames for services and insulation. The floors, ceilings, and roofs of all manufacturers were constructed using either timber I-joists, web joists, or CLT. The product types of each company are compared in Table 3.

Size, Weight, and Transport

In general, the surveyed off-site timber systems had similar dimensions (Table 4). The volumetric systems differed from the panels in that they had greater length dimensions and included a specified width dimension. Both the panel and volumetric systems had heights of approximately 3 m, varying between 2.9 m (UKP3) and 3.8 m (EUV3 and EUV4). Where small differences existed between module manufacturers, in special cases a manufacturer was selected among their competition because of the greater length, width, or height possibilities of their system. For example, the EUV3 modules had the largest width, 5.3 m, compared with 4.2–4.95 m of the other EUV manufacturers.

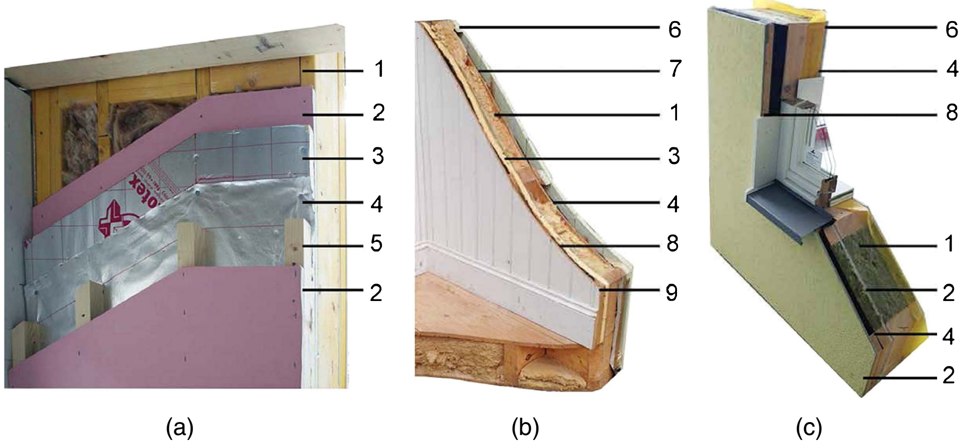
Among the panel manufacturers, the size of the panel production equipment seemed to be the greatest influence on the standard panel sizes, because the companies explained that transport did not impose limits. UKP2 noted that closed-panel systems transport more air than do open-panel systems, and therefore less construction area can be transported in one truck load. UKP3 explained that they produced oversized panels (that did not fit the automated assembly lines) on benches using manual methods, which was typical practice among panel manufacturers, and that in this case transport regulations and trailer sizes did impose limits.

The most significant factor which determined the module sizes was road legislation, that is, the distinction between permitted standard and oversized loads. The road regulations are different in each country, which is reflected in the different product dimensions discussed previously. In the United Kingdom the main restricting dimensions is width: a standard load is up to 3.6 m (incl. 0.3-m overhang on each side), and an oversized load width is up to 4.3 m. The distinctions between size and shipping methods of the stacked panel and volumetric systems are shown in Fig. 5.

(a)

(b)

Fig. 5. Examples of different transport methods for off-site timber panels and a volumetric module, the height of which necessitates the use of an articulated trailer: (a) standard trailer with stacked open timber panels; and (b) articulated trailer with a volumetric timber module. (Images by Tsvetomila Duncheva.)



1 - Timber stud frame with loose insulation

2 - Gypsum board (plasterboard)

3 - Solid insulation

4 - Breather membrane or Damp Proof Course

5 - Timber studs with services gap

6 - Lightweight cladding

7 - Oriented Strand Board (OSB)

8 - Timber studs with ventilation gap

9 - Internal wall finish board

Fig. 6. Construction detail examples per company type: (a) UKP; (b) UKV; and (c) EUV. (Images by Tsvetomila Duncheva.)

Two UK volumetric manufacturers (UKV1 and UKV2) designed their modules within the standard load, and therefore no police escort or advance permits were required, whereas UKV3 designed either standard-load or oversized modules, depending on the client's specification. UKV1 transported two modules per truck load, aligned lengthwise on a standard (for the UK) 18-ft trailer. Interestingly, one UK manufacturer had designed projects for unconventional air transport, which imposed even stricter size and load limitations on their module specifications. UKV2 occasionally designed, manufactured, and transported oversized module elements as panels, such as roofs with overhangs. In Europe, there was a different approach to design and logistics integration. Two EU volumetric companies (EUV3 and EUV4), for instance, designed their modules for both road and water transport and sent them in batches of 30–60 modules 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. Loss of six modules had occurred at the time of interview among different projects. Each lost module caused delays to progress on site because the module had to be refabricated and retransported during the scheduled construction work.

Off-Site Completion

As confirmed by the literature review, the timber panel manufacturers had a lower level of off-site completion than did the volumetric manufacturers. UKP1 had the highest level of off-site completion among the panel manufacturers, because 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 best-selling products were open timber panels, which had a low level of off-site completion and included only the structural frame and OSB sheet on one side. Fig. 6 compares three examples of off-site construction systems, and demonstrates that the construction details of the panel and volumetric products were similar in principle but had some differences in material specification. The volumetric timber products included the structure, insulation; airtightness membranes; internal finishes; cladding; windows; doors; mechanical, electrical, and plumbing (MEP) services; fittings; built-in furniture; staircases; roofs; and outdoor entrance areas (Table 5).

There were several exceptions to this observation, such as projects which did not require staircases due to having only a single story and situations such as that for UKV2 in which multistory projects with external staircases were delivered by a subcontractor. In addition, most volumetric manufacturers did not construct roof systems, because this was deemed to be the responsibility of the main contractor. Exceptions to this were UKV1 and UKV2, who delivered roof structures either as part of the module or constructed on-site using traditional methods, i.e., as trusses at 600 mm on center connected with longitudinal ties and sheeted with OSB. UKV1 was unusual because it included the outdoor entrance areas in one of their products because their house types resembled traditional homes; UKV3 included IT and other specialist equipment as a choice in their commercial modules. This enabled quick plug-and-play installation on site. Overall, the volumetric timber manufacturers stated that they constructed approximately 90% of the buildings in the factories, and UKV2 intended to increase this figure to 98%.

The off-site manufacturers were often flexible with the level of prefabrication to suit each specific client and project requirements. Four of the seven volumetric manufacturers aimed to construct as much in the factory as possible, however, and offered only complete products, which they justified by stating the benefits of improved build quality in the factory.

On-Site Activities

All system 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 summarized in Table 6. The panel systems required a higher number of on-site activities,

Table 5. Factory comparison based on off-site work activities

Component	UKP1	UKP2	UKP3	UKV1	UKV2	UKV3	EUV1	EUV2	EUV3	EUV4
Structure	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Insulation	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Airtight mbr.	Y	Y	Y	—	Y	Y	Y	Y	Y	Y
Int. finishes	—	—	—	Y	Y	Y	Y	Y	Y	Y
Cladding	Y/N	—	—	Y	Y	Y	Y	Y	Y	Y
Windows	Y	—	Y/N	Y	Y	Y	Y	Y	Y	Y
Doors	Y	—	—	Y	Y	Y	Y	Y	Y	Y
MEP	—	—	—	Y	Y	Y	Y	Y	Y	Y
Fittings	—	—	—	Y	Y	Y	Y	Y	Y	Y
Furniture	—	—	—	Y	Y	Y	Y	Y	Y	Y
Staircase	—	—	—	—	—	Y	Y	Y	Y	Y
Roof	—	—	—	—	Y	—	—	—	—	—
Porch	—	—	—	Y	—	—	—	—	—	—
Reported off-site completion estimate	45%	25%	29%	82%	90%	90%	90%	90%	90%	90%

Note: mbr. = membrane; int. finishes = internal finishes (skirting, painting, flooring, tiling, and so on); MEP = mechanical, electrical, and plumbing systems, including heating and HVAC; Y = yes; and N = no.

Table 6. Factory comparison based on on-site work activities

Dimension	UKP1	UKP2	UKP3	UKV1	UKV2	UKV3	EUV1	EUV2	EUV3	EUV4
Foundation[a]	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
MEP services	Y	Y	Y	—	—	—	—	—	—	—
Connection to mains	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Airtightness seal	Y	Y	Y	—	Y	—	Y	—	—	—
Plasterboard	Y/N	Y	Y	—	—	—	Y	—	—	—
Wall paint and tiles	Y	Y	Y	—	—	—	Y	—	—	—
Flooring	Y	Y	Y	Y/N	—	Y/N	Y/N	—	—	—
MEP fixtures	Y	Y	Y	—	—	—	—	—	—	—
Windows	Y/N	Y	Y/N	—	—	—	—	—	—	—
Doors		Y	Y	—	—	—	—	Y/N	—	—
Scaffold[a]	Y	Y	Y	Y/N	—	Y/N	Y/N	Y	Y	Y
Cladding	Y/N	Y	Y	—	—	—	—	Y	Y/N	—
Roof[a]	Y	Y	Y	Y/N	Y/N	Y	Y	Y	Y	Y
Insulation between elements	Y/N	Y/N	Y/N	—	—	—	Y	—	—	—
Crane required	Y/N	Y/N	Y/N	Y	Y	Y	Y	Y	Y	Y

Note: Y = yes; and N = no.
[a]Actions executed by the main contractor, who can also be the client.

whereas the on-site activities of the volumetric systems were fewer in number and required fewer trades on site.

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

Project Delivery Results

Contractual Relationships

Nine of the 10 companies reported that their roles were that of a subcontractor, delivering and often constructing the off-site timber system only (Table 7). Among the panel manufacturers, UKP1 and UKP3 sometimes constructed projects in collaboration with their sister companies, who were traditional masonry on-site contractors. The smaller companies, UKV1 and UKV2, had more responsibilities per project, including project design from concept to final production drawings. In addition, UKV1 was responsible for the entire project apart from the underbuilding masonry and services routing. The main contractual role of UKV3 was different, because they were responsible for the off-site system but preferred to be a main contractor on projects to give them the same authority as the on-site builder company. Within the EUV companies the only outlier was EUV4, who, in addition to providing modules for external companies and projects, acquired land and speculatively developed housing projects for private sale.

