

Offsite Manufacturing for affordable housing

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Abstract

Offsite manufacturing (OSM) has been recently highlighted as contributing to increase productivity and to tackle labour shortages in the housing sector. Whilst a range of OSM building technologies are already used for the construction of homes, few evidence-based studies report on the evaluation of associated performances beyond the circumstantial conditions of project delivery. A comparative analysis of housing developments using different OSM solutions was carried out as part of a live pilot project in Hertfordshire, UK, to gather tangible data on the performances of offsite construction (OC) in housebuilding projects on small infill sites that may not be the prime focus of the industry. A dedicated evaluation model was described as per to highlight the impacts of varied building technologies integrating offsite manufacture (OSM) processes on homes delivery performances in the low-rise housing sub-sector. Secondary data from case study exemplars was extracted to test the model and speculate on associated contributions to knowledge. Delays in the progression of the project suggested inherent challenges in working with partners at a local level on the implementation of innovative construction methods for housing that might present complex and intricate contexts as well as a lack of economy of scale. The increase of risk and lateness of executive choices resulting from the adoption of OSM highlighted both the relative immaturity of the OSM market and the need to simplify procurement through dedicated business models.

Keywords: Housing, Industrialised Construction, Design for Manufacture and Assembly, Offsite, low-rise housing

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1. Introduction

Summary of the research problem

More affordable homes need to be built in the United Kingdom. The government's Housing White Paper stated it without ambiguity: the construction industry lacks productivity and homebuilders are too few (DCLG, 2017). The housebuilding market is also characterized by insufficient capacity and competition, with SMEs being responsible for just 12% of new homes in 2017 (HBF, 2017; Homes England, 2018).

Amongst current efforts from both academia and industry to research and develop new technologies to address low productivity and reconcile construction with industry 4.0, a case is repeatedly being made for prefabrication to be (re)adopted at scale, together with the integration of recent innovations in advanced automation, digital technologies and data driven models (Farmer, 2016; McKinsey Global Institute, 2017). There is also a growing belief that the success of any strategy linked to the uptake of these Modern Methods of Construction (MMC) incorporating Offsite Manufacture (OSM) in the housing sector is dependent on the definition of the project teams' roles and business models adopted for its implementation (Arif, Killian, Goulding, Wood, & Kaushik, 2017; Wei Pan & Goodier, 2012; Sinclair et al., 2016).

Private housebuilding firms with vertically integrated manufacturing capability and housebuilder/manufacturer joint ventures models seem to prevail in mitigating the financial risks of operating OSM factories in relation to the building production's flexibility needed to address the fluctuations of the housing market (NHBC, 2018). However, concerns still exist on the adequacy of the necessary repetition of large quantities of proprietary pattern book unit types to reach economies of scale with regard to varied sites' local planning requirements, end users experiences and quality of the built environment (Lang et al, 2016). For smaller builders and developers, the accessibility to OSM seems to be restricted by a lack of knowledge about a number of issues including systems specifications and availability, associated costs or warranties together with a lack of maturity of supply chains (HCA, 2010; Pan and Goodier, 2012).

Amongst emerging initiatives, Watford Community Housing (WCH), a Hertfordshire-based local housing association, set up a pilot project in 2018 with aim to provide best practice guidance on offsite construction (OC) and share new knowledge with communities and public sector housing providers. The project was initially based on the provision of affordable housing constructed using a range of MMCs on six distinct small infill sites. It presented an opportunity to collect evidence on the performances of building technologies integrating OSM processes and to compare solutions available on the market. Through the evaluation of varied aspects of OSM, the research seeks to discover the implications of OC implementation in small projects for existing supply chains and housebuilders. This in turn underpins the potential developments and deployments of offsite solutions for the low-rise sub-sector in parallel with aggregations of demand.

Aims and Objectives

This study adopts the perspective of a local housing provider seeking to encourage the adoption of OSM in construction projects for the low-rise housing sub-sector.

The research aims to contribute to the development of a dedicated evaluation model to compare the performances of building technologies integrating OSM processes and to assess associated impacts on housing delivery models.

The supporting objectives are to:

- Investigate the issues, characteristics, terms and considerations of using Offsite Manufacturing systems in the UK housing sector. (Chapter 2)
- Identify the factors, indicators, benchmarks associated with the successful delivery of homes in the low-rise housing sub-sector (Chapter 4)
- Describe and test a model dedicated to the evaluation of varied building technologies integrating OSM processes and associated impacts on homes delivery performances in the low-rise housing sub-sector (Chapter 5)

Scope of contribution to knowledge

The research explores the problem of evaluation of OSM performances from the perspective of the project's sponsor (WCH) focused on the promotion of solutions dedicated to the delivery of homes in Hertfordshire, UK. The scope of the research has therefore been limited to restrict the parameters of evaluation of building technologies in view of the local context and urban fabric. The study focuses on low-rise affordable housing projects to be designed, developed and built on small infill urban sites. Findings may be extrapolated to theorise on evaluation approaches to OC performances and associated impacts within varied housebuilding contexts.

Impact

This thesis contributes to knowledge on construction engineering and management through insights on OC implications on housing delivery models with views to facilitate its uptake in current design practices. The description of a speculative evaluation model to be further tested provides opportunities for discussions, improvements and validation as a basis of future research. It is also expected that the project sponsor will be able to use research outputs to inform future developments' procurement strategies and appointments of contractors. Findings could also be shared with industry stakeholders involved in projects of a similar nature to address the general lack of engagement with innovation and nurture current debates on the evaluation of innovative building technologies at a local level.

