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

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Abstract

Offsite 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, projects delivery and management strategies of offsite construction have been studied in this research through a multi-faceted qualitative exploration of offsite timber management strategies across ten manufacturers, including three UK panel, three UK volumetric and four European (EU) volumetric timber manufacturers. A comparative productivity analysis was carried out in this research project and its sensitivities were analysed which led to the conclusion that the labour productivity of the surveyed UK panelised and EU volumetric manufacturers were comparable, but the UK volumetric manufacturers' productivity was lower. As a result, the level of automation and the lean and Design for Disassembly (DfD)

applications of the manufacturers were all explored to understand these productivity differences within the context of current market trends.

Introduction

Modern Methods of Construction (MMC) and offsite construction have been ‘hot topics’ in industry in recent years because of the need to optimise the resource efficiency of the construction industry (Chevin 2018; Hairstans and Smith 2017). This is due to the fact that 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)

Offsite construction is defined as 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 offsite 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 offsite brings opportunities for construction productivity improvement (UK Government 2017; WPI Economics 2017). However, a historic stigma relating to offsite construction in the UK 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 offsite construction in the context of increasing economic pressures in the UK.

This research study focusses on timber systems and investigated two offsite structural timber systems, namely two-dimensional (2D) panels and three-dimensional (3D) volumetric as shown in **Fig. 1**. Timber was selected because it is a renewable material, sequesters carbon and is an under-utilised 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 UK; whilst 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 timber manufacturers were interviewed from the UK and four from mainland Europe to explore their offsite timber systems, project delivery and management strategies.

Literature review

Economic context

Offsite as part of the solution to pressing economic challenges

Research publications have suggested that offsite construction is the only viable method to alleviate what has been referred to as the 'housing crisis' in the UK (Booth 2015; Miles and Whitehouse 2013). To mitigate the housing shortage, the offsite construction industry would need to have the capability 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 maximum capacity to deliver only approximately 140,000 out of the required 240,000 homes per year in England alone. In addition:

> *'there is evidence to suggest that the use of offsite 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 entitled 'Modernise or die' highlighted that there is a need for immediate technological revolution in the construction industry to mitigate the stagnation in the construction industry labour productivity (Farmer 2016). Labour productivity may be defined by 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 labour productivity calculation **Equation 1** below**:**

Equation 1

$$Labour\ Productivity = \frac{Output\ (number\ of\ homes\ or\ monetary\ output)}{Labour\text{-}units}$$

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 optimisation (Bimforum et al. 2016). Indeed, Recommendation 8 of the Farmer Review 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 offsite 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, labour resources and strategies for resource optimisation.

The effect of offsite construction on output capacity and productivity

In 2006,the total value of the UK offsite construction market was evaluated at approximately £6bn out of £131 bn construction industry output in 2006 (Mtech Group and Gibb 2007; ONS 2016a). A subsequent study from 2008 estimated the gross output value of the offsite sector to be £5.7 bn, which was approximately 7% of the UK construction industry output (Taylor 2010). Within this estimate the output of open timber panels was £528 m, whilst closed panels had an output of only £20 m and Structurally Insulated Panels (SIPs) only £3 m. Taylor presented data for two types of volumetric systems, permanent and temporary, without distinguishing between different structural materials. Therefore, it is not clear how many percent of the £329 m were volumetric timber systems. Overall, there appears to be a consensus among the literature that the valuation of the offsite 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 literature with varying growth projections (Gambin et al. 2012; UKCES 2013).

If there was a higher uptake of offsite construction in the UK, it is expected that this could have a positive effect on the stagnation of construction productivity. Indeed, Eastman and Sacks (2008) proved that within the USA context, the value added per employee of offsite manufacturing was 43% higher compared to onsite construction, whereas the growth of offsite construction was approximately 0.9% more than 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% to 25%, and their findings were that an additional £4.3 bn GVA would be added across the UK. (WPI Economics 2017).

Offsite systems categorisation

Offsite timber systems may be categorised as sub-assemblies, panelised, pods and volumetric solutions, however the literature on offsite 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', 'Non-volumetric preassembly', 'Volumetric preassembly' and 'Complete buildings', the *Building Offsite An Introduction* differentiates between 4 sub-categories of 2D elements with applications for walls, floors and roofs, and 3D modules (Gibb and Pendlebury 2013; Hairstans 2015). An additional complexity on the consistency of semantics is placed by geographic preferences for key terminology, such as 'Industrialised Building System (IBS)', 'modular' and 'prefabrication' (Ma et al. 2015). Indeed, further differences in offsite systems classifications are shown in **Fig. 2** (Gibb and Isack 2003; Hairstans 2015; MMC Wales 2008; Oliveira et al. 2017; Smith 2011).

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

Volumetric timber systems characterisation

The main drivers for offsite timber construction uptake in the UK 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 offsite timber construction characteristics but with increased values due to the higher offsite completion level (up to 95% cited in literature) (Smith 2016). The volumetric timber attributes which make the systems instrumental in mitigating the abovementioned industry challenges, are summarised 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 labour 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 resources, the greater their quality of life (Mankiw and Taylor 2010). In statistical data sets, productivity output is mostly measured in either 'total output', Gross Value Added (GVA) or Gross Domestic Product (GDP); input units can be either materials or labour (ONS 2007). National productivity is most prevalently measured in GDP per person, a type of labour 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 multi-factor productivity measurements, where only the output growth due to increased efficiencies is measured. The two dominant types of multi-factory productivity measures are labour-capital value added, where increase in GVA is mapped to increases in labour and capital; and KLEMS total output productivity (capital, labour, energy, materials, business services) (O'Mahony and Timmer 2009). More detailed multi-factor 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 onsite (Kenley 2014). Four levels of construction productivity measurement have been theorised and are summarised in **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 labour unit and number of people required on site (Hager 2014; Kamali and Hewage 2016; Yu et al. 2013). With volumetric building, the onsite labour can be reduced by approximately two-thirds compared to traditional construction method (Lawson et al. 2014; NAO 2005). Moreover, according to the cited studies, the building could be made water-tight and wind-tight in a fifth of the time compared to traditional methods, whereas panelised systems would require half the time compared to 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 onsite processes. Lawson and colleagues estimated that this could result in approximately 10% cost reductions in volumetric unit production processes benchmarked against traditional construction. In the context of the USA it has been estimated that approximately 250 labour-hours were required to produce one module with an area of approximately 55 m^2, equivalent to 5 labour-hours per unit area (Mullens 2011).

Management strategies

Different offsite 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 offsite 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 towards offsite 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 offsite construction. Other researchers have investigated the actual and apparent cost challenges to the industry in the UK (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 offsite manufacturers should have a higher priority than manufacturing strategies (Goulding et al. 2012, 2014).

Automation

Volumetric manufacturing systems which utilise automation through combination of Computer Aided Design (CAD), Computer Aided Manufacturing (CAM) can benefit from standardised product quality and reduction of rework as a result from human error (Gibb 1999). Although manufacturing tend to be unique to each company, there are three key components to volumetric assembly lines: framing stations, working tables and turning tables (Lawson et al. 2014). Volumetric timber manufacturing strategies can be categorised as:

1) manual, where traditional building methods are transferred to an enclosure,
2) those with some CAM applications (e.g. nailing bridge and/or optimising saw)
3) and the technologically extreme, where automated digital manufacturing techniques and resource efficiencies are transplanted from the automotive industry to the offsite 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 UK more moderate automation of offsite systems is observed (Buntrock 2017; Dalgarno 2015; Hairstans 2015). Automation may furthermore be linked to increased opportunities for digitisation 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 offsite manufacturing. Lean process improvements aim to reduce 'muda' (Japanese for 'waste' (Womack and Jones 2003)) within manufacturing, management and supply chain process, and these include eight key 'muda' types: 'transportation, inventory, motion, waiting, over-production, over-processing, defects and skills misuse' (Corfe 2013). A research study by Meiling et al. (2015) which surveyed two volumetric timber manufacturers in Sweden indicated that all surveyed staff felt that they were active participants the newly implemented Lean 5S strategy and therefore suggested that continuous process improvements could be planned in the long-term (Meiling et al. 2015). However, the research discovered differences in the perceptions of management and production staff regarding the production processes, which suggested clarification and communication is needed between management and production personnel. Moreover, a case study of a Canadian volumetric manufacturer revealed that companies who originated as on-site traditional contractors and subsequently transferred to or branched out to offsite manufacturing, tended to implement onsite management strategies in the factory environment (Yu et al. 2013). Therefore, there was additional potential to improve factory processes using the Lean 5S system. Indeed, results from a half year pilot implementation project demonstrated an increase in production and productivity with simultaneous reduction in labour-hours.

DfMA and DfD

Design for Manufacture and Assembly (DfMA) is further recent strategy for materials and labour optimisation, and its principles are generally applied by offsite manufacturers in the UK (Hairstans 2015). In accordance with DfMA, products are designed for optimum cost efficiency in the manufacture and assembly processes and the optimisation can include reduction in part numbers, use of standard parts or reduction of time required to assemble the product (Boothroyd 1994). A shortcoming of DfMA is that it does not include considerations for the product's full life-cycle stages, such as adaptation, maintenance and disposal. However, Design for Disassembly (DfD) principles can be used in conjunction with DfMA to create products adaptable to function change, upgrade and optimum re-use of their components at the end of the products' life-cycle. DfD in combination with DfMA can therefore be used to implement circular economy principles in the construction industry. A circular economy is a concept in which products and materials are re-used, repaired or recycled before disposal, therefore reducing waste and improving resource-efficiency (Sinclair et al. 2013). DfD is a familiar technique in the automotive industry, which is often used as a comparator to offsite construction. (Bogue 2007), There still however seems to be a gap in DfD application in the technical design of buildings, as 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 offsite timber systems.

The gap in knowledge

In summary, the above research studies discussed either generalised industry-wide trends or management strategies of one to two offsite companies. Moreover, in current literature offsite systems tend to be grouped together which does not reflect the incremental levels of offsite completion for the different offsite systems namely: sub-assemblies, panelised, pods and volumetric. Therefore, this research study builds upon previous work by analysing different product, process and management strategies amongst panelised and volumetric timber manufacturers. The results are discussed in the context of the pressing labour productivity challenges, with consideration of the different levels of offsite completion between systems and generalised DfMA strategies which may improve resource efficiency.

Methodology

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

A multi-faceted in-depth qualitative survey method was therefore applied in this research study to explore the products and processes of volumetric (and panelised) timber manufacturers using semi-structured interviews (Reason 1994). This study explored different approaches to the management of offsite timber systems in the UK, as well as in Central and Northern Europe. The discussion topics for the interviews contained 36 questions overall, grouped in six general topics: 1) Manufacturing line stages, 2) Building elements, 3) Modules / Panels, 4) Process, 5) Projects and 6) Volumetric timber. The context given was the next 5 years and a complete list may be found in **Appendix A**. In addition, non-scheduled exploratory questions were asked where the company had a specific area of expertise (Reason 1994). The length of the interviews was between 3 and 8 hours and the interviews with 8-hour durations took place over two days. Some interviews were preceded by a presentation by the company representative on their strategy and projects and some were followed by building visits. All interviews included a factory tour, where the manufacturing process was discussed step-by-step and most interviews ended with site visits of 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 offsite timber panel manufacturers were selected in the UK, three offsite volumetric timber manufacturers were further selected in the UK and four volumetric timber manufacturers were selected in central and northern Europe. This sampling strategy was informed by previous research findings that timber panels were mainstream methods of construction in the UK, whereas the volumetric timber market was more mature in mainland Europe than in the UK (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 had manufactured the modules for (at the time) the tallest timber building in the world, whereas others participated in the production of the Ikea-based BoKlok system (Bjertnæs and Malo 2014; Fern 2014). As a starting point, available literature on volumetric timber and panelised timber manufacturers was collected and synthesised (Modularize 2015). From the created database, twelve offsite timber manufacturers were contacted across the UK and mainland Europe via e-mail and follow-up telephone conversations to arrange face-to-face interviews. Ten of these manufacturers were finally sampled for this research study based on data availability, for more details please refer to the *Limitations* sub-section. The 15 interviewees were representative of a variety of occupations, including architects, production managers and directors as shown in **Fig. 3**.