Market Opportunities

At the time of the interviews, all manufacturers were producing residential projects. There was an overall pattern of mainly house production in the United Kingdom and apartment production in Europe. The projects in the factories varied between high-end bespoke solutions and low-specification refugee shelters. In addition, UKP1 were constructing 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 off-site timber construction. These are

Table 7. Factory comparison based on contractual role

Dimension	UKP1	UKP2	UKP3	UKV1	UKV2	UKV3	EUV1	EUV2	EUV3	EUV4
Designer	—	—	—	Y	Y	—	—	—	—	—
Subcontractor	Y	Y	Y	Y	Y	—	Y	Y	Y	Y
Main contractor[a]	Y/N	—	Y/N	Y	—	Y	—	—	—	—
Developer	—	—	—	—	—	—	—	—	Y	—

Note: Y = yes; and N = no.
[a]The main contractor may be a sister company.

Table 8. Building types manufactured per factory

Building type	UKP1	UKP2	UKP3	UKV1	UKV2	UKV3	EUV1	EUV2	EUV3	EUV4
Apartments	Y	Y	Y	—	Y	Y	Y	Y	Y	Y
Houses	Y	Y	Y	Y	Y	Y	Y	N	N	Y
Affordable housing	Y	Y	Y	Y	Y	—	Y	—	Y	—
Student residences	Y	Y	Y	—	—	—	Y	—	Y	Y
Retirement homes	Y	Y	—	—	Y	—	Y	Y	Y	Y
Emergency housing	—	—	—	—	—	—	Y	—	—	Y
Schools	Y	Y	Y	—	Y	N	Y	Y	Y	Y
Nurseries	Y	Y	—	—	—	—	—	—	Y	Y
Healthcare[a]	Y	—	Y	—	Y	—	—	Y	—	Y
Offices	Y	Y	—	—	—	—	Y	—	—	—
Recreation	—	Y	—	—	Y	Y	—	—	—	Y
Rooftop extensions	—	Y	—	—	—	—	Y	Y	Y	—
Remote locations	—	Y	—	—	Y	—	Y	—	—	—
Commercial[a]	—	Y	—	—	—	Y	—	—	—	—

Note: Y = yes; and N = no.
[a]Projects with relatively small footprints for their sector.

summarized in the first 6 rows of Table 8. Nine of the 10 surveyed companies manufactured off-site systems for apartment buildings, 8 did so for private housing, and 7 did so for affordable housing.

In the United Kingdom the main targeted markets for off-site timber construction were private sale houses, private sale apartments, and affordable housing. In mainland Europe, multistory apartment buildings, student accommodation, and retirement homes were seen as the building types with the largest opportunity for growth. Three EU manufacturers explained that the single-family house market was oversaturated in their countries and therefore was not a prosperous option for volumetric timber construction. EUV4 added that volumetric timber manufacture was viable only if it was produced in countries with lower gross domestic products and reduced salary rates and exported to countries with higher GDPs and salary rates. This would therefore add value to their product through export to foreign markets. Examples of affordable and high-end housing built using off-site timber systems from manufacturers UKV3, UKP3 and EUV3 are shown in Fig. 7.

Within the nonresidential building typology, the education market was perceived as the most viable opportunity for off-site timber construction. Eight companies manufactured schools, and five companies manufactured healthcare facilities. Furthermore, recreation buildings (hotel and hospitality), nurseries, and extensions were manufactured by four companies. With respect to volumetric construction, two building types were perceived as especially suitable, namely projects in remote locations and rooftop extensions to existing buildings. Specifically, the addition of levels to existing buildings was mainly practiced by the European companies, although one of them had constructed a rooftop extension to a building in the United Kingdom. Generally, the UKP and EUV companies manufactured a similarly large variety of nonresidential projects, whereas only UKV2 had manufactured four nonresidential projects. This result can be explained by the specialization of UKV1 in the affordable housing sector and the explanation given by EUV3 that steel modules are conventionally used in volumetric educational building projects in the United Kingdom, especially lightweight steel modules used as temporary classrooms during new school building construction.

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 only two companies. UKP2 and EUV1 constructed the largest variety of building types, selling to 12 and 10 sectors, respectively, and UKP1 and EUV4 manufactured 9 building types. UKV1 and UKV3 constructed the smallest variety of building types, two and four, respectively, and on average the companies constructed seven building types per manufacturer.

Cost-Efficiency and Repetitive Design Elements

With respect to cost and repetition, in this research study the UK panel manufacturers shared the view that the level of repetition within one building did not influence the cost-efficiency of their products, but the project design and specification time could be reduced by having repetitive buildings within a project. This repetition, for example of house types within a development, had little effect on the manufacturing time and cost efficiency. Furthermore, because the panel companies ordered and stocked large quantities of typical materials, they stated that the panels were more cost-efficient than timber, masonry, or in situ concrete construction in which materials are purchased per project. For example, economies of scale with OSB or timber battens are more significant in a factory, where larger quantities of materials can be ordered and efficiently utilized for every project, compared with on-site projects in which smaller quantities are ordered and incorporated.

Fig. 7. Examples of typical off-site timber residential construction: (a) UK affordable homes; (b) UK high-end homes; (c) EU affordable homes; and (d) EU high-end homes. (Images by Tsvetomila Duncheva.)

There was an interesting contrast in the views of the UK volumetric manufacturers in relation to their outlook and attitude to repetitive elements in their projects. UKV1 considered that their product was only cost-efficient for houses with up to five modules, which ranged in size from studio apartments to two-bedroom house types. UKV2 emphasized their preference that any new project had to resemble one of their previous designs, so that manufacturing processes were familiar to their staff. UKV3 stated that repetitive modules were essential to making volumetric timber cost-efficient in the United Kingdom. They were supportive of variations being incorporated into facades or potential balconies, 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 it had caused delays due to client design changes, which had in turn had adversely affected the factory line layout for another project.

The European volumetric manufacturers stated that the cost-efficiency of projects was subjective according to the clients. Their projects were mainly multistory apartment buildings with approximately 150 modules (Fig. 8), but they also accepted contracts for single-module projects. EUV4 emphasized that although the apartments were all identical in footprint, the owners purchased them in advance and requested modifications such as bespoke kitchen furniture, window relocation, or different finishes in the interior.

Energy Efficiency

The buildings' operational energy was carefully considered by all companies, and variations in specification could be delivered on an individual project basis. Typical U-values for some of the standard off-site timber systems are summarized in Table 9. The table shows that the EU companies constructed to stricter energy-efficiency standards than did those in the United Kingdom. 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, and UKP2 and UKP3 had developed standard details for different thermal performances. Three companies had standard energy performance values for their homes and standard

Fig. 8. Seven-story volumetric timber apartment block buildings in EU. (Image by Tsvetomila Duncheva.)

Table 9. Typical off-site product comparisons based on energy-efficiency metrics

Metric	Component	UKP3	UKV2	EUV4
U-value (W/m^2K)	Wall	0.44–0.1	0.15	0.18–0.12
U-value (W/m^2K)	Roof	0.15–0.08	0.16	0.13–0.1
U-value (W/m^2K)	Floor	0.14–0.09	0.15	0.17–0.1
Air flow (L/h @ 50 Pa)	Building	1.5	0.7	1.0–0.5

solutions (UKP3, UKV1, and EUV4), whereas three manufacturers (UKV2, EUV1, and EUV2) stated that they could build to any specified thermal conductivity and airtightness specification. However, in addition to their standard systems, the majority of manufacturers did state that they could construct to higher energy-efficiency standards as specified by the clients.

One timber stud volumetric manufacturer (UKV1) and the two CLT volumetric manufacturers (UKV2 and EUV2) were cautious about achieving low air flow values. For instance, UKV1 had made a design decision to maintain a higher air flow rate of 2.6 L/s @ 50 Pa and thus create a breathable timber building. EUV2 similarly remarked that "the airtightness 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 Standard Assessment Procedure (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, SAP calculations do not include embodied energy or embodied carbon calculations. Interestingly, only UKV2 stated that they were interested in embodied carbon, and their engineer essentially investigated embodied carbon in his personal time and calculated only key components. In contrast, the European companies did not calculate the embodied energy of their buildings.

Project Management Results

Factory Establishment

Five companies (UKP1, UKP2, UKV2, UKV3, and EUV3) had purchased industrial buildings and repurposed them for off-site timber manufacturing. Four manufacturers had purpose-built their factories and equipped them with a mixture of off-the-shelf and custom-designed off-site timber machines according to their manufacturing process. These were UKP3, EUV1, EUV3, and EUV4, and this indicated that this was more common among the surveyed European companies. UKV1, in contrast, used a temporary metal-framed building, which could be dismantled in 3 days if the workshop had to be relocated.

Four companies (UKP1, UKP3, UKV1, and UKV3) had started as conventional construction companies, and off-site timber was a new manufacturing technique for them to diversify their product and market ranges. EUV2 was similarly established but was part of a larger group of timber-product companies. EUV4 branched out as a new separate endeavor by employees of a neighboring off-site timber panel manufacturer. Within the sample surveyed, three manufacturers (UKV2, EUV1, and EUV3) had started their companies specifically for volumetric timber manufacturing and had progressively grown over the years, which included relocations to larger facilities. EUV1 had been in operation for 29 years, had established a daughter company for specialized modules, and had expanded their internal departments; similarly, EUV3 had been in operation for 20 years and in this time had developed into an umbrella organization containing five companies, one of which was dedicated to manufacturing.

Design Management

All manufacturers employed in-house technicians who were responsible for production drawings, but only UKV1 produced all design work internally. UKV2 had worked with external architects but mostly developed projects using their two internal architectural designers, two engineers, and one design and specification intern.