Structure of the thesis

The research explores the problem of evaluation of OSM performances and associated impacts in housebuilding projects on small infill sites.

The main concepts and definitions related to the implementation of OSM in the housing sector are explored in Chapter 2 through the review of literature. It presents categories of building technologies using OSM processes as well as a summary of current industry practices and debates that includes emerging innovation areas and business practices. It also seeks to discover OC main adoption drivers in the housing sector through a brief review of precedents and policies contexts.

Chapter 3 presents the methodological approach developed to address the problem of evaluation of OSM performances and associated impacts in housebuilding projects on small infill sites through the case study proposition presented by WCH.

Chapter 4 presents introductory notes on the case study proposition and context of data gathering, as well as the stakeholders involved. With views to explore project's team members' perspective on defining success for the delivery of the pilot project, a data collection methodology is developed and described based on a questionnaire survey.

Chapter 5 presents the evaluation model developed to measure OSM performances and associated impacts in housebuilding projects on small infill sites. It describes the rationale underpinning the selection of metrics to assess separately homes delivery performances and the degree of prefabrication of building systems used for superstructure. It also details the primary data collection envisioned to test the evaluation model through the case study proposition.

The conclusion formulated in Chapter 6 reports on the findings and limitations of the research programme and associated case study proposition. It presents critical insights on the implications of implementation of OC in housing projects on small infill sites as well as recommendations for future research.

2. Literature review: offsite manufacture (OSM) in housebuilding

2.0 Introduction.

The purpose of this chapter is to introduce main concepts and definitions related to the implementation of offsite manufacture (OSM) in the housing sector through the review of literature. It presents categories of building technologies using OSM processes as well as a summary of current industry practices and debates that includes emerging innovation areas and business practices. It also seeks to discover OC main adoption drivers in the housing sector through a brief review of precedents and policies contexts.

Academic as well as grey literatures including organizational, institutional and governmental resources were consulted through cross-referencing of bibliographies to identify major publications in order to form a short synthesis of current practices and knowledge. The search strings and terms include: *Off-site manufacture; Modern Methods of Construction; Design for Manufacture and Assembly; Modular Housing; Affordable housing; Pre-fabrication and Pre-manufacture* with inclusion criteria defined as: documents written in English and documents with focus on the residential sector.

2.1 Offsite Manufacture (OSM), definitions

a. Definitions

The term off-site manufacture (OSM) refers to the industrial production of building parts in remote or adjacent-to-site factories environment prior to installation and assembly onsite at their intended location.

Terminology

Whilst the concept is widely known in the popular culture as prefabricated construction, peripheral terms such as offsite production (OSP), offsite fabrication (OSF), industrialized building, system building, factory-built or pre-manufacture are in use in the architecture, engineering and construction (AEC) industry. Offsite manufacture processes and specifications for parts are subjected to a constant nomenclature speculation from industry and academia alike, however the broader term 'offsite construction' (OC) seems to prevail in most recent standards (Goodier, Fouchal, Fraser, & Price, 2019). It has been defined as '*the manufacture and pre-assembly of components, elements or modules before installation into their final location*' (Goodier & Gibb, 2007).

Practices

Quale and Smith have also proposed an extension to this definition in order to include corresponding practices such as “...*planning, design, fabrication and assembly of building elements at a location other than their final installed location to support the rapid and efficient construction of a permanent structure*” (Quale & Smith, 2016). Miles and Whitehouse (2013) took a different approach to defining off-site construction with a focus on value: “*Offsite is a construction term to describe a delivery method that adds substantial value to a product and process through factory manufacture and assembly intervention. The whole objective is to deliver to the construction site elements that are to an advanced state of completion thus removing site activity from the construction process. In some cases, this may be in a three-dimensional volumetric form or more commonly for housing in open or closed panel form.*”

For purpose of clarity, this report will refer mostly to the terms off-site manufacture (OSM) and offsite construction (OC) as defined above with aim to focus on the implications of using various industrialized components in the delivery of housing projects as opposed to on-site construction.

b. Categories

From offsite manufactured primary structural systems to sub-assembly components, the nature and scale of parts to be integrated in building projects show the degree of engagement of projects with Offsite Construction (OC) and suggest different workable implementation strategies.

Levels of OSM

Gibb (1999) categorized offsite construction (OC) into 4 gradual levels: Component manufacture & sub assembly; Non volumetric pre-assembly; Volumetric pre-assembly and Whole building. In the UK, the Housing Corporation (2003) introduced a classification of similar structure to list categories of innovative MMC for housing as an alternative to conventional methods such as bricks and blocks which comprised: 1. Off-site manufactured – Volumetric; 2. Off-site manufactured – Panelised ; 3. Off-site manufactured – Hybrid; 4. Off-site manufactured – Sub-assemblies and components and 5. Non off-site manufactured modern methods of construction (NHBC & Building Research Establishment, 2006).