The ten manufacturers varied between family-run and international businesses, recently and long-established companies and those with either a single or several manufacturing facilities; and represented five 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 high variety of business models and stakeholders from offsite 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 emphasise important points. The EU participants did not consent to interview recordings and therefore hand-written notes were the data sources, where to ensure accuracy the notes were written during and within 24 hours of the interviews with factory tours. Photographs were taken with permission using a DSLR camera with time and date metadata for each photograph. Overall 15 interviews were transcribed and more than 2,300 photographs were taken to supplement the interview data.

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 (Bazeley 2013). Indeed, this approach was trialled with the manufacturers, for each of whom a report was produced with section titles responding to the interview questions and inserted selected images from the factory tours with captions and dates. This allowed for 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, where each of the survey question responses was transformed into ultimately 230 rows of data organised in six main themes to create a data-base for the survey (Hesse-Biber 2010). This allowed for identification of patterns in survey responses and categorisation of reported opportunities and challenges according to five main themes: production, market, design, BIM and carbon. The production outputs were unfortunately reported using different units and their transformation to a normalised comparative unit of measurement was therefore only possible through quantitative secondary manipulations of the data (further details of the measurement units transformation may be found on 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 has been developed based on previous research studies in industrialised construction (Hairstans and Smith 2017; Nadim and Goulding 2011; Succar 2009). For example, Hairstans and Smith applied a method of semi-structured interviews and thematic analysis with a feedback loop to triangulate the data. Whereas Nadim and Goulding interviewed 54 stakeholders from four countries (Germany, The Netherlands, Sweden and the UK) using open-ended questions with emphasis on the variety of responses as opposed to instances of responses in an exploratory research study.

Limitations

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

It is important to state that 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 offsite timber construction.

Assumptions made in the units transformation of this survey are clearly stated in the *Analysis and discussion* section and every care has been 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 from this research study will be of relevance to architects, engineers, housing associations, local authorities and developers to name a few, the analysis of their role in offsite timber projects was outside the scope of this study. However, further information on the perceptions of built environment designers and comparative analysis of offsite construction projects may be found 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, etc. were excluded from the scope of the research.

Results

Offsite System Results

Product type

Three UK companies manufactured open or closed panel systems. The open panel systems prefabricate the frame with either an Oriented Strand Board (OSB) or Plasterboard (gypsum) board on one side and the closed panel systems further included insulation, board on both sides and service cavity battens with thicknesses varying between 90 and 240mm. 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 as panels and the other spaces were provided as modules. The most common construction method was the traditional timber stud frame at 600mm centres, examples of which are shown in **Fig. 4**.

All manufacturers included a timber stud frame in their products, even if it was limited to the internal serviced 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 factory 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 per company are compared in **Table 3**.

Size, weight and transport

In general, the surveyed offsite timber systems had similar dimensions, as shown in **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 2.9m (UKP3) and 3.8 (EUV3 and EUV4). Where small differences existed between module manufacturers, in special cases a manufacturer was selected amongst their competition because of the higher length, width or height possibilities of their system. For example, the EUV3 modules had the largest width of 5.3m, compared to 4.2m to 4.95m in the other EUV manufacturers.

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

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

Two UK volumetric manufacturers (UKV1 and UKV2) designed their modules within the standard load and therefore no police escort nor 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-foot trailer. Interestingly, one UK manufacturer had designed projects for unconventional air transport, which imposed even stricter size and load limitations on their module specifications. Whereas 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 6 modules had occurred at the time of interview amongst different projects. Each lost module caused delays to progress onsite because the module had to be re-fabricated and re-transported during the scheduled construction work.

Offsite completion

As confirmed by the literature review, the timber panel manufacturers had a lower level of offsite completion compared to the volumetric manufacturers. UKP1 offered the highest level of offsite completion amongst the panel manufacturers, as their products could include insulation, windows, doors, cladding and triangular openings with guide strings for services installation onsite. However, UKP2 and UKP3 stated that their highest selling products were open timber panels, which have a low level of offsite completion and included only the structural frame and OSB sheet on one side. A comparison between three examples of offsite construction systems is shown in **Fig. 6**, which demonstrates that the construction details of the panel and volumetric products were similar in principal but had some differences in material specification. The volumetric timber products included the structure, insulation, air tightness membranes, internal finishes, cladding, windows, doors, Mechanical, Electrical and Plumbing (MEP) services, fittings, built-in furniture, staircases, roofs and outdoor entrance areas, as can be seen in **Table 5**.

There were several exceptions to this observation, such as the example of projects which did not require staircases due to being single-storey and situations such as UKV2 where multi-storey projects with external staircases had been delivered by a sub-contractor. In addition, most volumetric manufacturers did not construct roof systems, as 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 centres connected with longitudinal ties and sheeted with OSB. UKV1 was unusual in that it included the outdoor entrance areas in one of their products, because their house types resembled traditional homes, whereas 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 building in the factories and UKV2 had intentions to increase this figure to 98%.

Of note is that the offsite manufacturers were often flexible with the level of prefabrication to suit each specific client and project requirements. Four 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.

Onsite 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 summarised in **Table 6**. The panel systems required a higher number of onsite activities, whilst the onsite activities of the volumetric systems were fewer in number and required fewer trades onsite.

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

Project Delivery Results

Contractual relationships

Nine out of the ten companies reported that their roles were that of a sub-contractor, delivering and often constructing the offsite timber system only - see **Table 7**. Amongst the panel manufacturers, UKP1 and UKP3 sometimes constructed projects in collaboration with their sister companies, who were traditional masonry onsite contractors. The smaller companies, UKV1 and UKV2, had more responsibilities per project, which included the project design from concept to final production drawings. In addition, UKV1 were responsible for the entire project, apart from the underbuild masonry and services routing. The main contractual role of UKV3 was different, in that they were responsible for the offsite system, however preferred to be a main contractor in projects to give them the same authority as the onsite 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 UK 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 offsite timber construction. These are summarised in the top 6 rows of **Table 8**, above the double line. Nine out of the ten surveyed companies manufactured offsite systems for apartment buildings, eight for private housing and seven for affordable housing.

In the UK the main targeted markets for offsite timber construction were private sale houses, private sale apartments and affordable housing. In mainland Europe multi-storey apartment buildings, student accommodation and retirement homes were seen as the building types with the largest opportunity for growth. Three EU manufacturers explained that the single-family house market was over-saturated in their countries and therefore was not a prosperous option for volumetric timber construction. EUV4 added that volumetric timber manufacture was viable only if it was produced in countries with lower Gross Domestic Products (GDPs) and reduced salary rates and the 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 offsite timber systems from manufacturers UKV3, UKP3 and EUV3 are shown in **Fig. 7**.

Within the non-residential building typology, the education market was perceived as the most viable opportunity for offsite timber construction. Eight companies manufactured schools, followed by five companies, who manufactured healthcare facilities. Furthermore, recreation buildings (hotel, 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 UK. Generally, the UKP and EUV companies manufactured a similarly large variety of non-residential projects, whereas only UKV2 had manufactured four non-residential projects. This result can be explained by the specialisation 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 UK, especially lightweight steel modules 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 twelve and ten sectors, respectively, and UKP1 and EUV4 manufactured nine building types. UKV1 and UKV3 constructed the smallest variety of building types; namely 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 & 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, however 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, would have little effect on the manufacturing time and cost efficiency. Furthermore, because the panel companies ordered and stocked large quantities of typical materials, they stated that the panels were more cost-efficient than timber, masonry or in-situ concrete construction where 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 utilised for every project compared to onsite projects where smaller quantities are ordered and incorporated.

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 emphasised 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 UK. 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 multi-storey apartment buildings with approximately 150 modules as shown in **Fig. 8**, but they also accepted contracts for single module projects. EUV4 emphasised 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 offsite timber systems are summarised in **Table 9**. The table shows that the EU companies constructed to stricter energy-efficiency standards compared to the UK. Five companies (UKP1, UKP2, UKP3, UKV3 and EUV3) referred to the Passivhaus standard as a measure of their ability to achieve high energy efficiency. UKP1 had a matrix with different options for achieving different standards and UKP2 and UKP3 had developed standard details for different thermal performances. Three companies had standard energy performance values for their homes and standard solutions, UKP3, UKV1 and EUV4 whereas three manufacturers (UKV2, EUV1 and EUV2) stated they could build to any specified thermal conductivity and air tightness 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 made a similar remark:

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

When asked about embodied energy calculations, in general the UK companies responded that they conducted 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 re-purposed them for offsite timber manufacturing. Four manufacturers had purpose-built their factories and equipped them with a mixture of 'off-the shelf' and "custom-designed" offsite timber machines according to their manufacturing process. These were UKP3, EUV1, EUV3 and EUV4 and this indicated that this was more common amongst the surveyed

European companies. UKV1, in contrast, used a temporary metal-framed building, which could be dismantled in three days if the workshop had to be relocated.

Four companies (UKP1, UKP3, UKV1 and UKV3) had started as conventional construction companies and offsite 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 endeavour by employees of a neighbouring offsite 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 re-locations to larger facilities. EUV1 had been in operation for 29 years and had established a daughter company for specialised modules and had expanded the internal departments and similarly EUV3 had been in operation for 20 years and in this time had developed into an umbrella organisation 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 offsite panels which could be manufactured on their assembly lines. For example, UKP3 re-designed buildings specified as brick and block construction. The three panel manufacturers stated that the process should be more stream lined and the involvement of the manufacturer should be earlier; in other words that the design and manufacturing process should be more collaborative.

The situation was similar in UKV3, EUV1 and EUV4, in that the manufacturer was involved after tender stage and re-worked designs by external architects to be buildable using their volumetric timber systems. However, UKP1, UKP2, EUV1, EUV4 had large design and specification capacities with design teams comprising 12, 18, 16 and 12 people respectively, compared to 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 project. Despite these efforts, design re-work and exchanges of revised drawings were frequent and sometimes delayed the project progress, either due to manufacturing or regulatory issues.

Production management

Eight manufacturers structured the 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, at times 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, whilst finishing their qualifications. Similarly, EUV1 employed 50% skilled workers and 50% unskilled workers, who were gaining technical skills. Examples of manual and automated processes and typical factory production environments are shown in **Fig. 9**.

The UKP and EUV companies reported a continuous pipe-line of projects, which were said to reduce the unproductive labour hours and provide a driver for process optimisation. Interestingly, UKV3 pointed out that a week of 'down-time' between projects was useful to reconfigure and prepare for the following project, such as procure materials, setting-up the manufacturing lines and 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-hour days, which started between 07:00 and 09:00 and ended between 15:30 and 17:30. EUV3 explained that working longer hours or two shifts would lead to bottlenecks in the process, mainly because of the concrete floor curing time. In contrast, the UKP3 production teams worked in two shifts, from 06:00 to 16:30 and from 16:30 to 04:30 - in total 22 hours and 30 minutes per day. The number of permanent production line staff varied between approximately 12 (UKV1) to 220 (EUV4) with a mean value of 40 people employed by UKP3 and UKV3.