The UK panel manufacturers were conventionally sent drawings by external architects, typically specifying brick and block construction. Preferably, the architect would have been in conversation with the manufacturer from the early design stages, but unfortunately designs were often sent to the manufacturer at a late stage in their development, and internal teams were then responsible for transforming the project into off-site panels which could be manufactured on their assembly lines. For example, UKP3 redesigned buildings specified as brick and block construction. The three panel manufacturers stated that the process should be more streamlined and the manufacturer should be involved earlier; in other words, 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 the tendering stage and reworked designs by external architects to make them buildable using their volumetric timber systems. However, UKP1, UKP2, EUV1, and EUV4 had large design and specification capacities, with design teams comprising 12, 18, 16, and 12 people, respectively, compared with 5 designers at UKV3. Teams included a mixture of architects, engineers, and timber-frame technicians. EUV2 and EUV3 differed from this model in that their engineers worked collaboratively with the external architects from the early stages of the projects. Despite these efforts, design rework and exchanges of revised drawings were frequent and sometimes delayed the project progress, due to either manufacturing or regulatory issues.

Production Management

Eight manufacturers structured production management with hierarchical levels of staff, supervised by team leaders per manufacturing line. These leaders reported to production managers, who worked alongside procurement, technical, and other managers, all of whom were managed by the factory manager. This hierarchy was increased by UKV2, UKV3, and EUV2 through the outsourcing of plumbing and electrical trades when required. EUV2 outsourced decoration personnel as well, and employed 50% permanent production staff and 50% outsourced production staff. This strategy was adopted to increase the flexibility of the work distribution, and the extra staff were employed full-time when the production was behind schedule.

The exceptions to this arrangement were UKV1 and UKV2, who did not use assembly lines and therefore had less of a hierarchical system, comprising more-senior and less-senior manufacturing staff workers. Both companies employed college students or apprentices who were receiving training in volumetric timber manufacturing while 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 Fig. 9.

The UKP and EUV companies reported a continuous pipeline of projects, which were said to reduce unproductive labor hours and provide a driver for process optimization. Interestingly, UKV3 pointed out that a week of down-time between projects was useful to reconfigure and prepare for the following project, such as procuring materials, setting up the manufacturing lines, and

(a) (b) (c)

Fig. 9. Examples of automated and manual working environments in the off-site timber factories: (a) UKP; (b) UKV; and (c) EUV. (Images by Tsvetomila Duncheva.)

distributing the tasks per manufacturing station. In comparison, UKV1 and UKV2 reported lengthier gaps between projects, time which could be used to improve the company's processes as well as secure new projects.

Nine companies worked 8-h 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, a total of 22 h 30 min/day. The number of permanent production line staff varied between approximately 12 (UKV1) and 220 (EUV4), with a mean value of 40 people employed by UKP3 and UKV3.

Building Information Modeling

Overall, 9 of the 10 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, and sequence of manufacturing. UKV2 and UKV3 had applied BIM up to Level 2 [information exchange through industry foundation class (IFC) models], although 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 summarized 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 program that can analyze 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 organize the output.

Within the main BIM levels, the surveyed companies also reported on their application of BIM dimensions (3D, component; 4D, time; 5D, cost; 6D, facilities management; and 7D, energy analysis) (Sanchez et al. 2016). At the time of interviews, seven companies were using 3D components with attached information for modeling 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 was 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, that is, they designed their houses in AutoCAD only. However, because of their simplified dwelling designs and small-scale production this was deemed the most suitable drawing production method for their company. Among the surveyed companies, none had applied BIM to a fully collaborative Level 3; however, one UKV2 and one EUV2 manufacturer were optimistic that this would happen. UKP2 and UKV4 were more skeptical about BIM as a sustainable process of work in the near future.

The most widely used software among the surveyed manufacturers was AutoCAD, reported by five volumetric manufacturers. The second most used software tools were hsbCAD and Revit, each of which was reported by three manufacturers. The use of Revit was mostly associated with internal tests of BIM workflows, and only one company used this as the established software platform for architectural design. One manufacturer had conducted tests with hsbCAD and AutoCAD for BIM collaboration through IFC model exchange. Furthermore, two UKV companies used SketchUp, although for different purposes—one for conceptual architectural design and the other for BIM workflow tests including component data and automated schedule 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.

Analysis and Discussion

Exploratory Analysis of Productivity Improvement Strategies

The results were explored through coding in NVivo according to the previously identified productivity improvement strategies of

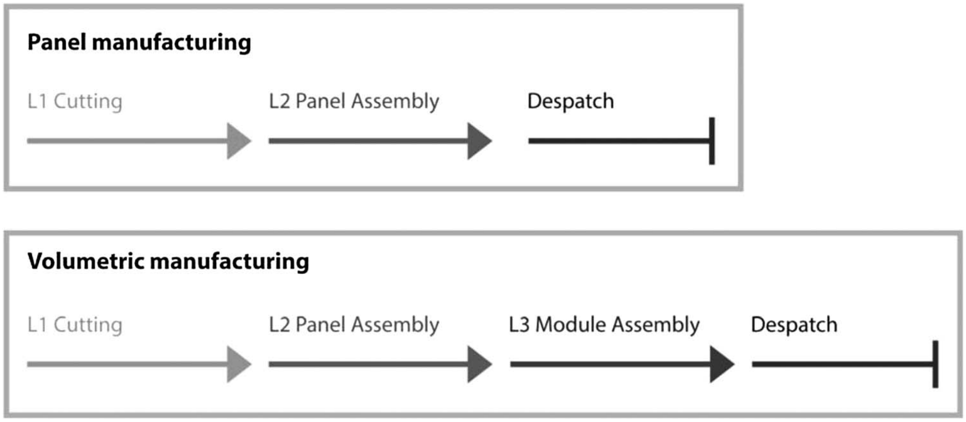


Fig. 10. Generalized panel and volumetric timber manufacturing lines.

automation and lean improvement. The analysis was carried out per manufacturing line with the aim of exploring productivity improvement strategies while reducing the impact of individual company strategies on the research findings. In this way, the observations made regarding the off-site systems production and process strategies can be generalized to a greater degree.

Manufacturing Line Stages Generalization

The panel and volumetric manufacturers shared many practices, especially in panel assembly and timber stud panel manufacturing. Essentially, the main manufacturing stages may be generalized as shown in Fig. 10.

Although the manufacturing sequence followed the generalized manufacturing lines described previously, the actual number of manufacturing lines and sequence of each company varied. The panel manufacturers had the highest number of manufacturing lines, despite producing a lesser percentage of off-site construction than the volumetric manufacturers (Fig. 11). The EU volumetric fabricators employed an average of four manufacturing lines. In contrast, the UK volumetric manufacturers mostly used 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 as in a workshop. 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 Fig. 11.

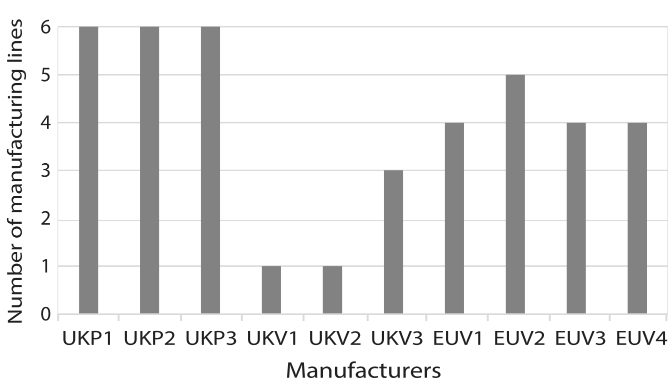


Fig. 11. Number of manufacturing lines per company.

Automation and Mechanization

The opportunities for automation were observed mainly in the initial stages of manufacturing, in materials handling and from cutting through door and window installation (Fig. 12). Automation was mostly used in the frame assembly stage, which was automated using a framing station. 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.

The other forms of automation applied in the factories were nailing bridges and Computer Numeral Control (CNC) saws which were also operated using CAM files. After framing, the panels were rolled to the nailing bridge, where sheet material (e.g., plasterboard or OSB) was automatically squared, stapled, and nailed to the frame. The CNC saws could cut timber board materials in five directions to create both intricate and accurate shapes.

In addition to automation, mechanized production tools also reduced the risks in construction, mainly by removing the need for heavy lifting. Butterfly tables, cranes, and vacuum machines are all examples of mechanization and their use is recorded in Fig. 13. These tools were used in 10 manufacturing lines among the studied companies, and the greatest examples of mechanization were

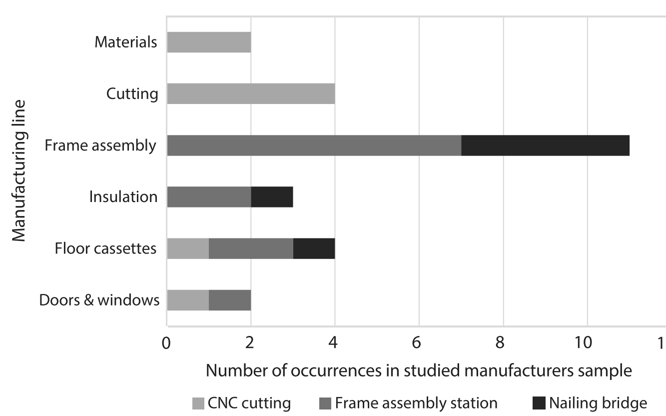


Fig. 12. Automation equipment use per manufacturing line. (Unit: application in one manufacturing stage.

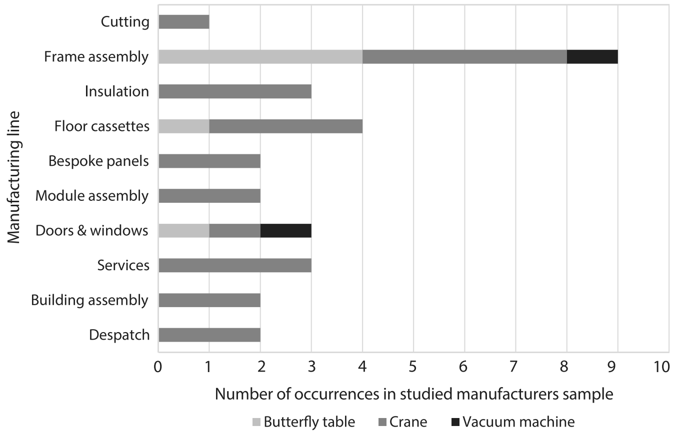


Fig. 13. Mechanization per manufacturing line.