Modern Methods of Construction

Modern Methods of Construction (MMC) is a term used broadly to describe a wide range of processes that might involve aspects of management of construction as well as description of OSM components (Oliveira et al., 2017). Indeed OC may be considered as falling in the range MMC, but ‘*not all MMC can be regarded as ‘offsite’*’ (Goodier & Gibb, 2007). Overall, there has been some lack of clarity about this terminology and in April 2019, a dedicated cross industry working group of the Ministry of Housing, Communities and Local Government published an official classification with aims to regularize the identification of the spectrum of innovative construction techniques and to allow the generation of structured datasets (MHCLG, 2019). The 7 MMC categories identified in this official terminology are:

1. Pre-manufacturing 3D primary structural systems
2. Pre-manufacturing 2D primary structural systems
3. Pre-manufacturing Non systemized structural components
4. Pre-manufacturing additive manufacturing
5. Pre-manufacturing non-structural and sub-assemblies
6. Traditional building product led site labour reduction/productivity improvements
7. Site process led labour reduction/productivity improvements

Where it happens

This new terminology which describes *'A range of approaches which spans off-site, near site and on-site pre-manufacturing, process improvements and technology applications'* (MHCLG, 2019) emphasizes the distinction between 'offsite' and 'pre-manufacture'. This suggests that manufacturing processes applied to the production of components or sub-assemblies prior to final installation could be carried out and valued independently from the location in which the work happens. Indeed the term pre-manufacturing *'encompasses processes executed away from final workforce, including in remote factories, near site or on-site 'pop up' factories'* (MHCLG, 2019). This definition questions the notion of manufacturing itself as well as the necessary conditions for industrialized processes of production to happen.

The MMC definition framework provides a classification promoting innovative construction methods to better support access to mortgage finance, insurance and assurance. The insistence on the term 'pre-manufacture' also participates in promoting a recent industry metric dedicated to the evaluation of MMC adoption in construction projects, namely 'Pre-manufactured Value' (PMV). The intricate approach to categorization of this framework that mixes up components functions, conditions and locations of production, as well as post completion qualitative assessment -such as labour reduction or assurance improvements- may however limit the relevancy of this terminology for AEC professionals engaged in the design and development phases of projects and systems.

c. Offsite manufacture (OSM) and the concept of labour – productivity

Offsite Manufacture has been identified as pivotal in construction transformations, with potential impact on productivity performance, labour, skills and evolution of business models.

The problem of productivity

Construction has a long record of poor productivity globally (World Economic Forum, 2016). The value added by construction workers per hour of work, otherwise defined as labour-productivity, has stagnated for decades compared to other sectors that engaged with manufacturing or digitally enabled approaches to procurement and supply-chain management. (Mckinsey Global Institute, 2017). The shift of many aspects of building activity away from traditional onsite projects has been identified as one of the main levers to drive productivity improvements in the industry, with benefits of improved certainty, quality or pace and positive impacts on the availability and relative costs of construction labour (Bertram et al., 2019).

The problem of labour

Whilst low productivity, low predictability and lack of innovation have been reported repeatedly in the UK (Egan, 1998; Farmer, 2016), it is now the future predicted labour shortage that is put forward as the main driver for the construction industry to 'Modernise or Die' (Farmer, 2016). In this milestone report, Mark Farmer affirms that the '*real ticking bomb is the industry's workforce size and demographics*' and that the unprecedented scale of the labour model dysfunction with an ageing workforce, the migration of EU workers or the lack of interest from the younger generation is the main driver for change in the industry. Both the controlled environment of OSM factories with improved health and safety/work conditions and the enablement of digital technologies/automation have been identified as a potential to create an appeal to a new workforce including women and young talents that could participate in tackling labour shortages (Farmer, 2016).

From labour-productivity to new practices

Reducing the level of on-site labour requires implicitly to adopt an approach by which design is developed to ease the manufacture of the parts that will form the building and to optimise their assembly on site. These principles are described by the engineering community as Design for Manufacture and Assembly (DfMA) and can be applied in construction projects at all levels ranging from the standardization of components to completely pre-finished volumetric solutions (Ray O'Rourke et.al, 2013). The adoption of DfMA principles underpins efficient integration of manufacturing constraints, elimination of work redundancy and higher productivity performances (Bertram et al., 2019). In 2016, the Royal Institute of British Architects (RIBA) updated their plan of work guidance framework for consultants and clients to integrate the DfMA approach for buildings. The document details the steps of efficient off-site fabrication and onsite assembly for construction projects, and recommend a critical assessment on OSM integration at Stage 2 / Concept Design to test the buildability of the designs (Sinclair et al., 2016). The report also suggests the need for an update of the project team members' roles, for the adoption of digitalization to increase collaboration whenever possible including Building Information Modelling (BIM), and more broadly for a cultural shift in the way of erecting buildings from a construction tradition to assembly principles (Sinclair et al., 2016).

The pressure on productivity and labour in the construction industry together with a wider digitalization and innovation agenda call for the development of offsite manufacture (OSM) at scale and suggest a necessary update of associated business models.

2.2 Offsite Manufacture in Housebuilding, crisis and systems

a. Historical precedents, from crisis to prefabrication

Labour shortages have impacted the construction industry before. Historical records of residential buildings made of prepared components may be associated with major crisis or migrations that formed contexts for experiments on building technologies to be carried out and for a wide range of prefabrication systems to be developed in the UK.