Building Information Management (BIM)

Overall, nine out of the ten surveyed companies had applied BIM up to at least Level 1, as defined by the BIM Industry Working Group (BIWG 2011)**.** That is, they used 3D models with component information attached to the visual representation of the model elements, such as dimensions, cost, availability, sequence of manufacturing. UKV2 and UKV3 had applied BIM up to Level 2 (information exchange through ifc models) 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 summarised their BIM strategy in the following way:

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

Within the main BIM Levels, the surveyed companies also reported on their application of BIM Dimensions (3D components, 4D time, 5D cost, 6D facilities management and 7D energy analysis) (Sanchez et al. 2016). At the time of interview, seven companies were using 3D components with attached information for modelling of their projects. Only UKV2 applied BIM for production time estimation, 4D and 5D cost estimation and procurement. However, UKP2 and EUV2 speculated that 4D and 5D BIM could be useful for their companies, such as for time on site estimation, on site information availability and productivity estimation of the factory processes. Similarly, UKV2 were the only company who had applied BIM for 6D facilities management and 7D energy analysis. 6D was executed by providing as-built information to the client including the specification and maintenance requirements of the installed components. For 7D BIM application, the structural engineer of the company worked on reducing the carbon footprints of the buildings in terms of embodied and in-use energy.

Regarding other BIM levels, UKV1 had applied BIM only up to Level 0, 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. Amongst 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 sceptical about BIM as a sustainable process of work for 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 in only one company was this 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, however 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, 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 Automation and Lean improvement. The analysis was carried out per manufacturing line with the aim of exploring productivity improvement strategies whilst reducing the impact of individual company strategies on the research findings. In this way, the observations made regarding the offsite systems production and process strategies can be generalised to a higher degree.

Manufacturing line stages generalisation

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

Although the manufacturing sequence followed the generalized manufacturing lines above, each company varied in the actual number of their manufacturing lines and sequence. As shown in **Fig. 11**, the panel manufacturers had the highest number of manufacturing lines, despite producing a lesser percentage of offsite construction than the volumetric manufacturers. The EU volumetric fabricators employed an average of four manufacturing lines in a similar form to the system described above. In contrast, the UK volumetric manufacturers mostly utilised 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**.

Automation and mechanisation

As shown in **Fig. 12** below, the opportunities for automation were observed mainly in the initial stages of manufacturing, in materials handling and cutting through to door and window installation. 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, 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, mechanised 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 mechanisation and their observations are recorded in **Fig. 13**. These tools were used in ten manufacturing lines amongst the studied companies and the greatest examples of mechanisation were observed in the frame assembly stage. The mechanised assembly tool with the highest number of observations were cranes, which were used to lift and transport components and panels between manufacturing lines. 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 mechanised production efficiency improved, some companies were also observed to employ lean methods, which reduced time wastage, space 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, shown in the **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 despatch 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 and 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 non-timber components. One manufacturer demonstrated that they 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 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, clips), therefore disassembly was theoretically possible, but because this had not been designed for would be technically challenging. UKP3 expressed a similar opinion and added that the insulation and services would make disassembly and re-use of materials unrealistic. EUV2, EUV3 and EUV4 stated that refurbishment and repurpose of the modules was not feasible because of practical considerations such as planning, disruptions to neighbours, knowledge of load transfer and services installed in the building.

UKV1, UKV2 and UKV3 provided more positive responses in that building adaptation could be possible because of standardised connections, compacts services cores and internal non-loadbearing walls. In fact, at the time of 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.

Offsite completion percentage

The starting point of the data analysis was the calculation of percentages for onsite and offsite activities of the studied offsite timber systems. The data from Tables 3 and 4 was used to propose a quantification of the offsite completion levels amongst the surveyed companies, where a value of 1 was attributed to elements, which were included in the offsite products, and a value of 0.5 was attributed to elements, which may or may not be included in the factory production process. Previous studies did not present methodologies for estimation of offsite level percentages and although this method has its limitations, it is has been utilised in this instance. This approach produced the following results, shown in **Fig. 15**, which highlight that the offsite completion levels of the investigated systems tended to be within more moderate ranges compared to the higher percentages of offsite completion often attributed to volumetric timber construction in the literature (Smith 2011). These results also demonstrate that the levels of offsite completion between systems sharing an offsite classification could be said to vary significantly; according to this research, by up to 15%. On average, the UKP companies utilised 25% offsite completion, the UKV companies 70% and the EUV companies 65%. This is generally in line with the estimates of Lawson and colleagues (Lawson et al. 2014).

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

Production and productivity

The production output of each company was reported in different units shown in **Table 10**, which is reflective of findings from previous research that construction productivity measurement is inconsistent (CITB 2017). Some examples of the reporting of the production output by interviewees are described as follows: ‘In the open panel assembly line each station takes approximately 2.5 minutes per panel. They produce approximately 50 floor cassettes per day.' and '5-6 days to manufacture a module from start to finish. Each panel/module progresses to the next station each day.'. Therefore, although in an ideal world a unified international offsite production metric system could be utilised across all manufacturers, due to the practicalities of this industry-based research, it was necessary to transform these units to a single unit of measurement.

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

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

To illustrate the unit conversion for the calculation, the more complex of the examples above, will be reported (time per open timber panel). Firstly, the working hours per week were extracted from the production management results regarding shift patterns; these were then multiplied by the reported panel sizes to extract linear meter panel outputs per week (with respective minutes to hours to week conversions). The resulting number was divided by the linear wall metres of the one-bedroom common unit of measurement extract output per week results. This was multiplied by the previously calculated offsite percentage for open panel construction and this generated a normalised offsite output per week. The input was calculated in labour-hours by the multiplication of working hours per week by the number of staff reported working on the shop floor. This allowed for differentiations in the numbers and durations of production shifts per day described in the final results. Finally, according to **Equation 2** the output and input were divided to arrive at a figure for labour productivity, comparable across the ten surveyed manufacturers. The results from the pilot comparative productivity analysis are shown 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 B**.

Equation 2

$$Lp1 = \frac{P1\ x\ OC1\%}{Lh1}$$

Where:

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

P1 = Production in 1-bedroom living unit per week

OC1% = Offsite Completion Percentage (reported); and

Lh1= Labour hours per week

2-bedroom living unit with calculated offsite percentage estimates

The selection of a common unit of measurement was an important consideration for this research study and the identified common unit was derived from methodologies applied in previous research studies in the field (Monahan and Powell 2011; Quale et al. 2012; Smith et al. 2013). Previous research by Monahan and Powell utilised a three-bedroom, two-storey case study house in the context of the UK; Quale and colleagues based their findings on a 4-module 2,000 square foot (185 m^2) two-storey house in a hypothetical context; whereas Smith and colleagues evaluated 'homes/units' outputs irrespective of the differences in home sizes. To decide the living unit-equivalent utilised in this study the data from literature was triangulated with results from 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), as shown in **Fig. 16**. In addition, the selection of a neutral living unit of measurement, mitigated the potential impact on results favouring one company.

An observation of the latest available UK census data from 2011 in **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 2-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% as seen in **Table 13** (Quale et al. 2012). To make the results comparable to previous offsite reviews, the output units were changed to living unit-equivalent per annum and the labour units were altered to number of staff (Smith et al. 2013). These alterations resulted in calculations using **Equation 3**.

Equation 3

$$Lp2 = \frac{P2 \ x \ OC2\%}{Lr}$$

Where:

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

P2 = Production in 2-bedroom living unit per annum

OC2% = Offsite Completion Percentage (calculated); and

Lr= Labour resources per manufacturer

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

However, this quantitative exploration of the data does reflect the qualitative nuances between the surveyed companies. For example, the quantitative productivity comparison did not accommodate for differences in business models amongst the surveyed manufacturers. EUV4 employed a significantly higher number of production staff; 5 times more than EUV3. The EUV4 workforce costs were significantly less per hour compared to their market country, where they exported and constructed modules. Therefore, in 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 number of workforce at UKV2 compared to EUV2 and UKV3 combined with the establishment of EUV2 as a daughter company to a much larger organisation. 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, mechanisation and lean improvement potential. The highest opportunities for automation were observed in the panel production stages, whereas the volumetric production stages included manual workmanship of services and finishes. Therefore, it could have been expected that the labour productivity of the panelised timber manufacturers would be higher than that of volumetric timber manufacturers, whose work included in addition highly manual labour-intensive tasks. However, the results from this sample suggest that labour efficiency in modular production can be similar to panelised timber production. Increased labour productivity in certain manufacturers such as EUV1 may be connected to higher output capacity, due to a high number of years in trading with associated opportunities for growth and investment in R&D.

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 amongst the surveyed manufacturers. Practical considerations regarding the international regulations on transport load dimensions in individual countries and their effect on the possibility of producing this unit in each surveyed country were not included in this production calculation. 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 of this 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 meters, or 13% of total 185.6 linear meters). The sensitivities of this observation should moreover be considered when drawing conclusions.

Benchmark

The main precedent for this research was the *Strategic Review* of the offsite sector in Scotland, whose value was estimated at £125 million based on surveyed companies, with potential to grow to £230 million excluding increases in numbers of manufacturing facilities (Smith et al. 2013). The sector at the time produced 6,000 homes per annum, however the existing facilities had capacity to produce 16,500 homes per annum. Therefore, it can be speculated that the sector was operating at approximately 37% of maximum capacity, on average. The value of the sector was £125 m, with potential to expand to £230 m, including a doubling of exports to England. Moreover, the number of people employed by the interviewed companies was 1,450.

Using these figures for input vs. output calculations, the productivity of the sector may be expressed as the ratio between the outputs (either living unit-equivalent or value output) and the labour input (number of production staff employed) as per Equation 1. Thus the estimated labour productivity was approximately 4.13 homes (living-unit equivalents) output per person, or £86,200 output per person per annum 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 per person, or £155,000 output per person per annum. These values are visualised in **Fig. 19,** where the x axis shows 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 offsite sector's productivity and management strategies with differentiation between systems with different levels of offsite 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 and colleagues 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 UK, which will however require an increase in the volumetric timber market maturity.

Sensitivity analysis

Through the exploration of different methods for offsite completion percentage calculation and living unit equivalent, this paper has explored the sensitivities of the methodology. The rankings of manufacturers' productivity differed between the two methods as shown in **Table 15**, which suggests that the difference between reported offsite percentage completion and calculated offsite completion percentage had the largest impact on the differences in ranking, which ultimately lead to EUV manufacturers being ranked on average higher than UKP manufacturers in the updated benchmarkable metrics. Because of the sensitivity of these measurements, it is suggested that UKP and EUV manufacturers have similar labour productivity rates, which leads to a gap for potential productivity growth of UKV manufacturers.

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

With the low 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 amongst 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 UK is important within the context of the research findings that an increase in the offsite market share from 7% to 25% would increase the Gross Value Add (GVA) of £4.3 bn across the UK (WPI Economics 2017).