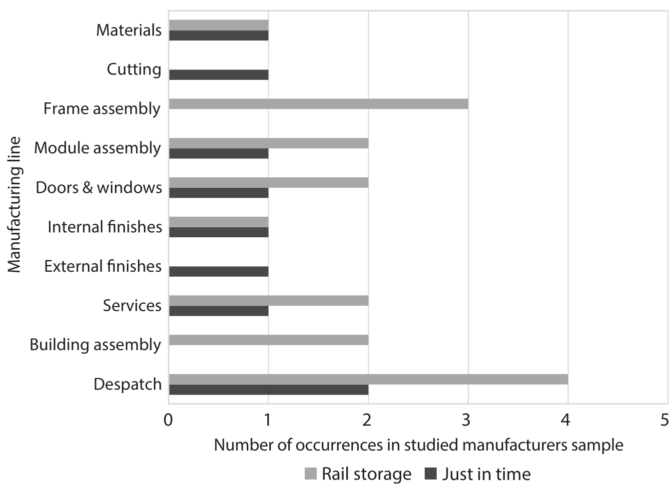


Fig. 14. Lean space-saving strategies per manufacturing stage.

observed in the frame assembly stage. The mechanized assembly tool with the greatest use was cranes, which were used to lift and transport components and panels between manufacturing lines. Vacuum lifting machines, which were 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 window and door assembly stages.

Lean: Time, Space, and Inventory Waste

In addition to automated and mechanized production efficiency improvements, some companies used lean methods, which reduced time and space wastage and the inventory in their factories. The most widely used space-saving strategy was the use of rail storage for completed panels, which was observed in seven manufacturing stages among the surveyed manufacturers (Fig. 14). In addition, two modular manufacturers used the vertical panel storage stage for paint drying, which removed the paint drying stage from the module assembly stages.

Just-in-time delivery was another widely used technique, used not only in the module dispatch stage but also in the material preparation stages. One manufacturer employed kits of components per manufacturing line station. These kits were assembled just in time when required, which removed the need for operatives to look for components during their work. A further method of space and time waste reduction was the control of inventory. This was applied mostly for nontimber components. One manufacturer 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.

Design for Disassembly

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

UKV1, UKV2, and UKV3 provided more-positive responses that building adaptation could be possible because of standardized connections, compact services cores, and internal nonloadbearing walls. In fact, at the time of the visit, UKV1 had 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.

Off-Site Completion Percentage

The starting point of the data analysis was the calculation of percentages for on-site and off-site activities of the studied off-site timber systems. The data from Tables 3 and 4 were used to propose a quantification of the off-site completion levels among the surveyed companies, where a value of 1 was attributed to elements which were included in the off-site 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 off-site level percentages, and although this method has its limitations, it was used in this instance.

This approach produced the results in Fig. 15, which show that the off-site completion levels of the investigated systems tended to be within more moderate ranges compared with the higher percentages of off-site completion often attributed to volumetric timber construction in the literature (Smith 2011). These results also demonstrate that the levels of off-site completion of systems sharing an off-site classification could be said to vary significantly: according to this research, by up to 15%. On average, the UKP companies used 25% off-site completion, the UKV companies used 70%, and the EUV companies used 65%. This is generally in line with the estimates of Lawson et al. (2014).

However, the preceding approach is limited by the exclusion of labor-hours and value added on a task level. Such an investigation could be the object of further work, the data of which could be analyzed to provide rankings of the different elements included in the off-site process. For example, it is anticipated that the roof of a two-bedroom house would require greater labor and materials input and would result in higher added value compared with the provision of a patio in the off-site completion of the system.

J. Constr. Eng. Manage., 2019, 145(8): 04019043

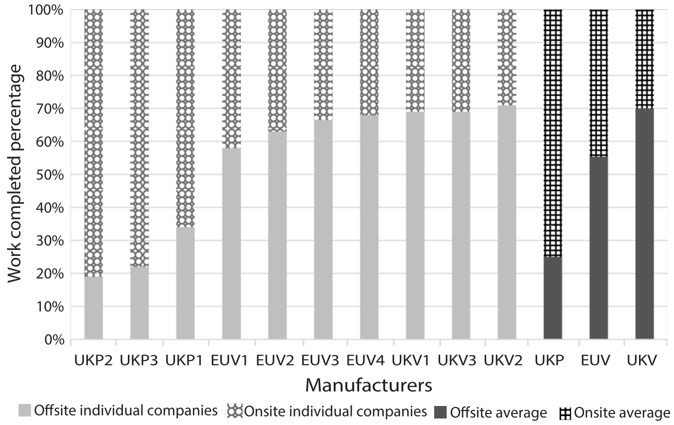


Fig. 15. Off-site and on-site building completion percentage calculated values.

Production and Productivity

The production output of each company was reported in different units (Table 10), 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 min 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 off-site production metric system could be used across all manufacturers, due to the practicalities of this industry-based research, it was necessary to transform these units into a single unit of measurement.

Pilot: One-Bedroom Living Unit with Reported Off-Site Percentage Estimates

Initially a pilot study was conducted using a simple one-bedroom apartment unit with the dimensions listed in Table 11.

To illustrate the unit conversion for the calculation, the more complex of the preceding examples is reported (time per open timber panel). First, 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 extracted output per week results. This was multiplied by the previously calculated off-site percentage for open panel construction, and this generated a normalized off-site output per week. The input was calculated in labor-hours by multiplying working hours per week by the number of staff reported working on the shop floor. This allowed differentiations in the numbers and durations of production shifts per day described in the final results. Finally, according to Eq. (2) the output was divided by the input to arrive at a figure for labor productivity comparable across the 10 surveyed manufacturers. The results from the pilot comparative productivity analysis are listed in Table 12. These findings were validated by the respective interviews by reviewing extracts from the results and analysis relevant to each respective manufacturer. A specimen of this data validation sheet is shown with a worked example in Appendix S2

$$Lp1 = \frac{P1x\text{OC}1\%}{Lh1} \tag{2}$$

where $Lp1$ = labor productivity (one-bedroom living-unit-equivalent/labor h); $P1$ = production of one-bedroom living units/week; OC1% = off-site completion percentage (reported); and; $Lh1 = \text{laborh}/\text{week}$.

Two-Bedroom Living Unit with Calculated Off-Site Percentage Estimates

The selection of a common unit of measurement was an important consideration for this research study, and the identified unit was derived from methodologies applied in previous research studies in the field (Monahan and Powell 2011; Quale et al. 2012; Smith et al. 2013). Monahan and Powell (2011) used a three-bedroom, two-story case study house in the context of the United Kingdom; Quale et al. (2012) based their findings on a four-module 2,000-ft^2 (185-m^2) two-story house in a hypothetical context; whereas Smith et al. (2013) evaluated homes/units outputs irrespective of the differences in home sizes. To decide the living-unit equivalent in this study, the data from the literature were triangulated with results from market opportunities and product type sections, technical volumetric specifications available from SINTEF, and data from national statistical records (National Record of Scotland 2013; Office for National Statistics 2018; SINTEF 2013) (Fig. 16). In addition, the selection of a neutral living unit of measurement mitigated the potential impact on results favoring one company.

Table 10. Reported units for off-site products production

Unit	UKP1	UKP2	UKP3	UKV1	UKV2	UKV3	EUV1	EUV2	EUV3	EUV4
Buildings/year	—	—	—	—	Y	—	Y	—	Y	—
Buildings/h	—	—	Y	—	—	—	—	—	Y	—
Modules/year	—	—	—	—	—	—	Y	Y	—	Y
Panels/year	—	—	—	—	—	—	—	—	—	Y
Panels linear meters/day	Y	—	—	—	—	—	—	—	—	—
Panels area/week	—	Y	—	—	—	—	—	—	—	—
Panels/shift	—	—	Y	—	—	—	—	—	—	—
Min/open panel	—	—	Y	—	—	—	—	—	—	—
Min/closed panel	—	—	Y	—	—	—	—	—	—	—
Weeks/module	—	—	—	Y	Y	Y	—	Y	Y	Y
Modules/week	—	—	—	—	—	Y	—	Y	Y	Y
Modules/day	—	—	—	—	—	—	Y	—	Y	—
Total output measurement unit types reported/manufacturer	1	1	4	1	2	2	3	3	5	4

Note: Y = yes.

Table 11. One-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

Table 12. Comparative production and productivity analysis for one-bedroom living unit

Variable	UKP1	UKP2	UKP3	UKV1	UKV2	UKV3	EUV1	EUV2	EUV3	EUV4	UKP	UKV	EUV	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%
$Lh1$/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

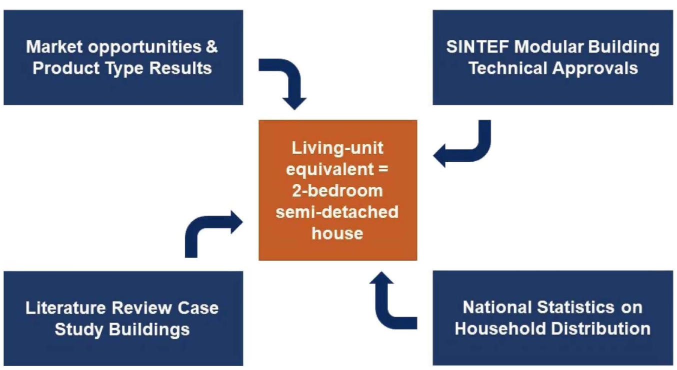


Fig. 16. Living-unit-equivalent selection methodology applied in this research.