Migrations, skills and ease of assembly

Lightweight, portable and demountable buildings made of prepared components such as tensile structures or covered armature frames have been described through the study of military campaigns or nomadic civilizations (e.g. Prussin, 1997). The need for erecting structures quickly with minimum tooling and skilled labour also characterized the development of British prefabrication during the age of colonial expansion. BRE (2004) notes exports of whole timber-based building systems to North America in 1624 and has records of cast-iron houses being shipped to Australian colonies. In the 1800s, the 'Manning Portable Colonial Cottage', developed by a London carpenter for shipment became an archetype of these colonial home export ventures. It consisted in a series of components easy to carry and which assembly only required unskilled labour without '*nails, joints or cutting*' (New London Architecture, 2018). The relation between transportability and ease of assembly is still debated today as a mean to compare performances of 2d flat pack systems versus 3d volumetric modules with perspectives on traffic movements, embodied carbon or lifting and handling operations requirements.

Labour crisis and ease of manufacture

The ambition for ease of manufacture also defined the development of a wide range of prefabricated systems during circumstances of scarcities. Following both World Wars, the shortage of manpower and trained operatives together with high demands for new dwellings pushed British authorities to research and develop new methods of construction that could use '*labour and industrial capacity normally outside the building industry*' (BRE,2004). The limited range of available materials and the constraints related to the reclamation of industry manufacturing capacity generated new housebuilding technologies using pre-cast and in-situ concrete, steel and occasionally cast iron. BRE's (2004) publication 'Non-traditional houses: Identifying non- traditional houses in the UK 1918 - 75' presents a chronology on the recent evolution of British Prefabricated Low-rise housing, however concludes on the limited scale and scope of these experiments with '*records of over 500 non-traditional construction systems listed in between 1919 and 1976 and with 1000000 homes delivered with these techniques*' (BRE,2004).

Design for whole life performance?

Beyond ease of assembly, ease of manufacture or ease of transportation/logistics, recent historical precedents point to the need of delivering on standardization and whole-life performance. In the context of post war housing in the UK, concerns on defects, decay and maintenance grew in the long term. Difficulties in replacing components intended for temporary use, discontinued or which installation relied on specialist knowledge affected consequently end users with 'Right to buy' commitments (BRE, 2002). Overall, the lack of quality of building materials and general poor workmanship during the post-WW2 period have been pointed at as potential reasons to explain resistance, suspicion and general negative perceptions from the public towards innovative building systems and prefabricated homes (Parliamentary Office of Science and Technology, 2003; O'Neill & Organ, 2016). Lobbying and misinformation on the quality and weathertightness of systems (e.g. 'World in Action' broadcast, 1980) added to the impact of unfortunate accidents such as Ronan Point after a gas explosion in 1968 also affected the market (BRE, 2002).

Brick and Blocks British culture

There can be only speculation about how masonry construction is rooted in British culture as a tradition or symbol of ownerships' longevity and how its prominence has been an obstacle to the development of lighter construction systems integrating prefabrication. As Colin Davies (2005) puts it '*Architecture draws much of its prestige from its linguistic association with all that is solid and reliable*'. Furthermore, it has been noted that home buyers often resist any products that do not resemble a traditional house. (Arif et al., 2017). In the 40s, the *BISF house (British Iron and Steel Federation)* or most widely manufactured non-traditional system as part of the *Ministry of Works Emergency Factory Made housing programme*, had been designated by government officials as 'uglier' than traditional housing (Hayes, 1999; O'Neill & Organ, 2016). In the beginning of the 21st century, following the introduction of the term MMC partly as a mean to avoid the stigma attached to the notion of 'prefabrication', the adoption's rate of innovative building systems amongst housebuilders has been recognizably slow (Rahman, 2014; Pan et al., 2008), despites lobbying and reports of benefits on quality, pace, costs, productivity, health and safety (Pan et al., 2008).

The evolution of prefabricated construction in the UK seems to run in parallel with a history of crisis which may have contributed in forming its reputation as a circumstantial alternative to traditional masonry construction imposed by restricted accessibility to material, tools and labour. Prefabrication still suffers from a poor image and seems to never have been the first choice for Britons.

b. Today's UK housebuilding sector effort

The large number of industry reports on the housing crisis in the UK and the current undersupply of new homes point to systemic construction industry deficiencies in terms of capacity and productivity and suggest new opportunities lying in the re-evaluation of the nation's approach to building (Farmer, 2016).

Housing Crisis

"The housing market in this country is broken, and the cause is very simple: for too long, we haven't built enough homes. Since the 1970s, there have been on average 160,000 new homes each year in England. The consensus is that we need from 225,000 to 275,000 or more homes per year to keep up with population growth and start to tackle years of under-supply. [...]The problem is threefold: not enough local authorities planning for the homes they need; house building that is simply too slow; and a construction industry that is too reliant on a small number of big players." (Department for Communities and Local Government, 2017).

More homes are needed in Britain. The UK gov Housing White Paper stated it without ambiguity: the construction industry lacks productivity and homebuilders are too few (DCLG, 2017). The housebuilding market is also characterized by insufficient capacity, diversity and competition, with SMEs being responsible for just 12% of new homes in 2017 (HBF, 2017; Homes England, 2018). Industry failures in providing an adequate supply of affordable new-build housing to the market using traditional methods of construction have been identified as drivers to develop and adopt MMC at scale (Farmer, 2016). The role of the policy makers in initiating a momentum for the uptake of OSM in the housebuilding sector was highlighted in the Farmer Review (2016) and since the publication of this stepping stone report, the government acted in varied manners to support MMC's adoption through policy measures.