Conclusion

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

Overall the EUV and UKP manufacturers shared similar productivity rates of five 2-bedroom living unit-equivalent outputs per labour resource per annum. Yet EUV manufacturers' products had a higher offsite completion percentage, up to approximately 70% of materials and work, compared to approximately 25% for UKP. These results suggest that for the surveyed sample 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 labour productivity results, it is suggested that the UKV manufacturers have high potential for growth in both market size and productivity in the UK. 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 offsite timber construction, including residential, healthcare, education and commercial, however volumetric timber manufacturers who participated in this survey mainly operated in the residential market. All companies reported market fluctuations as a challenge to growth, with emphasis on the residential market. Therefore, it could be theorised that operation in a higher number of market segments could potentially increase the resilience of the offsite manufacturers 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 have suggested that offsite timber construction is suitable for a wide spectrum of residential market segments, across the affordable, middle and high-end ranges.

European manufacturers additionally tended to construct extensions to existing buildings using volumetric timber construction. This potential to retro-fit existing building fabric using offsite construction methods seems to be under-used in the UK considering that £1.9 billion of UK construction output is due to the refurbishment of existing housing (Lawson et al. 2014; ONS 2016b). Moreover, the companies tailored each project to the specific brief to achieve the design intent specified by the client. These findings contradict the prevailing offsite perception in the UK regarding monotonous ‘prefab’ housing estates. When this individuality of design output is considered alongside the high energy efficiency of the surveyed offsite products, this highlights the need for a change to 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 offsite timber manufacturers in BIM implementation, mostly through use of digital design using 3D components with attached information linked to CAM equipment; with one example of a UK volumetric manufacturer who had applied all 7 BIM dimensions. Overall there are therefore great technological opportunities in advanced offsite timber manufacturing, which could in turn result in increased productivity.

This study moreover highlighted a disconnection between designs received by the manufacturers and the offsite system to be used in construction, which ultimately resulted in design re-work. With this in mind, the findings from this research may be summarised in the five main observations based on the reported results from this survey's sample (**Table 16**) which are categorised as Size, Weight & Transport; Energy Efficiency; Contractual Relationship; Market Opportunities & Cost-Efficiency and Repetitive Design. It must be noted that all these conclusions are drawn within scientific limitations of the work, which could be addressed through exploration of further work.

Further work

This study has looked at 10 companies in five European countries, however, the study could be enhanced with more representative countries, more offsite 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 hypothesise which business approaches could enhance offsite timber productivity. Lastly, the combination of offsite and onsite process productivity will be investigated using construction case studies in the authors' further work to enable a more comprehensive comparative productivity analysis of offsite timber systems.

Data availability statement

Data generated or analysed during the study are available from the corresponding author by request.

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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) (Armistead 1999) (NAO 2005)
Opportunity & 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) (Polat et al. 2006)
Opportunity	Labour 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) (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; 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) (Li et al. 2014)
Opportunity & Challenge	Logistics	Road transport legislation limits the size of modules in different contexts, however the number of and carbon footprint of people and materials transport is reduced with volumetric timber systems	(Krug and Miles 2013) (Goulding and Arif 2013) (Quale et al. 2012) (Dainty and Brooke 2004)
Opportunity	Low carbon construction	The climate change impact potential of volumetric timber systems is much lower than 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) (Dodoo et al. 2014)
Challenge	Specification guidelines	There is no single technical guideline resource for designers and specifiers of volumetric timber in the UK	(Lawson et al. 2014) (SINTEF 2013) (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) (Johnsson and Meiling 2009)

Opportunity	Health & Safety	Improved conditions due to a controlled factory process and equipment use can help mitigate the construction skills shortage	(Goulding & Arif 2013; Lawson et al. 2014; Hairstans 2015) (Court et al. 2009)

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

Level	Reference	Productivity	Knowledge gap
Industry	(Nasir et al. 2013) (Vilasini et al. 2014)	A comparison between 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 offsite 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.	There is a connection between the technological investment in a company and their profitability.
Project	(Isaac and Navon 2013)	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)	By measurement of physiological indicators such as heartrate a connection was discovered between strain and productivity.	The relationship between physical strain and activity productivity.

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 and larger products can be assembled manually.

Table 5. Factory comparison based on offsite 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 offsite completion estimate	45%	25%	29%	82%	90%	90%	90%	90%	90%	90%

Note: mbr. = membrane; int. finishes = internal finishes (skirting, painting, flooring, tiling, etc.); MEP = Mechanical, electrical and plumbing systems, including heating and HVAC; max = maximum; Y=Yes, N=No

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

Dimension	UKP1	UKP2	UKP3	UKV1	UKV2	UKV3	EUV1	EUV2	EUV3	EUV4
Foundation*	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
Air tightness 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*	Y	Y	Y	Y/N		Y/N	Y/N	Y	Y	Y
Cladding	Y/N	Y	Y					Y	Y/N	
Roof*	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

* Actions executed by the main contractor, who can also be the client. Y=Yes, N=No

Table 7. Factory comparison based on contractual role.

Dimension	UKP1	UKP2	UKP3	UKV1	UKV2	UKV3	EUV1	EUV2	EUV3	EUV4
Designer				Y	Y					
Sub-contractor	Y	Y	Y	Y	Y		Y	Y	Y	Y
*Main contractor**	Y/N		Y/N	Y		Y				
Developer									Y	

*Main contractor role may be sister-company. Y= Yes, N=No

Table 8. Factory comparison - 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*	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*		Y				Y				

*Projects with relatively small footprints for their sector. Y=Yes, N=No

Table 9. Typical offsite product comparisons based on energy efficiency metrics.

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

Table 10. Reported units for offsite products production.

Unit	UKP1	UKP2	UKP3	UKV1	UKV2	UKV3	EUV1	EUV2	EUV3	EUV4
Buildings per year					Y		Y		Y	
Buildings per hour			Y						Y	
Modules per year							Y	Y		Y
Panels per year										Y
Panels linear meters per day	Y									
Panels area per week		Y								
Panels N per shift			Y							
Minutes per open panel			Y							
Minutes per closed panel			Y							
Week per module				Y	Y	Y		Y	Y	Y
Modules per week						Y		Y	Y	Y
Modules per day							Y		Y	
Total output measurement unit types reported per manufacturer	**1**	**1**	**4**	**1**	**2**	**2**	**3**	**3**	**5**	**4**

Note: Y=Yes

Table 11. 1-bedroom living unit dimensions schedule.

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

Table 12. Comparative production and productivity analysis for 1-bedroom living unit.

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

Table 13. 2-bedroom living unit dimensions schedule.

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

Table 14. Comparative production and productivity analysis for 2-bedroom living unit equivalent.

Variable	UK P1	UK P2	UK P3	UK V1	UK V2	UK V3	EU V1	EU V2	EU V3	EU V4	UK P	UK V	EU V	AV RG
P2	231	225	532	12	8	83	595	259	345	213	329	34	353	239
OC2%	19%	22%	34%	58%	63%	67%	68%	69%	69%	71%	25%	63%	69%	54%
Lr	86	140	74	10	20	60	80	40	50	220	100	30	98	76
Lp2	**2.69**	**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**

Table 15. Labour productivity sensitivity analysis.

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

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

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

Figure list

(a) (b)

Fig. 1. Examples of offsite timber systems studied in this paper: (a) Closed timber panels; and (b) Volumetric timber module. Photograph(s) taken by: Duncheva, T.

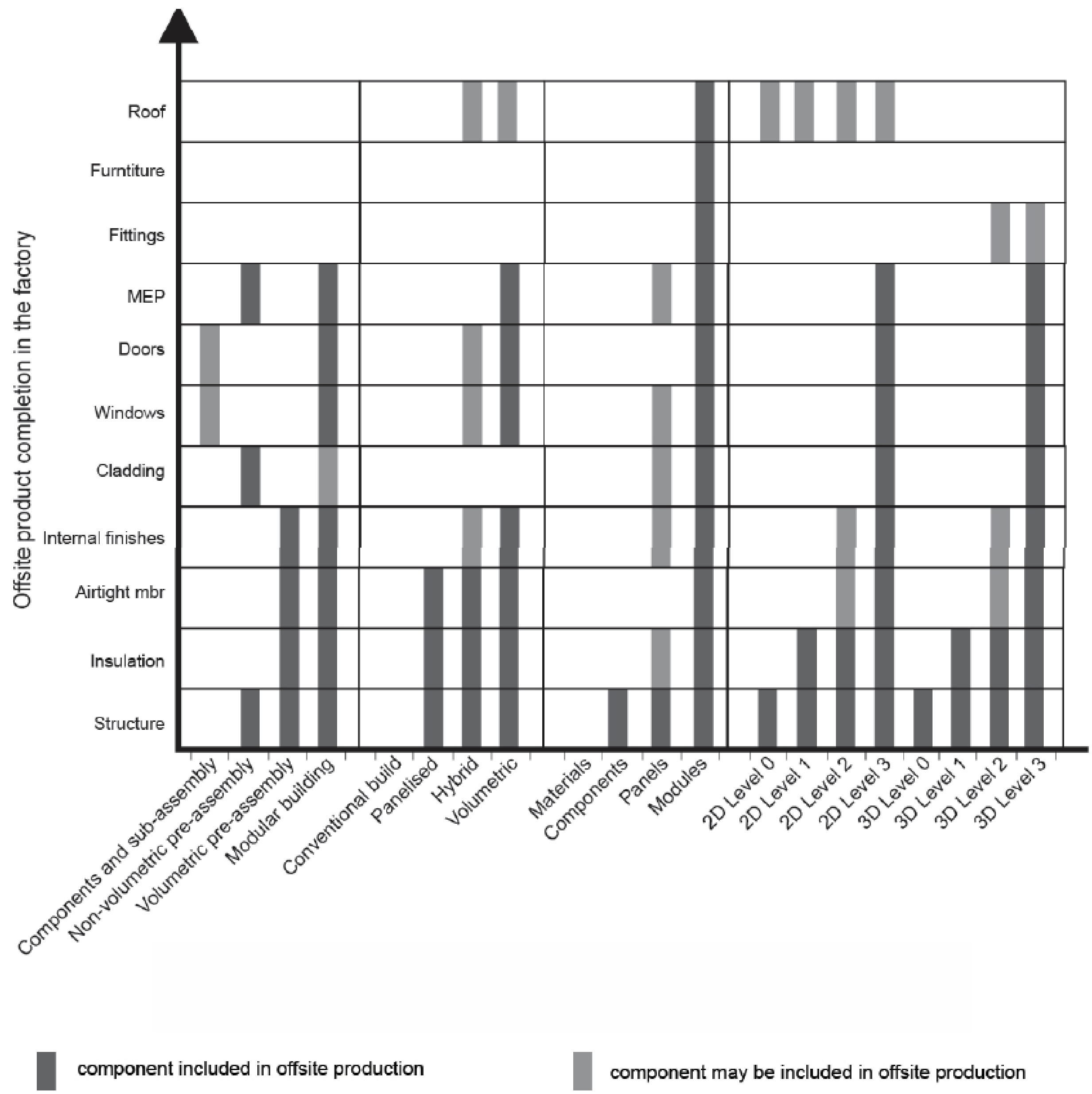

Fig. 2. Offsite systems classification comparative review according to building elements completion in the factory. (Data from Gibb and Isack 2003; Hairstans 2015; MMC Wales 2008; Oliveira et al. 2017; and Smith 2011.)