An observation about the latest available UK census data from 2011 (Fig. 17) could be that the most typical UK households were two- and three-bedroom households. In addition, dimensional guidance was sourced from modular building technical approvals. Moreover, a more complex two-bedroom semi-detached living unit incorporated findings from previous studies that volumetric construction results in double walls/floor elements, which could result in approximately a 25% difference in material input, whereas in this study the difference was 13% (Table 13) (Quale et al. 2012). To make the results comparable to previous off-site reviews, the output units were changed to living-unit-equivalent per year and the labor units were altered to the number of staff (Smith et al. 2013). These alterations resulted in

$$Lp2 = \frac{P2xOC2\%}{Lr} \tag{3}$$

where $Lp2$ = labor productivity (two-bedroom living-unit-equivalent/labor resource); $P2$ = production of two-bedroom living units/year; OC2% = off-site completion percentage (calculated); and Lr = labor resources/manufacturer.

The results from the data transformation are given in Table 14 and Fig. 18. This analysis suggested that the EUV manufacturers' productivity was the highest, with approximately 5.45 two-bedroom living-unit-equivalent output per labor resource per year, whereas the UKP average was approximately 70% that of EU and

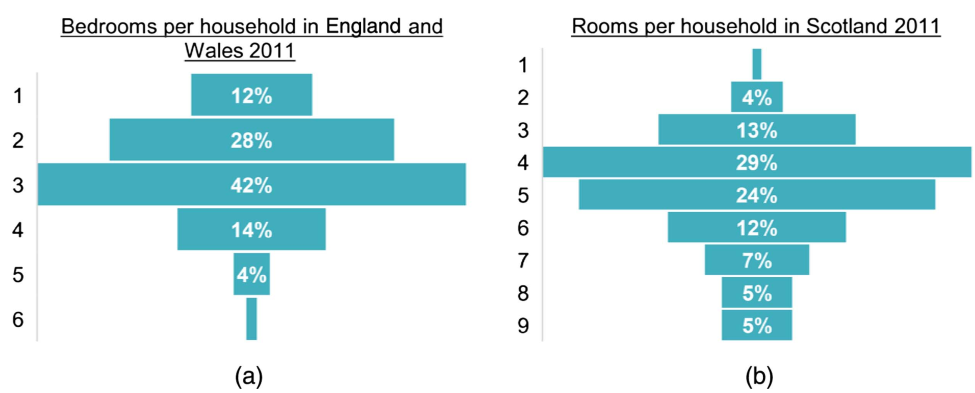


Fig. 17. Household distribution in the UK, 2011: (a) England and Wales (data from Office for National Statistics 2018); and (b) Scotland (data from National Record of Scotland 2013).

Table 13. Two-bedroom living unit dimensions schedule

Product	Length (m)	Width (m)	Height/depth (m)	Area (m^2)	Number
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

Table 14. Comparative production and productivity analysis for two-bedroom living unit equivalent

Variable	UKP1	UKP2	UKP3	UKV1	UKV2	UKV3	EUV1	EUV2	EUV3	EUV4	UKP	UKV	EUV	Average
$P2$	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
$Lp2$	2.69	1.61	7.19	1.16	0.39	1.39	7.44	6.47	6.90	0.97	3.83	0.98	5.45	4.45

the UKV was approximately 18% that of EUV. The UKV manufacturers, however, tended to have lower production output rates compared with the other surveyed manufacturers, which suggests that these organizations had lower production capacity, which in turn was limiting their opportunities for productivity growth. The values for UKP3 and EUV1 were the highest by a large degree, and this could be explained by their reporting of having full pipelines of work secured so that the factory experienced no down time.

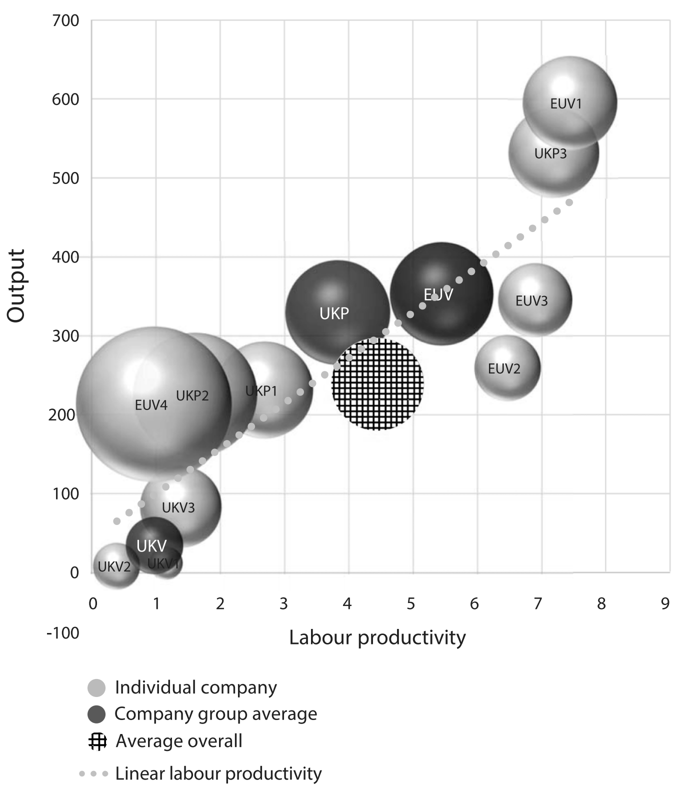


Fig. 18. Comparative productivity analysis of labor productivity (two-bedroom living-unit-equivalent output/person/year). The center of bubble indicates values for output and labor productivity, whereas the size indicates the number of people employed.

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

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. This difference can be explained by the smaller size and the smaller workforce of UKV2 compared with EUV2 and UKV3, combined with the establishment of EUV2 as a daughter company to a much larger organization. This would have made available increased resources and more extensive experience in this field.

The productivity rates should furthermore be explored through the lenses of automation, mechanization, 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 labor productivity of the panelized timber manufacturers would be higher than that of volumetric timber manufacturers, whose work included in addition highly manual labor–intensive tasks. However, the results from this sample suggest that labor efficiency in modular production can be similar to that in panelized timber production. Increased labor productivity in certain manufacturers such as EUV1 may be connected to higher output capacity due to a high number of years in trade, with associated opportunities for growth and investment in R&D.

Assumptions

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. 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. Practical considerations regarding the international regulations for 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. Because this method is intended for comparison of different management strategies and their effect on production output, as opposed to calculating and predicting actual capacity rates, the individual logistics legislation was outside the research scope. 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 m, or 13% of total 185.6 linear m). The sensitivities of this observation should be considered when drawing conclusions.

Benchmark

The main precedent for this research was the strategic review by Smith et al. (2013) which estimated the value of the off-site sector in Scotland at £125 million based on surveyed companies, with potential to grow to £230 million excluding increases in numbers of manufacturing facilities. The sector at the time produced 6,000 homes/year, but the existing facilities had the capacity to produce 16,500 homes/year. Therefore, it can be speculated that the sector was operating at approximately 37% of maximum capacity, on average. The potential to expand to £230 million included a doubling of exports to England. The number of people employed by the interviewed companies was 1,450.

Using these figures for input versus output calculations, the productivity of the sector may be expressed as the ratio of the output (either living-unit equivalent or value output) to the labor input (number of production staff employed) as per Eq. (1). Thus, the estimated labor productivity was approximately 4.13 homes (living-unit equivalents) output/person, or £86,200 output/person/year on average across the sector. With consideration of the projections for growth in output value, output units and jobs created, these values would be updated to 8.5 units/person, or £155,000 output/person/year. These values are visualized in Fig. 19, where the x-axis shows the number of living units output per person, the y-axis shows the value output per person, and the size of the bubble indicates the number of employees. However, these are secondary interpretations of the 2012 study, and further studies are required to investigate the granulation of the off-site sector's productivity and management strategies with differentiation between systems with different levels of off-site completion.

These research study results may be used as a benchmark for this research study as shown in Fig. 20, which seems to suggest that the findings are comparable to those by Smith et al. (2013) for panel timber manufacturers. However, the UK volumetric timber manufacturers' productivity was significantly lower than this. This is in line with previous observations that the UK volumetric timber manufacturing represents a small segment of the UK manufacturing capacity. Moreover, the findings demonstrate the potential for increased capacity and productivity of volumetric timber manufacturers in the United Kingdom, which will, however, require an increase in the volumetric timber market maturity.

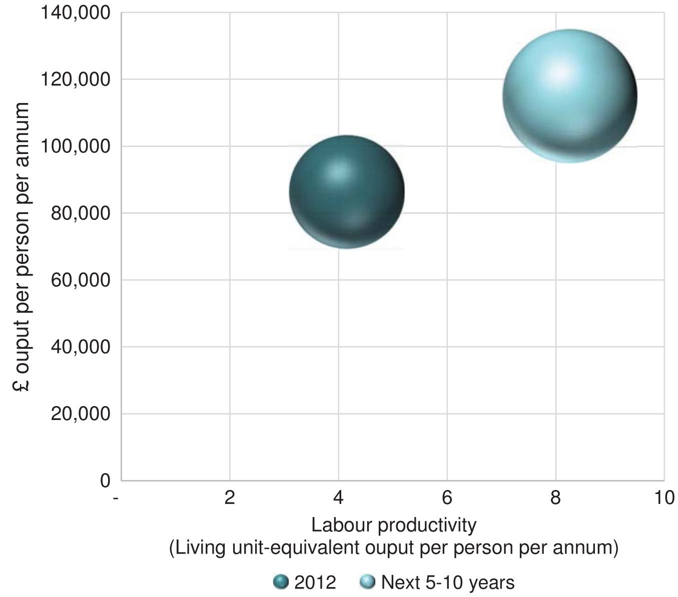


Fig. 19. Scottish off-site sector productivity. Unit: 1 home = 1 house or 1 apartment. Bubble size denotes number of employees. (Secondary data calculations based on findings from Smith et al. 2013.)