Policy context

The Housing White Paper *'Fixing our broken housing market'* (2017) confirmed the commitment of the Government to *'stimulate the growth of this sector through our Accelerated programme and the Home Builders' Fund'* and to *"support a joint working group with lenders, valuers and the industry"* to ensure access to finance for homes delivered with offsite construction. Inquiries into offsite manufacturing for construction (House of Lords - Science and Technology Select Committee, 2018) and Modern Methods of Construction (House of Commons, 2019) also point to the general increase of interest and knowledge from decision and policy makers. Further, government housing accelerator 'Homes England' is to support the uptake of MMC through dedicated contracts and lead parallel research aiming at gathering a large data set to form evidence of its benefits (Homes England, 2018). As discussed by Zhang et al. (2019) UK government policy documents have supported offsite construction over the past 15 years through long standing themes including *'targets for construction productivity, challenges of labour shortages and skills, desire to learn across sectors and a need to develop new business models'*. Themes in more recent policy reports are developed around digitalisation, BIM or platform approaches, however these don't apply directly to housing. The associated relevancy of cross sector learning was re-affirmed strongly in the latest industry strategy sector deal (HMG, 2018).

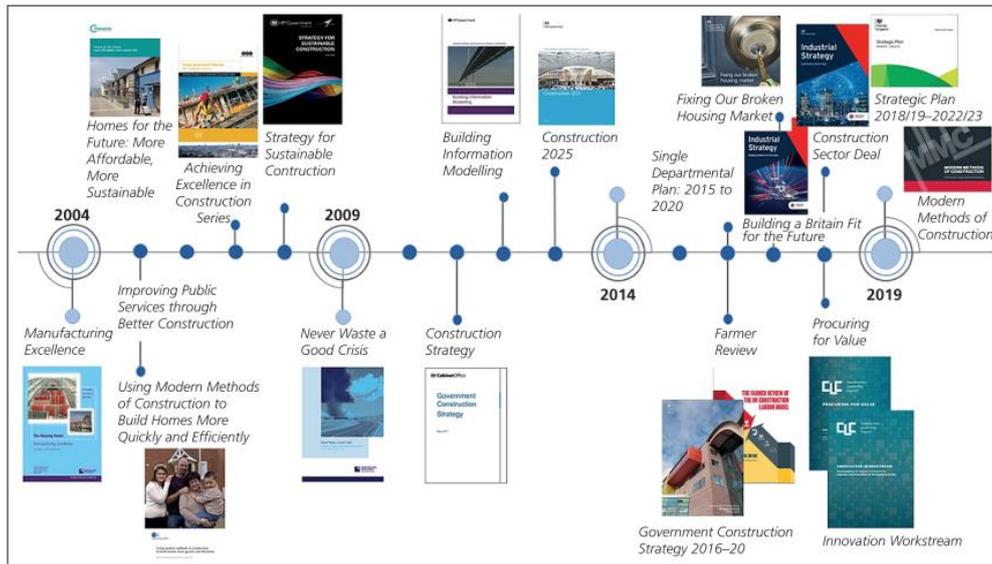


Figure 1: Selected recent UK policies and reports over the last 15 years (Zhang et al., 2019)

Cross sector research efforts

A vast on-going challenge aiming to ‘*Transforming Construction*’ managed by UK Research and Innovation (UKRI) is bringing together the manufacturing, construction, digital and energy sectors to support the development and adoption of technologies to enable ‘*buildings to be constructed 50% faster, 33% cheaper and with half the lifetime carbon emissions*’ as mentioned in the construction sector deal (HMG, 2018). Industry and researchers are being brought together by the Construction Innovation Hub (CIH) to look at reviewing and implementing approaches from other sectors in collaboration with organizations such as the Manufacturing Technology Centre (MTC), the Building Research Establishment (BRE), the Centre for Digital Built Britain (CDBB). The Active Building Centre together with university of Warwick is also specifically looking at ‘*energy generation, storage and release technologies*’ (UKRI, n.d.). Research on emergent technologies and associated business models has been described as intertwined and critical for future industry transformation. (Zhang et al., 2019).

Circumstances call for construction and housebuilding to being transformed at scale in the UK to reach homes delivery targets. Whilst policy makers, industrials and academics are coming together in an unprecedented effort to support innovative technologies and business models, development strategies and research priorities are still widely debated and suggest a fragmentation of knowledge that resonates with the industry’s reputation.

c. The moment for technologies

Though the concept of prefabrication is not new and ‘*must undoubtedly have been known to some of the earliest human societies*’ (New London Architecture, 2018), recent progress in digital technologies, advanced automation and data driven work models form new conditions for the development of offsite manufacture (OSM) processes for the construction sector.

About industry 3.0

As Colin Davies notes about the production of *the Prefabricated Home* (2005): *'the twin revolutions of lean production' and computer-aided manufacture (not necessarily connected) have transformed modern industry. Mass-production of the old, Fordist kind is dead'*. Supposedly, offsite construction for housing shouldn't be about repeating identical standard dwellings in large volumes. Engineers from automotive brand Toyota proved in the past that the 'lean' factory could adapt to customers desires and deliver different cars' models through the same assembly line. Lean approaches aiming at the reduction of complexity and uncertainty by reducing waste and non-value-adding activities follow core principles: alignment of resources, material and information flows; coordination and harmonization of takt speed; just-in-time pull of resources and materials; continuous improvement of processes line (World Economic Forum, 2016). These ideas have been implemented in housebuilding by a range of companies including Toyota and Japan is considered as world industry leader in the prefabrication of homes.