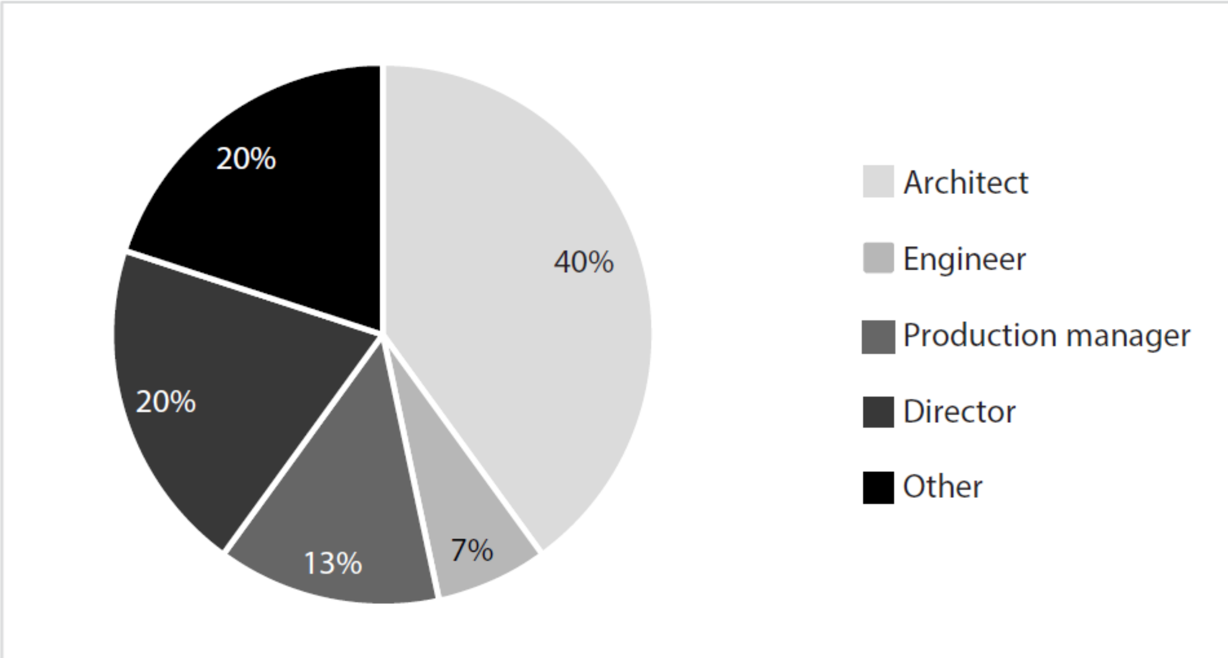

Fig. 3. Total survey sampling by profession.

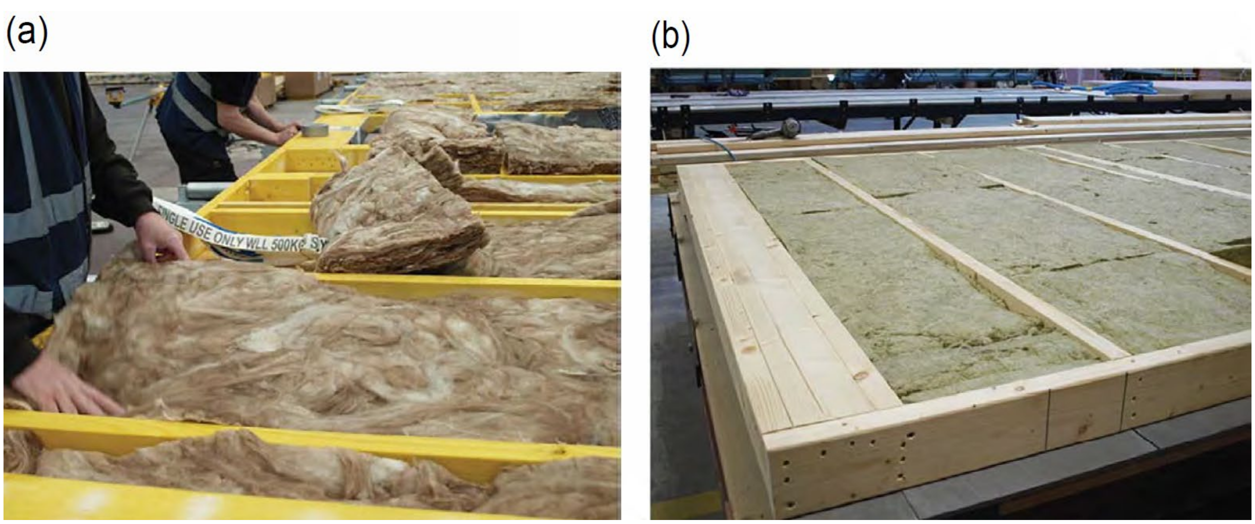

Fig. 4. Timber frame at 600mm centres closed panel examples at the insulation fitting stage: (a) UKP; and (b) EUV. Photograph(s) taken by: Duncheva, T.

Fig. 5. Examples of different transport methods for offsite timber panels and a volumetric module, whose height necessitates the use of an articulated trailer: (a) Standard trailer with stacked open timber panels; and (b) Articulated trailer with a volumetric timber module. Photograph(s) taken by: Duncheva, T.

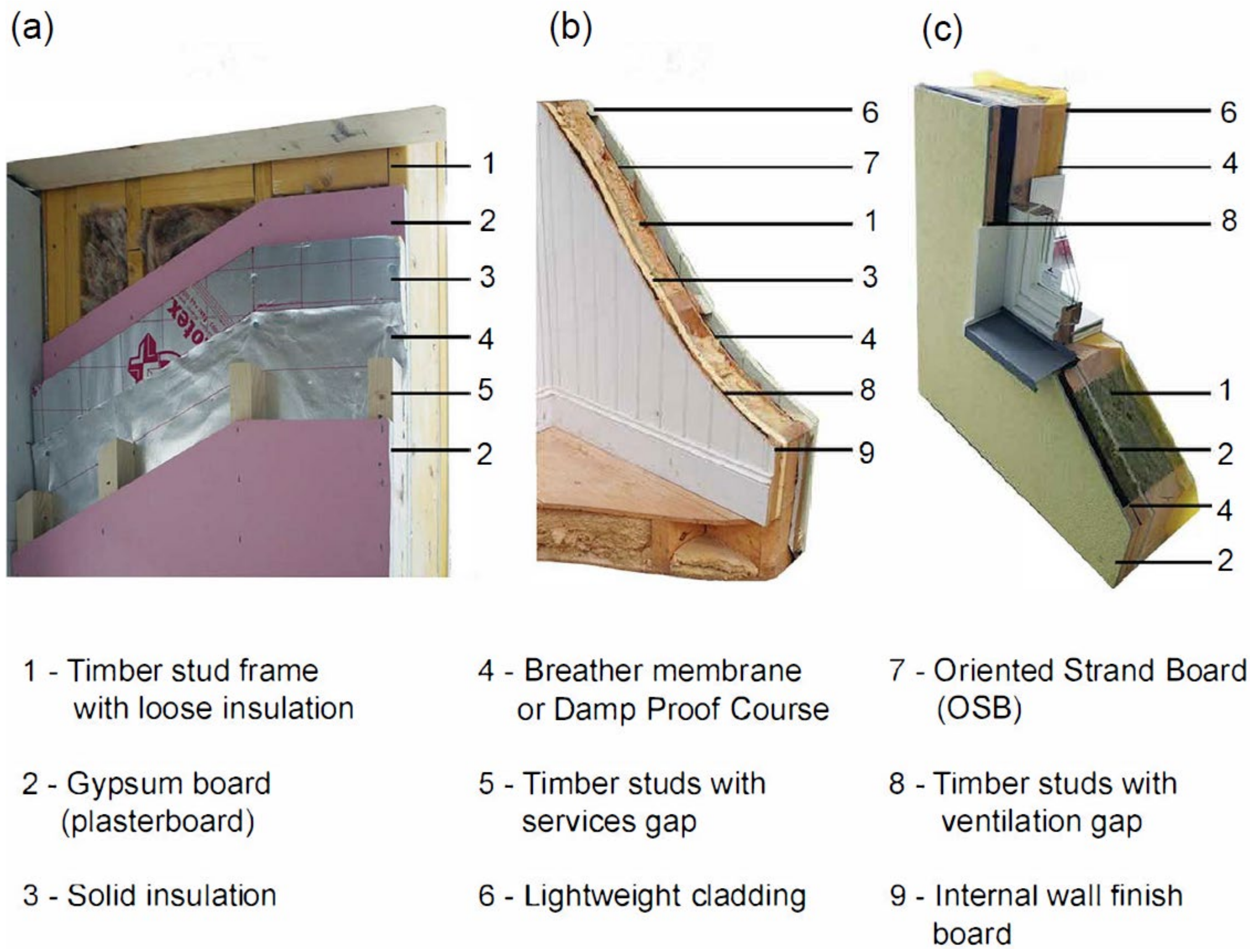

Fig. 6. Construction detail examples per company type: (a) UKP; (b) UKV; and (c) EUV. Photograph(s) taken by: Duncheva, T.

Fig. 7. Examples of typical offsite timber residential construction: (a) UK affordable houses; (b) UK high-end houses; (c) EU affordable houses; and (d) EU high-end houses. Photograph(s) taken by: Duncheva, T.

Fig. 8. Seven-storey volumetric timber apartment block buildings in EU. Photograph(s) taken by: Duncheva, T.

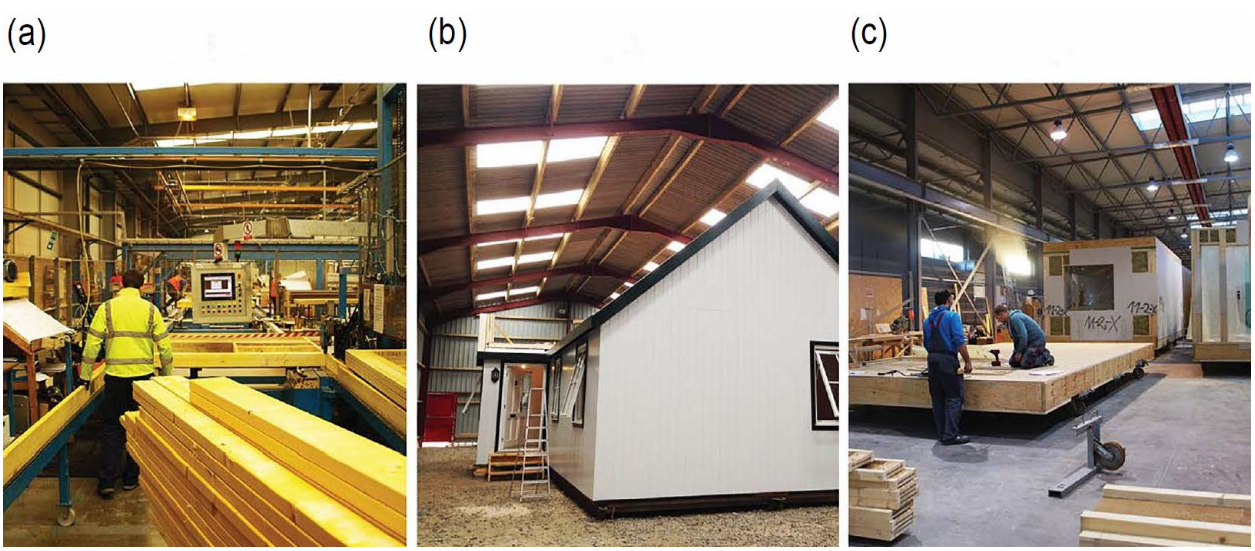

Fig. 9. Examples of automated and manual working environments in the offsite timber factories: (a) UKP; (b) UKV; and (c) EUV. Photograph(s) taken by: Duncheva, T.