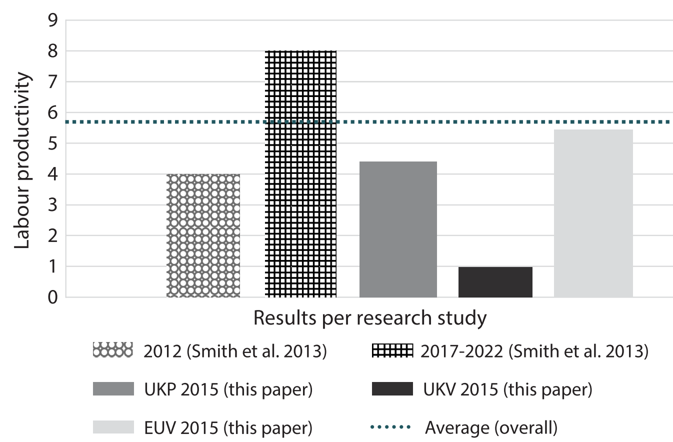


Fig. 20. Benchmark of labor productivity results (living-unit-equivalent output/person/year).

Sensitivity Analysis

Through the exploration of different methods for off-site completion percentage calculation and living-unit equivalent, this paper explored the sensitivities of the methodology. The rankings of manufacturers' productivity differed between the two methods (Table 15), which suggests that the difference between reported off-site percentage completion and calculated off-site 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 benchmarkable metrics. Because of the sensitivity of these measurements, it is suggested that UKP and EUV manufacturers have similar labor productivity rates, which leads to a gap for potential productivity growth of UKV manufacturers.

The low productivity of UKV companies may be explained by construction market issues. For example, an observation was made

Table 15. Labor productivity sensitivity analysis

Ranking	UKP1	UKP2	UKP3	UKV1	UKV2	UKV3	EUV1	EUV2	EUV3	EUV4	UKP	UKV	EUV
$Lp1$	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

that the surveyed companies with higher productivity tended to have been operating for longer and within more market types, which could be speculated to be a sign of a need for high resilience to fluctuations in the market, typical in the United Kingdom. In Scotland, for instance, in 2015 timber panel construction represented three-quarters of new built homes (NHBC Foundation 2016), which in turn represented 75% of Scottish construction. Furthermore, Smith et al. (2013) identified the distribution of off-site systems as 81% panelized systems versus 19% volumetric systems. Open timber panels represented 44% of the off-site market turnover, whereas volumetric construction with insulation, services, and finishes represented 11%, the highest among the volumetric categories. Therefore, it can be speculated that the panelized timber market had a high maturity, whereas the volumetric timber market had a low maturity and scope to grow.

With low market-maturing opportunities, it could be speculated that these companies would have less 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 demonstrated the potential to apply automation, upskilling, lean process waste reduction, and implementation of BIM processes and technologies to high standards. The opportunities for productivity improvement across the United Kingdom are important within the context of the research findings that an increase in the off-site market share from 7% to 25% would increase the gross value added by £4.3 billion across the United Kingdom (WPI Economics 2017).

Conclusion

Ten different off-site timber systems manufacturers were investigated in this qualitative survey to compare and contrast different off-site systems and project delivery and management strategies and to investigate variations in management strategies and their labor productivity (output per labor resource). The manufacturers varied in product type (panel, volumetric, stud frame, CLT, and SIP), year of establishment (between 1986 and 2013), and number of production staff (between 10 and 200). The 10 surveyed companies were from the United Kingdom and mainland Europe, and therefore captured different economic and market contexts, which have common aspects within the global context of developing economies. The methodologies for data collection and analysis were, in addition, rigorously designed with consideration of methods used in previous similar research studies, which increases the validity of the findings. The sensitivities of labor productivity calculation alternatives were explored through a pilot study and a benchmarked comparative productivity analysis. Qualitative data analysis of manufacturing lines, automation, mechanization, lean implementation, and Design for Assembly and Disassembly (DfMA+D) was used to hypothesize their potential effects on productivity, in the context of market trends.

Overall, the EUV and UKP manufacturers shared similar productivity rates of 5 two-bedroom living-unit-equivalent outputs/labor resource/year. However, EUV manufacturers' products had a higher off-site completion percentage, up to approximately 70% of materials and work, compared with approximately 25% for UKP. These results suggest that for the surveyed sample and similar manufacturers in the EU, similar productivity improvement potential exists despite the low opportunities for automation in the module assembly stages. In addition, by examining the EUV labor productivity results, it is suggested that the UKV manufacturers have high potential for growth in both market size and productivity in the United Kingdom. In addition, the craftmanship and advanced technological applications of UKV manufacturers must not be underestimated by the quantitative productivity comparison results.

Regarding market aspects, this research study demonstrated that a variety of building and market types were suitable for off-site 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 that market fluctuations are a challenge to growth, with emphasis on the residential market. Therefore, it could be theorized that operation in a higher number of market segments could potentially increase the resilience of the off-site manufacturers by providing alternative sources of work in times of residential demand decrease. This suggestion is relevant in the context of previous research findings that market fluctuations could lead to significant cash flow issues in volumetric timber construction due to the high requirement for capital investment (Lawson et al. 2014). The results suggest that off-site timber construction is suitable for a wide spectrum of residential market segments, across the affordable, middle, and high-end ranges.

European manufacturers additionally tended to construct extensions to existing buildings using volumetric timber construction. This potential to retrofit existing building fabric using off-site construction methods seems to be underused in the United Kingdom considering that £1.9 billion of UK construction output is due to the refurbishment of existing housing (Lawson et al. 2014; ONS 2016a). Moreover, the companies tailored each project to the specific brief to achieve the design intent specified by the client. These findings contradict the prevailing off-site perception in the United Kingdom regarding monotonous prefab housing estates. When this individuality of design output is considered alongside the high energy efficiency of the surveyed off-site products, it highlights the need for a change in the industry's technology and efficiency assumptions (Dalgarno 2015; Edge et al. 2002; Pan and Sidwell 2011).

Based on the results from this survey, volumetric timber construction seems to be more suitable for the 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 off-site timber manufacturers in BIM implementation, mostly through the use of digital design using 3D components with attached information linked to CAM equipment, with one example of a UK volumetric manufacturer

Table 16. Overall observations for volumetric timber application in UK economic context

N	Observation	Section reference
1	Logistics and site restrictions should be the first consideration for off-site projects, because these will determine the options for off-site systems utilization.	Size, weight, and transport
2	In projects in which 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 and workmanship of taping resulting from implementation of quality management systems (QMS).	Energy efficiency
3	Wherever possible, collaborative contracts should be utilized in which the design stage is informed by the subsequent manufacturing and construction activities with a view to optimize labor and material resources utilization. This emphasizes the need for early communication between the design, production, and construction stakeholders.	Contractual relationship and design management
4	Volumetric timber systems application should not be limited to low-rise residential construction in the United Kingdom, because there are additional opportunities for volumetric timber projects in the educational (especially nurseries), retail, office, healthcare, and retrofit markets.	Market opportunities
5	When a project may be designed as a repetition of identically sized modules (or variations of combinations with standard module sizes), the project will be more favorable to volumetric timber construction. The modules may be mass-customized with client-specific internal finishes and specifications.	Cost-efficiency and repetitive design elements

who had applied all seven BIM dimensions. Overall, there are therefore great technological opportunities in advanced off-site timber manufacturing, which could in turn result in increased productivity.

This study, moreover, highlighted a disconnection between designs received by the manufacturers and the off-site system to be used in construction, which ultimately resulted in design rework. With this in mind, the findings from this research may be summarized in the five main observations based on the reported results from this survey's sample (Table 16) which are categorized as size, weight, and transport; energy efficiency; contractual relationship; market opportunities and cost-efficiency; and repetitive design. All these conclusions are drawn within scientific limitations of the work, which could be addressed through exploration of further work.

This study looked at 10 companies in 5 European countries; however, the study could be enhanced with more representative countries, more off-site systems, and further investigation into more detailed company management strategies and business models. This could include company cost data such as cash flow and turnover to hypothesize which business approaches could enhance off-site timber productivity. Lastly, the combination of off-site and on-site process productivity will be investigated using construction case studies in the authors' further work to enable a more comprehensive comparative productivity analysis of off-site timber systems.

Data Availability Statement

Data generated or analyzed during the study are available from the corresponding author by request. Information about the Journal's data-sharing policy can be found here: http://ascelibrary.org/doi/10.1061/(ASCE)CO.1943-7862.0001263.

Acknowledgments

This research was funded through an Engineering the Future Ph.D. studentship generously provided by the University of Strathclyde to Tsvetomila Duncheva for the degree of Ph.D. Architecture. The authors also acknowledge the Ph.D. supervision provided by the University of Glasgow. The authors thank Edinburgh Napier University's Built Environment Exchange (beX) program for providing Tsvetomila Duncheva with industry-based off-site timber research experience, during which the ideas of this paper were contextualized. The authors express sincere gratitude to the anonymous survey participants who shared their time and knowledge and without whom this research paper would have been impossible.

Supplemental Data

Appendixes S1 and S2 are available online in the ASCE Library (www.ascelibrary.org).

References

Azman, M., M. Ahmad, T. Majid, and M. Hanafi. 2010. "The common approach in off-site construction industry." *Aust. J. Basic Appl. Sci.* 4 (9): 4478–4482.

Babič, N. C., P. Podbreznik, and D. Rebolj. 2010. "Integrating resource production and construction using BIM." *Autom. Constr.* 19 (5): 539–543. https://doi.org/10.1016/j.autcon.2009.11.005.

Bayliss, R. n.d. "Case study 13: HMP Dovegate expansion, Skanska." Accessed June 23, 2018. http://ciria.org/buildoffsite/pdf/Case%20studies/casestudy_HMPDovegate.pdf.

Bazeley, P. 2013. *Qualitative data analysis practical strategies*. London: SAGE.