Numerically controlled machine and CAD/CAM technologies have come to enable more straightforward links in between automated manufacturing and design and to ease the implementation of 'lean principles' for the delivery of cost-effective mass customization (Arif et al., 2017). With benefits of eliminating re-work and miscommunications on specifications, design practices integrating precision manufacturing can also lead to better optimization of material sizes and cutting, lower wastage of material, improved finishes and fewer defects (Ross, 2002). Most advanced automation processes are however factory-based, and the shift of building activities offsite remains a challenge despite the potential benefits of increased productivity. About the adoption of CAD/CAM in the UK, Mark Farmer states: *'in many respects, construction has not even made the transition to "industry 3.0" status which is predicated on large-scale use of electronics and IT to automate production'* (Farmer, 2016).

The factory of all trades

Automation is not to replace all traditional trades, but the advantages of shifting the latter into the factory's-controlled environment should not be underestimated. Operations such as tiling, plumbing, wiring or sub-assemblies as observed in manufacturers' premises are likely to be delivered through traditional methods only with further accuracy and quality. Chen et al. (2008) found the lack of tolerance standards between trades to be the main reason for elements not fitting together and interfaces, joints and connections have been identified as *'the most common contributors to construction problems'*. The reunion of multiple trades in the factory with provision for more tooling, reliable material storage, dust free environment is to favour the improvement of assemblies and finishes and the overall reduction of tolerances. Indeed a market is growing for 'room components' such as kitchen and bathroom volumetric pods integrating multiple trades and services testing prior dispatch as an alternative to traditional labour-intensive delivery in situ and as a way to lower latent defects and time consuming snagging work onsite (Ross, 2002). Offsite manufacture also enables the possibility of carrying out different phases of work simultaneously in a non-linear building sequence and reduce the overall build programme duration.

Concepts such as 'flying factories' have also been developed to apply lean manufacture principles in close-to-site, temporary and flexible factory environments. As an example, major contractor Skanska's venture to set up a factory next to their Battersea site in London to produce utility cupboards resulted

in significant savings as well as added social value through the employment local semi-skilled labour (Sinclair et al., 2016)(World Economic Forum, 2016).

Integrated use of digital technologies

The necessary interconnectedness for the implementation of common data environments represents the next challenge for construction to reach industry 4.0. Building Information modelling (BIM) which provide an environment for sharing digital models of a project down to the detail of every component has been identified as to positively impact construction management and decision making through eliminating work redundancies or facilitating precision in bills of materials (New London Architecture, 2018). Through enabling comprehensive workflows between different disciplines, BIM also provides a support for the assessment of components compatibility and for iterative communication loops between design teams and manufacturers (Abanda et al. 2017). The standard described as 'Level 2 BIM collaborative 3D modelling' now required for all government building projects is progressively being adopted by AEC professionals. However, discrepancies on tolerances, issues on disclosure of proprietary components details, intellectual property, and lack of testing protocols have been identified as to limit the creation of common data environments (Goodier et al., 2019). Further, evaluation studies on the impact of BIM on the implementation of OC are scarce and evidence on benefits are lacking (Abanda et al. 2017).

Combined with immersive technologies such as augmented-reality and virtual-reality (AR/VR), BIM could also support assembly processes through 3d visualization of sub-assemblies' components positions and post construction inspections (Mckinsey Global Institute, 2017). Related research on the concept of physical building digital duplicate or digital twin is being carried out in the UK by the Centre for Digital Built Britain (CDBB) at the University of Cambridge. Other technologies such as GIS, sensors and drones have also been mentioned as instrumental in the delivery of near-perfect surveying and geolocation (Mckinsey Global Institute, 2017).

Digitally enabled projects workflows

Data driven models are also used in construction to manage supply chains, transportation route planning, deliveries and components tracking. America based start-up Katterra has raised significant investment to develop a fully integrated digital solution with focus on '*leveraging insights from data in all stages of the construction process*' (Sinclair et al., 2016). The company recently launched a dynamic global sourcing model to help develop a supply chain for products and building materials in relation to potential market disruptions and '*predictive replenishment of supplies informed by inventories connected to the Internet of Things*' (Bertram et al., 2019). There is growing interest in data driven logistics management that enable operations such as just-in-time inventories or on-time deliveries and the recent involvement of company Amazon in the housebuilding sector suggests the relevancy of these new technologies in future practices (Bertram et al., 2019). Other examples of digital platform-based ecosystems focusing on the enablement of project workflows include software solutions from Autodesk, Bentley Systems or Trimble.

A plethora of digital tools are gradually being made available as new propositions for the construction industry to embrace. Whilst some of these technologies are integrated within construction businesses or available on the market as closed software, the evaluation of standards and practices is challenging

but appears critical to understand further the impacts of common data environments on building projects inherently collaborative. In the housebuilding sector, the impact of digitalization and data driven models on the development and implementation of offsite manufacture processes is yet to be evidenced at scale (Burgess et al., 2018).

2.3 Current practices

a. Delivery models

OSM has been identified as indeed strategically critical to build homes more quickly and more efficiently by multiple professional and governmental bodies in the UK and ventures in the sector are progressively evidenced and documented.