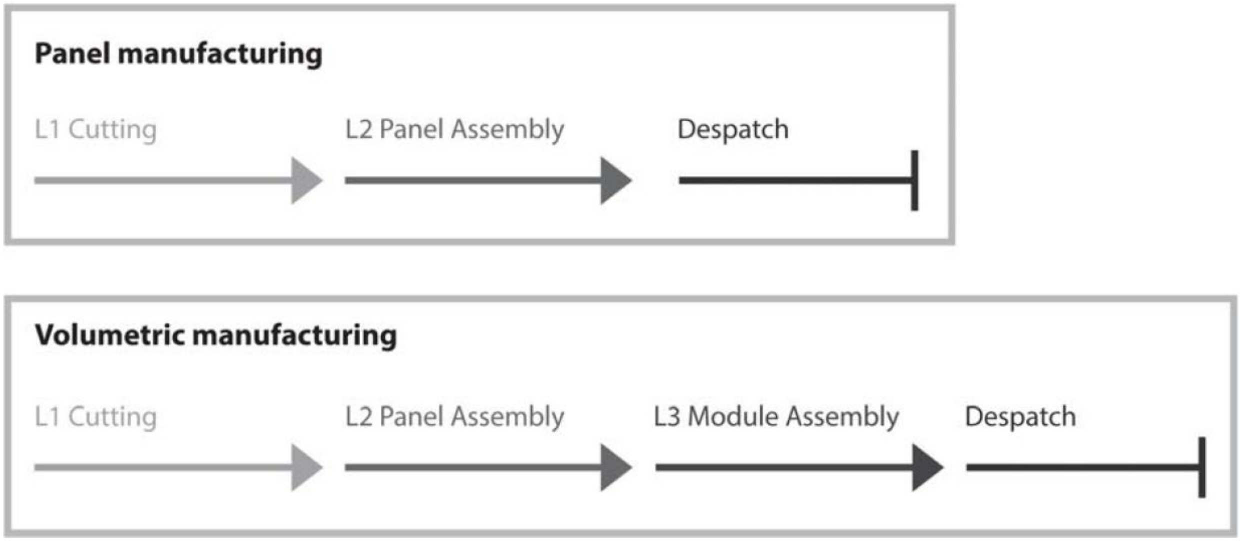

Fig. 10. Generalized panel and volumetric timber manufacturing lines.

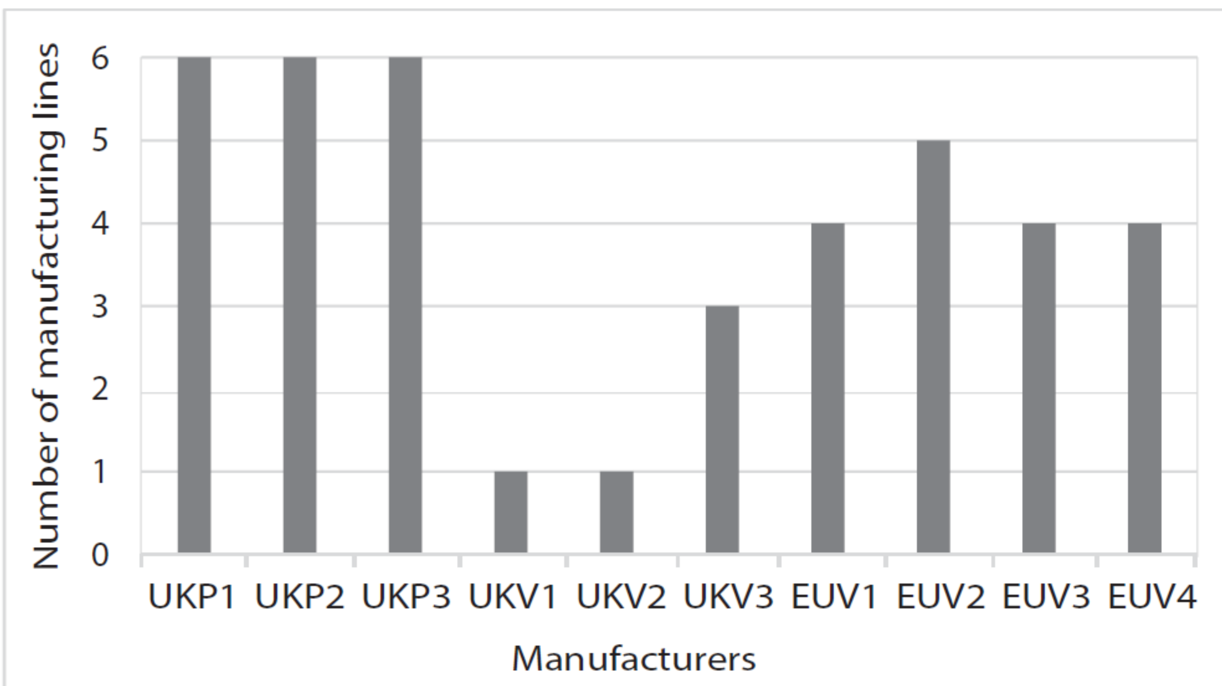

Fig. 11. Number of manufacturing lines per company (manufacturer).

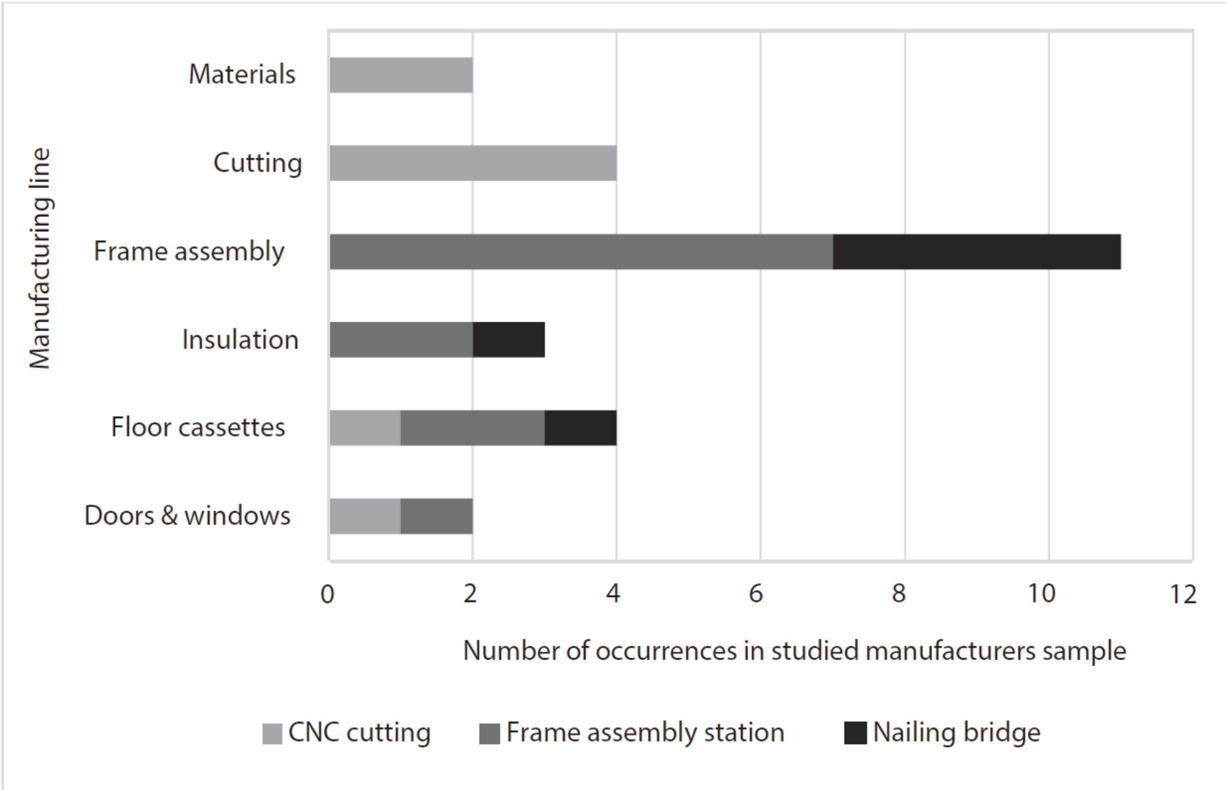

Fig. 12. Automation equipment use per manufacturing line, where 1 unit = application in 1 manufacturing stage.

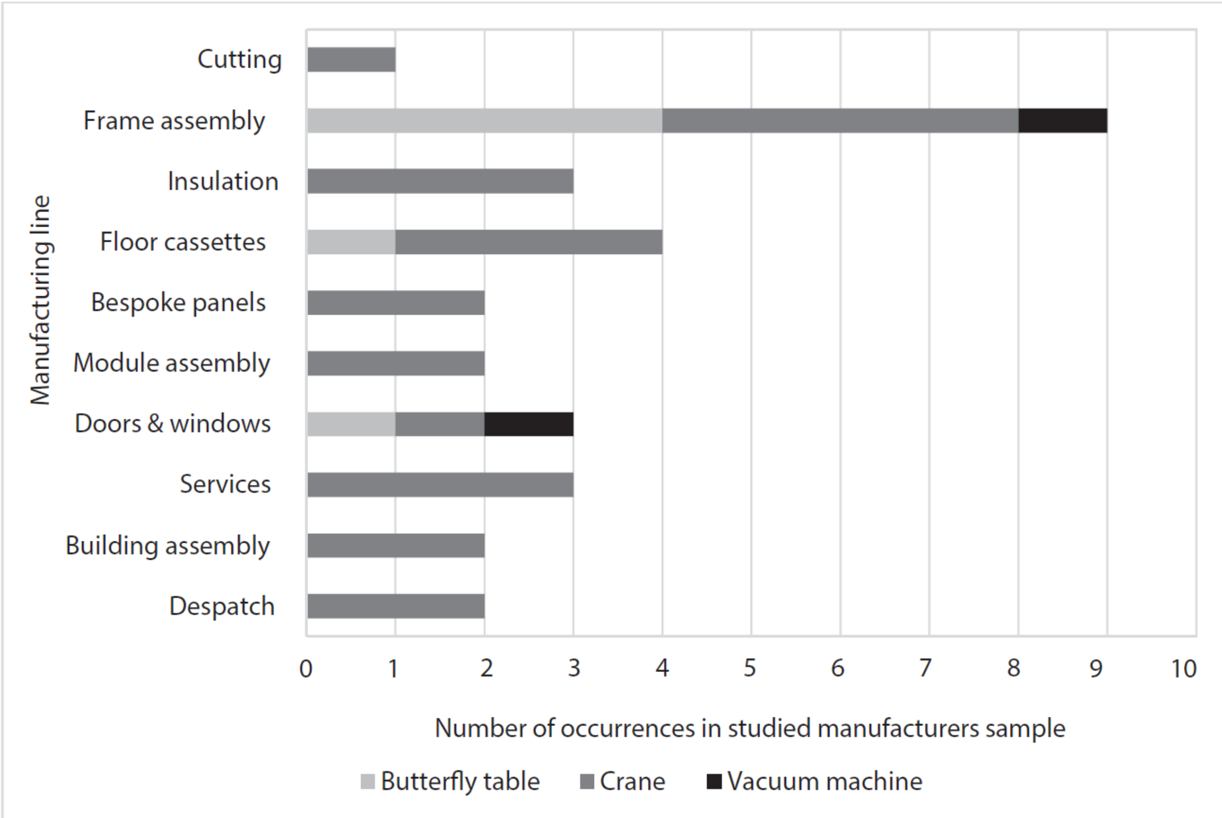

Fig. 13. Mechanisation per manufacturing line.