BIWG (BIM Industry Working Group). 2011. *Strategy paper for the Government Construction Client Group from the BIM Industry Working Group*. London: Dept. of Business, Innovation and Skills.

Bjertnæs, M. A., and K. A. Malo. 2014. "Wind-induced motions of 'Treet'—A 14-storey timber residential building in Norway." In *Proc., World Conf. on Timber Engineering*. Red Hook, NY: Curran Associates, Inc.

Bogue, R. 2007. "Design for disassembly: A critical twenty-first century discipline." *Assembly Autom.* 27 (4): 285–289. https://doi.org/10.1108/01445150710827069.

Booth, R. 2015. "UK housing crisis 'in breach of human rights'." *The Guardian*, April 28, 2015.

Boothroyd, G. 1994. "Product design for manufacture and assembly." *Comput. -Aided Des.* 26 (7): 505–520. https://doi.org/10.1016/0010-4485(94)90082-5.

Brennan, J., and C. Vokes. 2017. "Faster, smarter, more efficient: Building skills for offsite construction." Construction Industry Training Board. Accessed February 2, 2018. https://www.citb.co.uk/documents/research/offsite_construction/offsite_construction_full_report_20170410.pdf.

Buntrock, D. 2017. "Prefabricated housing in Japan." In *Offsite architecture. Constructing the future*, edited by R. E. Smith and J. Quale, 190. New York: Routledge.

Chevin, D. 2018. *Housing: Is offsite really the sector's panacea?* Bracknell, UK: CIOB Construction Manager.

CITB (Construction Industry Training Board). 2015. *The construction skills network programme, 2015–2016*. Final Rep. Bid Package 5. Norfolk, UK: CITB.

Construction Task Force. 1998. *Rethinking construction*. London: Construction Products Association.

Corfe, C. 2013. *Implementing Lean in construction: Lean and sustainability Agenda*. London: CIRIA.

Court, P. F., C. L. Pasquire, G. F. Gibb, and D. Bower. 2009. "Modular assembly with postponement to improve health, safety, and productivity in construction." *Pract. Period. Struct. Des. Constr.* 14 (2): 81–89. https://doi.org/10.1061/(ASCE)1084-0680(2009)14:2(81).

Creswell, J. W., and V. L. P. Clark. 2007. *Designing and conducting mixed methods research*. Thousand Oaks, CA: SAGE.

Crowther, P. 1999. "Design for disassembly to recover embodied energy." In *Proc., 16th Int. Conf. on Passive and Low Energy Architecture*, 6. Hong Kong: PLEA.

Dainty, A. R. J., and R. J. Brooke. 2004. "Towards improved construction waste minimisation: A need for improved supply chain integration?" *Struct. Surv.* 22 (1): 20–29. https://doi.org/10.1108/02630800410533285.

Dalgarno, S. 2015. "Internationalisation & Opportunities for innovation: A recent learning journey to Japan." In *Offsite Scotland: A strategy for up-skilling, culture change and internationalisation*, edited by Construction Scotland Innovation Centre. Glasgow, Scotland: Architecture and Design Scotland.

Dean, S. 2010. *Using local timber—Contributing to sustainable construction guidance for North Scotland*. Aberdeen, Scotland: North Scotland Partnership.

De Vaus, D. 2005. *Surveys in social research*. Abington, UK: Routledge.

Dodoo, A., L. Gustavsson, and R. Sathre. 2014. "Lifecycle carbon implications of conventional and low-energy multi-storey timber building systems." *Energy Build. Elsevier B.V.* 82: 194–210. https://doi.org/10.1016/j.enbuild.2014.06.034.

Eastman, C. M., and R. Sacks. 2008. "Relative productivity in the AEC industries in the United States for on-site and off-site activities." *J. Constr. Eng. Manage.* 134 (7): 517–526. https://doi.org/10.1061/(ASCE)0733-9364(2008)134:7(517).

Edge, M., T. Craig, R. Laing, L. Townsedn, and A. Hargreaves. 2002. *Overcoming client and market resistance to prefabrication and standardisation in housing*. Aberdeen, Scotland: Robert Gordon Univ.

Farmer, M. 2016. *The Farmer review of the UK construction labour model*. London: Construction Leadership Council.

Fern, C. C. 2014. *Developing a framework for prefabrication assessment using BIM*. Espoo, Finland: Aalto Univ.

Forestry Commission. 2014. "2014 forestry statistics." *Chapter 1 Woodland*. Edinburgh, UK: Forestry Commission.

Fried, H. O., C. A. K. Lovell, and S. S. Schmidt. eds. 1993. *The measurement of productive efficiency: Techniques and applications*. Oxford: Oxford University Press.

Gambin, L., T. Hogarth, G. Atfield, Y. Li, and D. Owen. 2012. *Sector skills insight: Construction sector skills insights*. London: UK Commission for Employment and Skills.

Gibb, A., and M. Pendlebury. 2013. *Glossary of terms 2013*. London: Buildoffsite.

Gibb, A. G. F. 1999. *Off-site fabrication: Prefabrication, pre-assembly and modularisation*. Caithness, Scotland: Whittles.

Gibb, A. G. F., and F. Isack. 2010. "Re-engineering through pre-assembly: Client expectations and drivers." *Build. Res. Inf.* 31 (2): 146–160. https://doi.org/10.1080/09613210302000.

Goodier, C. I., and A. G. F. Gibb. 2005. "Barriers and opportunities for offsite in the UK." In *Proc., Systematic Innovation in the Management of Project and Processes, Helsinki Int. Joint Symp.*, 148–158. Helsinki, Finland: Technical Research Centre of Finland/Association of Finnish Civil Engineers.

Goulding, J., and M. Arif. 2013. *Research roadmap report: Offsite production and manufacturing*. Rotterdam, Netherlands: CIB General Secretariat.

Goulding, J., F. P. Rahimian, M. Arif, and M. Sharp. 2012. "Offsite construction: Strategic priorities for shaping the future research agenda." *Architectonica* 1 (1): 62–73. https://doi.org/10.5618/arch.2012.v1.n1.7.

Goulding, J. S., F. P. Rahimian, M. Arif, and M. D. Sharp. 2014. "New offsite production and business models in construction: Priorities for the future research agenda." *Archit. Eng. Des. Manage.* 11 (3): 163–184. https://doi.org/10.1080/17452007.2014.891501.

Hager, H. 2014. "New York City: A tale of two modular construction projects." In *Modular construction prefabrication & logistics summit.* Houston: Modular Construction.

Hairstans, R. 2010. *Off-site and modern methods of timber construction. A sustainable approach*. High Wycombe, UK: TRADA.

Hairstans, R. 2011. "Timber frame: Modern and truly sustainable." *Timber industry yearbook 2011*, 35–37. High Wycombe, UK: TRADA.

Hairstans, R. 2015. *Building offsite. An introduction*. Edinburgh, Scotland: Arcamedia.

Hairstans, R. 2018. *Mass timber—An introduction to solid timber laminate systems*. Edinburgh, Scotland: Arcamedia.

Hairstans, R., and R. E. Smith. 2017. "Offsite HUB (Scotland): Establishing a collaborative regional framework for knowledge exchange in the UK." *Archit. Eng. Des. Manage.* 14 (1–2): 60–77. https://doi.org/10.1080/17452007.2017.1314858.

Hesse-Biber, S. N. 2010. *Mixed methods research*. New York: Guilford.

Homes for Scotland. 2015. *Mainstreaming offsite modern methods of construction (MMC) in house building*. Edinburgh, Scotland: Homes for Scotland.

Isaac, S., and R. Navon. 2014. "Can project monitoring and control be fully automated?" *Constr. Manage. Econ.* 32 (6): 495–505. https://doi.org/10.1080/01446193.2013.795653.

Jaillon, L., and C. S. Poon. 2014. "Life cycle design and prefabrication in buildings: A review and case studies in Hong Kong." *Autom. Constr.* 39 (1): 195–202. https://doi.org/10.1016/j.wasman.2008.02.015.

Johnsson, H., and J. H. Meiling. 2009. "Defects in offsite construction: Timber module prefabrication." *Constr. Manage. Econ.* 27 (7): 667–681. https://doi.org/10.1080/01446190903002797.

Jonsson, H., and M. Rudberg. 2014. "Classification of production systems for industrialized building: A production strategy perspective." *Constr. Manage. Econ.* 32 (1–2): 53–69. https://doi.org/10.1080/01446193.2013.812226.

Kamali, M., and K. Hewage. 2016. "Life cycle performance of modular buildings: A critical review." *Renewable Sustainable Energy Rev.* 62: 1171–1183. https://doi.org/10.1016/j.rser.2016.05.031.

Kamar, A. M., Z. A. Hamid, and N. A. Azman. 2011. "Industrialized building system (IBS): Revisiting issues of definition and classification." *Int. J. Emerging Sci.* 1 (2): 120. https://doi.org/10.1016/j.shaw.2017.05.004.

Kenley, R. 2014. "Productivity improvement in the construction process." *Constr. Manage. Econ.* 32 (6): 489–494. https://doi.org/10.1080/01446193.2014.930500.

Koszerek, D., K. Havik, K. M. Morrow, W. Roger, and F. Schonborn. 2007. *An overview of the EU KLEMS growth and productivity accounts*, 290. Brussels, Belgium: European Economy.

Krug, D., and J. Miles. 2013. *Offsite construction: Sustainability characteristics*, London: Buildoffsite.

Kuzel, A. J. 1992. "Sampling in qualitative enquiry." In *Doing qualitative research*, edited by B. F. Crabtree and W. I. Miller. Newbury Park, CA: SAGE.

Lawson, M., R. Ogden, and C. Goodier. 2014. *Design in modular construction*. London: CRC Press.

Lehmann, S. 2013. "Low carbon construction systems using prefabricated engineered solid wood panels for urban infill to significantly reduce greenhouse gas emissions." *Sustainable Cities Soc.* 6 (1): 57–67. https://doi.org/10.1016/j.scs.2012.08.004.