The new role of manufacturers

NHBC Report *'Modern Methods of Construction: Who is doing what?'* (2018) lists a wide range of approaches being researched and adopted by developers of new homes from vertically integrated manufacturing capability to exclusive partnerships with suppliers or proprietary product development. It confirmed an increasing level of engagement of industry partners with MMC driven by both ambitions of tackling the skills shortage and building more high quality homes (Hannah et al., 2018). OSM is by nature dependent on big capital investments to fund the development and operation of factory, machinery and digital infrastructures. The role of manufacturers is also becoming more significant as they need to integrate traditional 'wet and hot' trades, engage with clients from Concept Design stage despite projects uncertainty (Sinclair et al., 2016) and address *'design performance in order to deliver the more complex building solutions that they are manufacturing and offering as complete, turnkey solutions'* (Goodier et al., 2019). Resulting upfront costs and efforts suggest increased risks during operations and procurement calling for necessary evolutions of projects team roles and business models in parallel to the development of new construction methods (Lang et al., 2016).

Procurement processes

Large UK corporate players such as Berkeley Homes, Legal & General Homes or Ilke Homes are already operating from end-to-end through a 'housebuilder-developer-manufacturer' model as a proposition to retain control of supply chains, mitigate the risk of material and skills shortages and maximise income streams and return on investment. (Hannah et al., 2018). Other modes of delivery of prefabricated housing have been defined by the role of the client in the procurement process as:

- Assemble to order strategy, pioneered by Japanese housebuilder Toyota homes and Sekisui and developed around in-house design teams and partnerships with manufacturers and suppliers (Barlow et al., 2003; in Oliveira et al., 2017).
- Entire subcontracting process, through client's supervision of a team of contractors or order of turn-key solutions (Hsieh, 1997; in Oliveira et al., 2017).
- Joint ventures, with strategic partnering between housebuilders and manufacturers (Blackman 2007; in Oliveira et al., 2017).

The question of accessibility to industrialized housing

Achieving economies of scale in low-rise developments of limited size proves challenging with regards to the level of duplication needed for OSM suppliers to optimize production and secure returns on 'factory' big capital investment (Miles & Whitehouse, 2013). Whilst volume housebuilders with vertically integrated OSM capability are pushed to favour the repetition of proprietary 'pattern book unit' types resulting in blandness of schemes and lack of systems inter-operability (Lang et al, 2016), the rest of the supply chain is fragmented and collaboration ventures suffer from the lack of common knowledge (HCA, 2010; Pan and Goodier, 2012). Within the current trend towards OC among UK housebuilders, organisation-specific systems specifications tend to rely on in-house specialist knowledge and this results in 'lock-in' for the supply chain, preventing third party involvement in building delivery, 'service life' and 'design life'. To ease components and services exchange, modification or substitution, innovation towards the formation of new commonalities in design approaches and standards (Goodier *et al.*, 2019) can support vertically de-integrated ecosystems. This in turn underpins the idea of Platform Design for Manufacture and Assembly (P-DfMA), in which independent actors co-create value through the sharing of compatible knowledge.

While emerging Platform approaches have been identified as a strategy for components' marketplaces to be created and for a wide array of SMEs to compete and collaborate dynamically in the implementation and perpetual improvement of industrialised construction solutions (Bryden Wood & CDBB, 2018), the effort toward application in the housing sector is in its infancy. Large scale deployments of platform(s) knowledge and specifications in housebuilding may then present areas of opportunities for future development based on scopes for 'demand economies of scale' and network effects. Other innovative initiatives of collaboration such as *Renkap* (New London Architecture, 2018) or Building Better have also emerged to tackle this and generate propositions of demand aggregations that '*combines housing association pipelines to leverage the benefits offered by offsite manufacturing*' (Entwistle & Nicholls, 2018).

Whilst offsite construction is being developed through different routes in the housebuilding sector, vertical models integrating manufacturing capability within large corporations seem to mitigate best the risks associated with the large investments needed to fund factory and operations. The update of construction standards may ease OSM accessibility as well as participation of the wide array of SMEs currently active in the industry.

b. Building systems for low-rise housing

Offsite manufactured components are already implemented in the construction of low-rise housing projects, described as under 6 storeys (MHCLG- MMC working Group, 2019) and even traditional construction uses prefabricated components by default for applications commonly including pitched-roof structures with truss rafters or windows and door frames... This shows that the housebuilders are receptive to offsite construction solutions when it is in their commercial interests (Miles & Whitehouse, 2013) despite the bad reputation of the sector described as technologically 'lagging behind' other countries. (House of Lords - Science and Technology Select Committee, 2018)

Accreditations

With aims to de-risk the adoption of OC and ease access to finance and assurance, a group of organisations (BuildOffsite, BLP, RICS, Lloyd's register) set up the BuildOffsite Property Assurance Scheme (BOPAS) in 2013 as an accreditation system to certify the durability of non-traditional methods & materials for at least 60 years. There are currently fewer than 70 BOPAS accredited operations that can be classified according to systems types, all suitable for low rise housing:

- Timber frame systems, 11 certified systems
- Light Gauge Steel Frame, 9 certified systems
- Modular, 28 certified systems
- Other panelised, 7 certified systems
- Cross Laminated Timber, 6 certified systems
- Structural Insulated panels, 8 certified systems

The National House Building Council (NHBC) is also carrying out assessments relative to their Buildmark Warranty Cover scheme and propose a list of accepted systems for the construction of homes classified through type and materials that include:

- Volumetric: 2 x Light steel frame / 1 x CLT
- Panellised: 3 x Timber / 3 x SIPS / 18 x Light steel Frame
- Site based: 1 x permanent formwork / 11 x Insulated concrete form / 2 x timber / 3 x Thin Joint block work / 1x Aerated autoclaved concrete

Few updated construction standards apply to OSM and systems tend to be designed and manufactured as 'one off' through circumstantial selection of relevant regulations on thermal, acoustic, fire performance etc (Goodier et al., 2019). Detailed information on components may also be difficult to access due to manufacturers' concerns on Intellectual Property. The lack of open standards and transparency has been described as to cause difficult integration and connections of different materials/systems, limit flexibility and increase risk in the market place (Goodier et al., 2019). The development of new standards has also been identified as potentially triggering shared leanings and perpetual improvements of systems by incorporating lessons learnt.