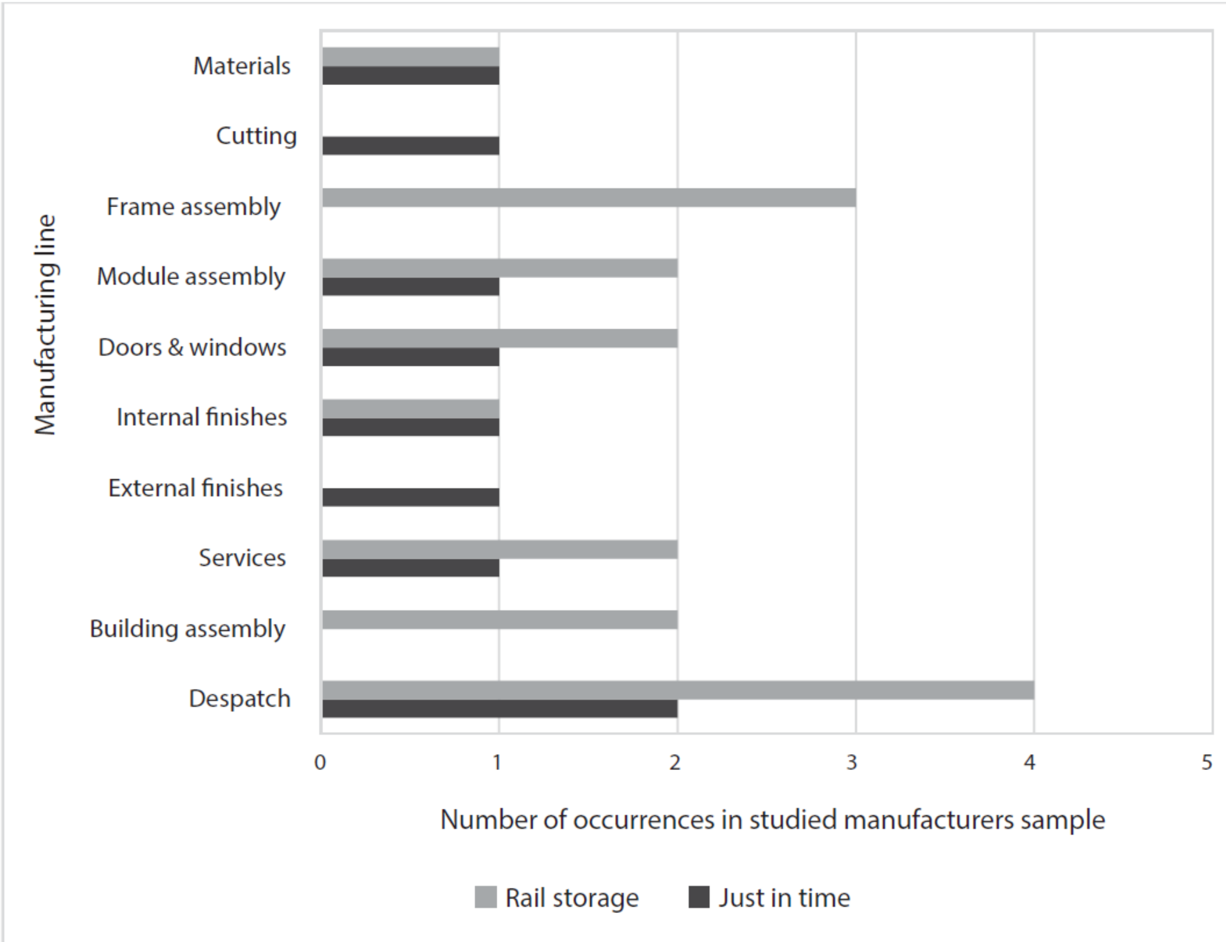

Fig. 14. Lean space saving strategies per manufacturing stage.

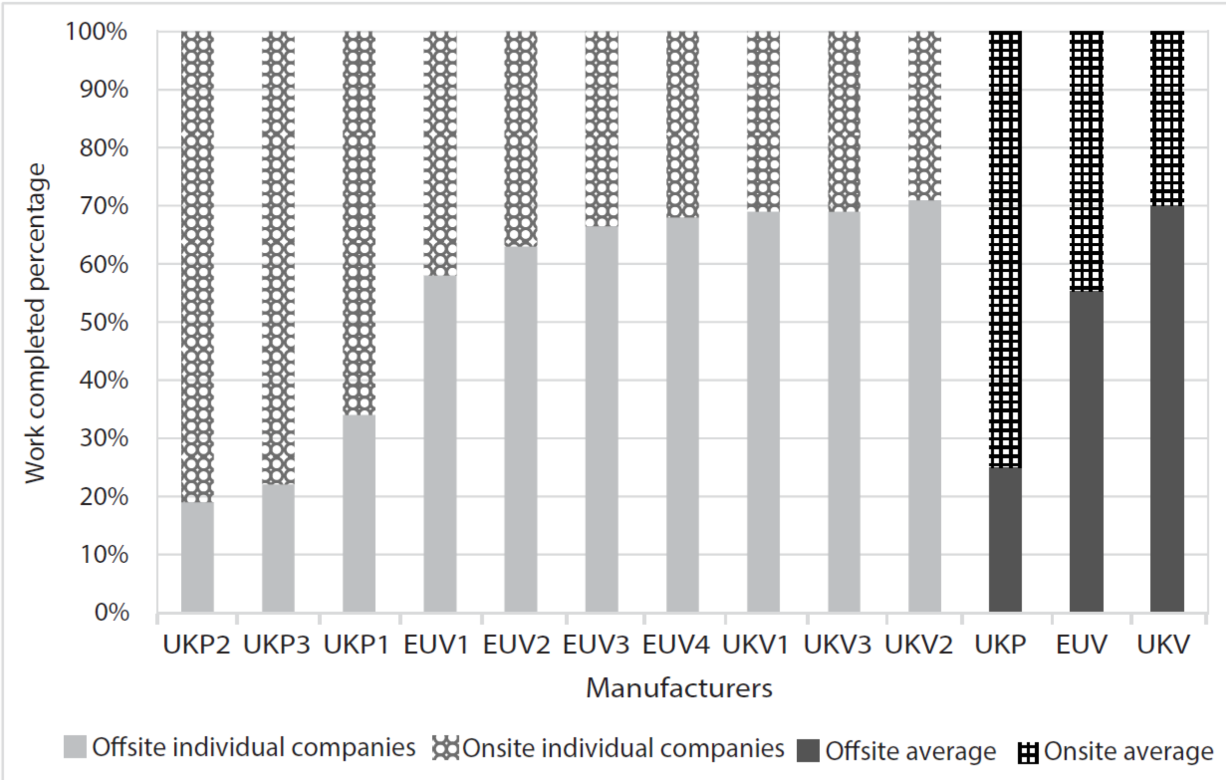

Fig. 15. Offsite and onsite building completion percentage calculated values.

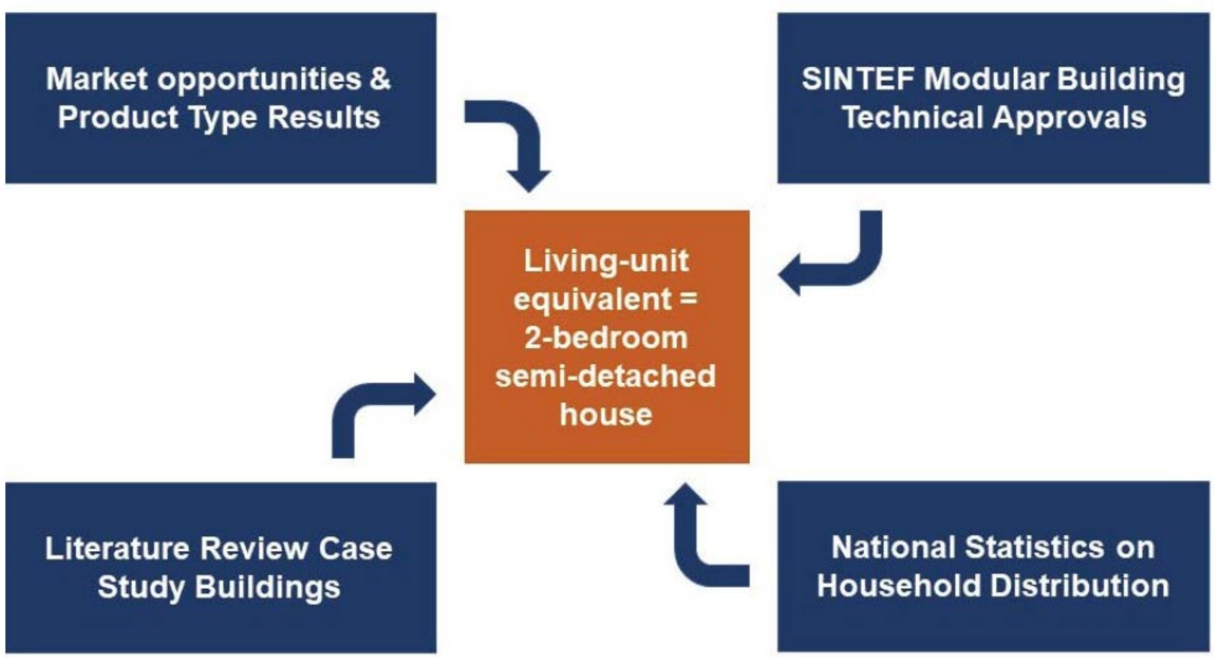

Fig. 16. Living unit-equivalent selection methodology applied in this research.

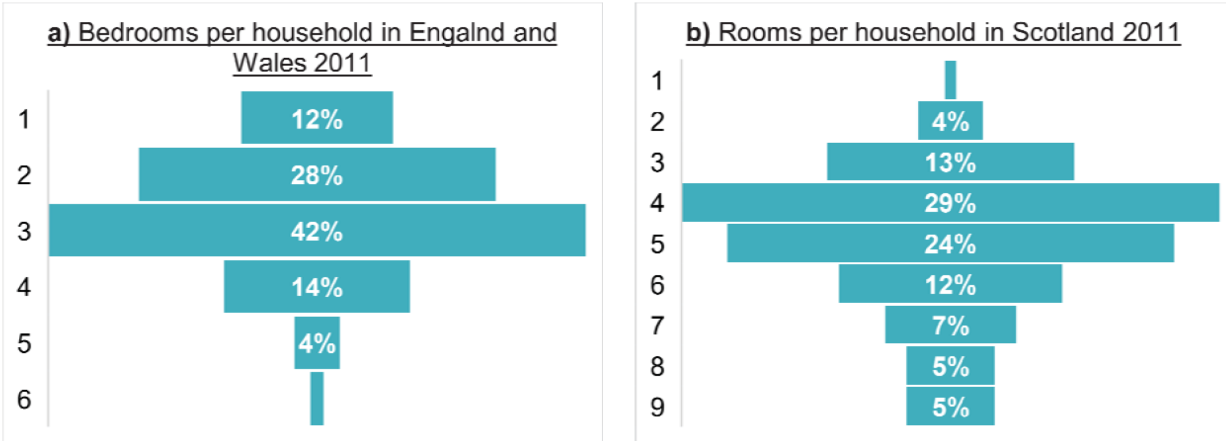

Fig. 17. Household distribution in the UK, 2011: a) England and Wales, data source (Office for National Statistics 2018); and b) Scotland, data source (National Record of Scotland 2013).