Li, Z., G. Q. Shen, and M. Alshawi. 2014. "Measuring the impact of prefabrication on construction waste reduction: An empirical study in China." *Resour. Conserv. Recycling* 91: 27–39. https://doi.org/10.1016/j.resconrec.2014.07.013.

Ma, G., L. Gu, and N. Li. 2015. "Defining and categorizing modules in building projects: An international perspective." *J. Constr. Eng. Manage.* 141 (10): 04015030. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001003.

Mankiw, N. G., and M. P. Taylor. 2010. *Economics*. London: Cengage Learning.

Mason, J. 1996. *Qualitative research*. London: SAGE.

Meiling, J., F. Backlund, and H. Johnsson. 2015. "Managing for continuous improvement in off-site construction: Evaluation of lean management principles." *Eng. Constr. Archit. Manage.* 23 (2): 237–260. https://doi.org/10.1080/01446190903002797.

Miles, J., and N. Whitehouse. 2013. *Offsite housing review*. London: Construction Industry Council.

Miller, F. 2015. "A third of headteachers say school buildings not fit for purpose." *The Guardian*, January 27, 2015.

MMC Wales. 2008. *Achieving modern methods of construction in Wales*. Cardiff, Wales: MMC Wales.

Modularize. 2015. "Modular manufacturers." Accessed June 23, 2018. http://www.modularize.co.uk/.

Monahan, J., and J. C. Powell. 2011. "An embodied carbon and energy analysis of modern methods of construction in housing: A case study using a lifecycle assessment framework." *Energy Build.* 43 (1): 179–188. https://doi.org/10.1016/j.enbuild.2010.09.005.

Mtech Group, and A. Gibb. 2007. *Offsite construction industry survey 2006*. London: Buildoffsite.

Mullens, M. A. 2011. *Factory design for modular homebuilding*. Winter Park, FL: Constructability.

Nadim, W., and J. S. Goulding. 2011. "Offsite production: A model for building down barriers: A European construction industry perspective." *Eng. Constr. Archit. Manage.* 18 (1): 82–101. https://doi.org/10.1108/09699981111098702.

NAO (National Audit Office). 2005. *Using modern methods of construction to build homes more quickly and efficiently*. London: NAO.

Nasir, H., H. Ahmed, C. Haas, and P. M. Goodrum. 2013. "An analysis of construction productivity differences between Canada and the United States." *Constr. Manage. Econ.* 6193 (6): 1–13. https://doi.org/10.1080/01446193.2013.848995.

National Record of Scotland. 2013. "Table QS407SC—Number of rooms. All occupied household spaces." In *Scotland's census 2011—National records of Scotland*. Edinburgh: Scotland's Census.

NHBC Foundation. 2016. *Modern methods of construction. Views from the industry*. Milton Keynes, UK: Buildoffsite.

Office for National Statistics. 2018. "CT0770_2011 Census—Number of rooms by number of bedrooms—Merged local authorities." Accessed June 23, 2018. http://www.scotlandscensus.gov.uk/ods-analyser/jsf/tableView/tableView.xhtml.

Oliveira, S., J. Burch, K. Hutchison, O. Adekola, S. Jaradat, and M. Jones, and Centre. 2017. *Making modular stack up: Modern methods of construction in social housing*. Bristol, UK: Univ. of the West of England.

O'Mahony, M., and M. P. Timmer. 2009. "Output, input and productivity measures at the industry level: The EU KLEMS database." *Econ. J.* 119 (538): F374–F403. https://doi.org/10.1111/j.1468-0297.2009.02280.x.

ONS (Office for National Statistics). 2007. *ONS productivity handbook*. Hampshire, UK: Palgrave Macmillan.

ONS (Office for National Statistics). 2016a. "Construction output in Great Britain: August 2016." http://www.ons.gov.uk/businessindustryandtrade/constructionindustry/bulletins/constructionoutputingreatbritain/may2016.

ONS (Office for National Statistics). 2016b. "Output in the construction industry: all work summary." Accessed November 8, 2016. http://www.ons.gov.uk/businessindustryandtrade/constructionindustry/datasets/outputintheconstructionindustryallworksummary.

Pan, W., A. G. F. Gibb, and A. B. Sellars. 2008. "Maintenance cost implications of utilizing bathroom modules manufactured offsite." *Constr. Manage. Econ.* 26 (10): 1067–1077. https://doi.org/10.1080/01446190802422161.

Pan, W., and R. Sidwell. 2011. "Demystifying the cost barriers to offsite construction in the UK." *Constr. Manage. Econ.* 29 (11): 1081–1099. https://doi.org/10.1080/01446193.2011.637938.

Polat, G., D. Arditi, G. Ballard, and U. Mungen. 2007. "Economics of on-site vs. off-site fabrication of rebar." *Constr. Manage. Econ.* 24 (11): 1185–1198. https://doi.org/10.1080/01446190500529432.

Quale, J., M. J. Eckelman, K. W. Williams, G. Sloditskie, and J. B. Zimmerman. 2012. "Construction matters: Comparing environmental impacts of building modular and conventional homes in the United States." *J. Ind. Ecol.* 16 (2): 243–253. https://doi.org/10.1111/j.1530-9290.2011.00424.x.

Reason, P. 1994. "Three approaches to participatory inquiry." In *Handbook of qualitative research*, edited by N. K. Denzin and Y. S. Lincoln, 112–126. Thousand Oaks, CA: SAGE.

Rupnik, I. 2017. "Mapping the modular industry." In *Offsite architecture. Constructing the future*, edited by R. E. Smith and J. D. Quale, 55–76. New York: Routledge.

Sanchez, A. X., K. D. Hampson, and S. Vaux. 2016. "Enablers dictionary." In *Delivering value with BIM. A whole-life approach*, 205–297. Abingdon, UK: Routledge.

Shahzad, W., J. Mbachu, and N. Domingo. 2015. "Marginal productivity gained through prefabrication: Case studies of building projects in Auckland." *Buildings* 5 (1): 196–208. https://doi.org/10.3390/buildings5010196.

Sinclair, D. 2013. "RIBA plan of Work 2013 and BIM." In *BIM task group newsletter*. 22nd ed., 23–29, London: BIM Task Group.

Sinclair, D., B., Wood, and S., McCarthy 2013. *RIBA plan of work 2013 designing for manufacture and assembly*. London: RIBA.

SINTEF (Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology). 2013. "Technical approvals." Accessed June 23, 2018. https://www.sintefcertification.no/Contents.

Smith, R. E. 2011. *Prefab architecture*. New York: Wiley.

Smith, R. E. 2016. "Off-site and modular construction explained." Accessed June 17, 2018. https://www.wbdg.org/resources/site-and-modular-construction-explained.

Smith, S., R. Hairstans, R. Macdonald, and F. Sanna. 2013. *Strategic review of the offsite construction sector in Scotland*. Edinburgh, Scotland: Institute for Sustainable Construction.

Succar, B. 2009. "Building information modelling framework: A research and delivery foundation for industry stakeholders." *Autom. Constr.* 18 (3): 357–375. https://doi.org/10.1016/j.autcon.2008.10.003.

Taylor, M. D. 2010. "A definition and valuation of the UK offsite construction sector." *Constr. Manage. Econ.* 28 (8): 885–896. https://doi.org/10.1080/01446193.2010.480976.

Taylor, S. J., R. Bogdan, and M. L. Devault. 2016. *Qualitative research methods*. Hoboken, NJ: Wiley.

Thormark, C. 2001. *Recycling potential and design for disassembly in buildings*, 104. Lund, Sweden: Lund Institute of Technology.

Tulenheimo, R. 2015. "Challenges of implementing new technologies in the world of BIM—Case study from construction engineering industry in Finland." *Proc. Econ. Finance* 21: 469–477. https://doi.org/10.1016/S2212-5671(15)00201-4.

UKCES (UK Commission for Employment and Skills). 2013. *Technology and skills in the construction industry*. London: HM Government.

UK Government. 2017. *Made smarter review*. London: UK Government, Dept. for Business, Energy and Industrial Strategy.

Van der Vlist, A. J., M. H. Vrolijk, and G. P. M. R. Dewulf. 2014. "On information and communication technology and production cost in construction industry: Evidence from the Netherlands." *Constr. Manage. Econ.* 32 (6): 641–651. https://doi.org/10.1080/01446193.2014.911932.

Venables, T., and R. Courtney. 2004. *Modern methods of construction in Germany—Playing the off-site rule*. Global Watch Mission Reports dti. London: UK Government, Dept. of Trade and Industry.

Vernikos, V. K., C. Goodier, and A. G. F. Gibb. 2013. "Building information modelling and offsite construction in Civil Engineering." In Vol. 167 of *Proc., ARCOM Doctoral Workshop on BIM Management and Interoperability*, 1–10. London: Association of Researchers in Construction Management.

Vilasini, N., T. Neitzert, and J. Rotimi. 2014. "Developing and evaluating a framework for process improvement in an alliance project: A New Zealand case study." *Constr. Manage. Econ.* 32 (6): 625–640. https://doi.org/10.1080/01446193.2013.874565.

Womack, J., and D. Jones. 2003. *Lean thinking*. London: Simon and Schuster.

J. Constr. Eng. Manage., 2019, 145(8): 04019043

WPI Economics. 2017. *The value of off-site construction to UK productivity and growth*. Stanmore: WPI Economics.

WRAP (Waste and Resources Action Programme). 2009. *Designing out waste: A design team guide for buildings*. Banbury, UK: WRAP.

WRAP (Waste and Resources Action Programme). 2014a. *Achieving good practice waste minimisation and management*. Banbury, UK: Practical Solutions for Sustainable Construction.

WRAP (Waste and Resources Action Programme). 2014b. *Setting a requirement for waste minimisation and management*. Banbury, UK: Procurement Guidance for Construction.

Yu, H., M. Al-Hussein, S. Al-Jibouri, and A. Telyas. 2013. "Lean transformation in a modular building company: A case for implementation." *J. Manage. Eng.* 29 (1): 103–111. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000115.