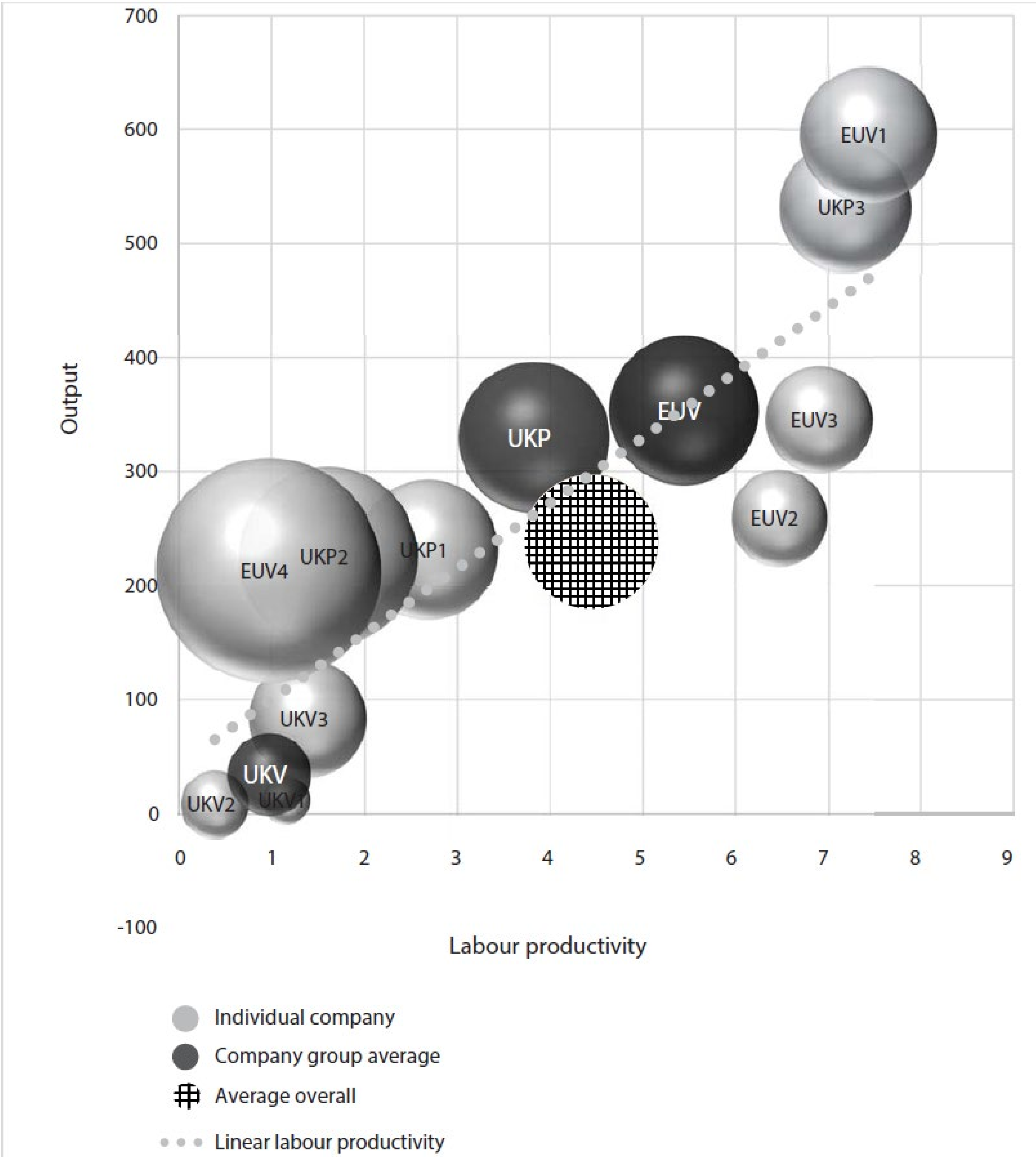

Fig. 18. Comparative productivity analysis of labour productivity (2-bedroom living unit-equivalent output per person per annum). The centre of bubble indicates values for output and labour productivity, whereas the size indicates the number of people employed.

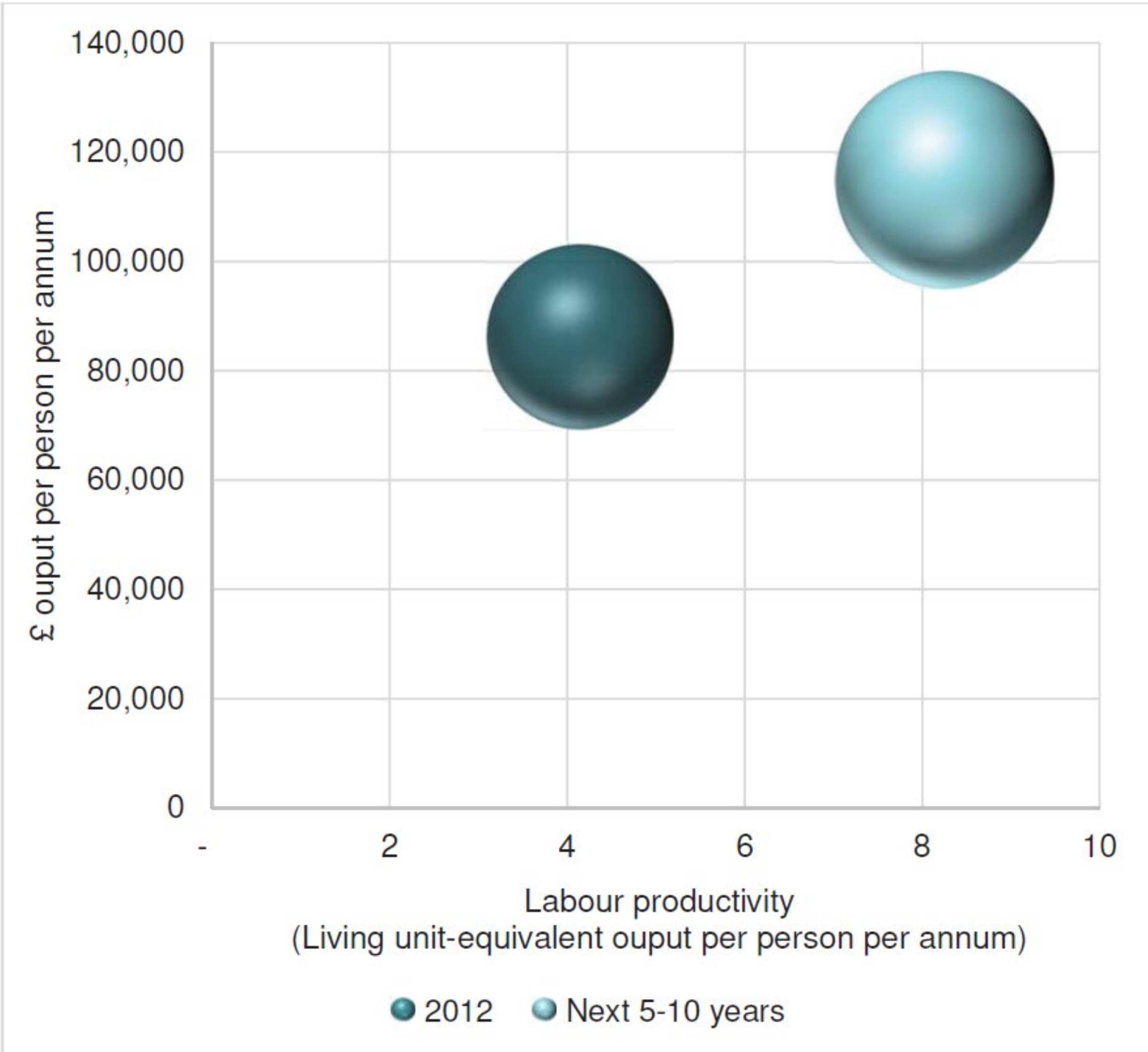

Fig. 19. Scottish offsite sector productivity. 1 unit = 1 home = 1 house OR 1 apartment. Bubble size is relevant to the number of employees. (Secondary data calculations based on findings from Smith et al. 2013.)

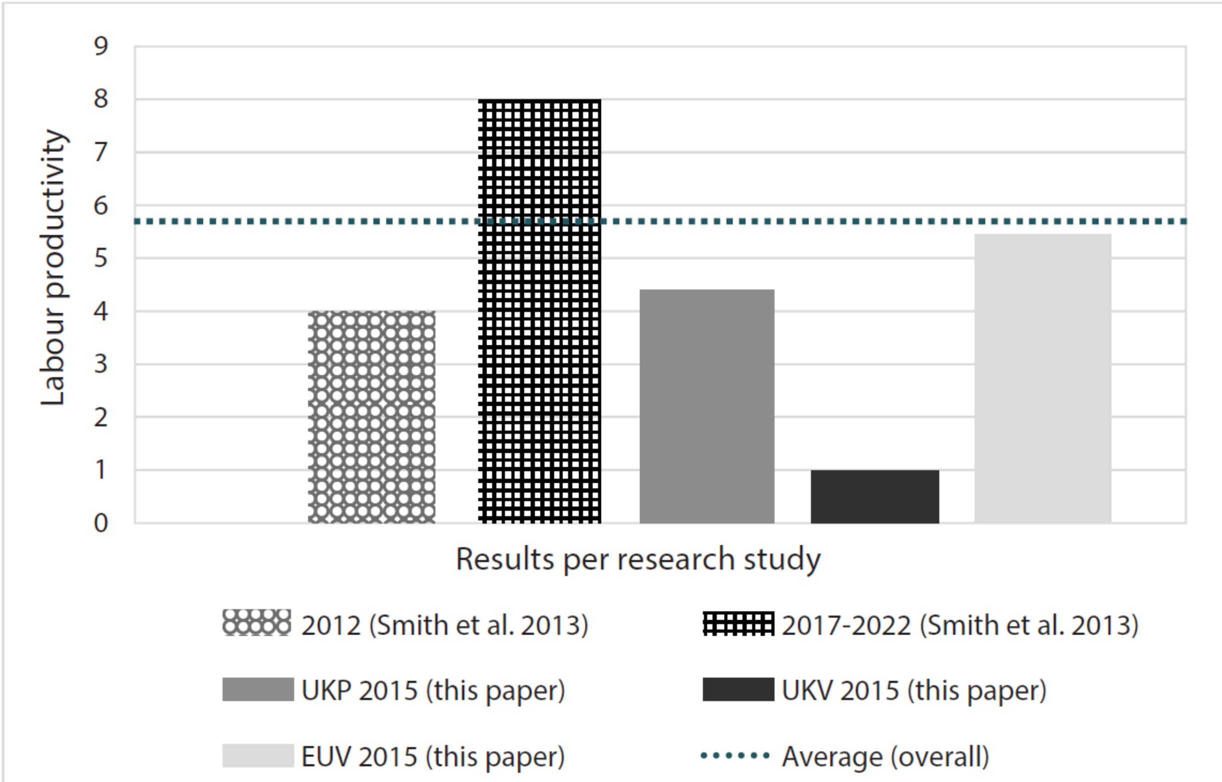

Fig. 20. Benchmark of labour productivity results (living unit-equivalent output per person per annum).