Low-rise residential pilot projects

While OC adoption has progressively increased in the housing sector, multiple research and development efforts support the development, demonstration and monitoring of systems. A range of residential full-scale buildings with innovative approaches is on display at the BRE Innovation Park (BRE, n.d.). Initially constructed for the 2005 '*£60K challenge*', the projects' selection evolved according to relevant standards and now includes amongst others the 'Green house' from Barratt, the 'Sigma house' from Stewart Milne Homes and 'Zedpods'. One of the biggest housing association in the UK, Home Group set up a live research project supported by Homes England aiming at comparing five different types of MMCs together with traditional brick and mortar. A total number of 41 affordable homes were delivered in Spring 2019 with building systems including different volumetric solutions, light gauge steel kits, hybrid timber frame/SIPs kits or Aerated Autoclaved Concrete kits. The homes are to be monitored at varied stages including post occupancy at 3, 12 and 36 months and reports on products and systems performances are awaited from research partners BRE and Northumbria University. As part of the Advanced Industrialised Methods for the Construction of Homes (AIMCH) initiative funded by Innovate UK aiming at developing new digital design tools and manufacturing

advancements, further offsite systems are being trialled and monitored through live housing projects. (<https://www.aimch.co.uk/>).

Innovation on building systems for the low-rise housing sector also includes multiple additive manufacturing experiments around the globe. Though not directly involving offsite components, concrete 3D printing applications in housebuilding are relevant in bringing perspectives on the evaluation of technologies adding value through ‘made it local, made it bespoke’ approaches and the engagement with local labour. Among pioneering initiatives, the project Yhnova in Nantes printed with 2 layers of insulating foam as a cast for concrete is now inhabited by a family and a large number of 3d printed shelters have been delivered recently by American start-up ICON. The exponential possibilities in mass-customisation are yet to be explored, however the application to multi-storey building is yet to be evidenced and the lack of maturity of technologies is still seen a barrier to volume housebuilders adoption.

Digitally aided decision making

As OSM market propositions develop rapidly in a complex market, tools are emerging as decision-making aids for professionals and clients. A digital design tool to support the adoption of MMC in the delivery of homes for Londoners commissioned by the Greater London Authority (GLA) was developed under the name of PRISM as a ‘browser based, free to use, user friendly’ app launched in June 2019.

PRISM presents users with the opportunity to deliver feasibility assessments on different systems types for specific projects through straightforward location-based 3D modelling with configurable-criteria such as floor height, units’ sizes, or program preferences to meet the developer requirements. Integrated analysis tool enables checks for conformance with London standards, optimisation of surfaces allocation, and review of MMC suitability. The guidance on systemisation appear to be driven by the confrontation of projects specifications such as height, spans, external walls to modules and components capabilities most commonly found on the market, however the precise formulation of this ‘learning’ algorithm is not revealed. While this offers a basic tool to start early site evaluation with built-in knowledge, it might result in an innovation conundrum where past approaches to typologies and systems’ design limit the app’s users’ perspectives on projects parameters and innovation sometimes associated with digital platforms. Added to the lack of options on export format that could avoid redundancies in iterative processes of work, the digital environment proposed seems to prioritise knowledge sharing dedicated to the developer community and support for consultants lobbying (<https://www.prism-app.io/>).

Whilst professionals are trialling different processes from design to assembly to make a difference in the construction of homes, the questions of how to monitor projects and feed common data sets on performances appears critical to nurture a virtuous cycle of improvements in this ‘lagging sector’.

2.4 The metrics

a. Challenges in evaluating construction methods for housebuilding

Productivity and labour are pointed at (qualitatively and quantitatively) as main drivers for construction to be transformed and for OSM adoption to increase. Despite these industry statements, the assessment of good practices presents challenges and disparities exist on the formulation of evaluation protocols associated with the comparison of building systems performances.

The value of addressing labour shortage

Historical examples showed that prefabricated systems have often been developed as responses to crisis during which accessibility to material, tooling and labour was restricted (see chapter 2.a). These constraints led to the development of housing production processes focused on the ease of manufacture, ease of assembly or transportation which suggest that the benefits of prefabrication were then circumstantial. If the industry today faced with a dysfunctional labour model is to 'modernise or die' (Farmer, 2016), strategies to address workforce shortages including the transfer of building activities in factories should be at the core of building projects evaluations to capture knowledge supporting the pollination of good practice.

While stating that '*local labour is not available in the right quantity and at the right time*' to carry out site-based activities in most building projects efficiently, BRE (2002) lists positive social impacts of factory-based production such as bringing employment in areas where needed or with good transport links, reducing operatives commute and fuel use, improving work conditions and health and safety leading to more training opportunities, creating new technology-based skilled labour roles. These potential benefits of OC are also referred to by an engineer from Laing O'Rourke commenting on work in their factory: '*One of the key reasons that we've been trying to measure productivity and activity as we go offsite is the churn of labour that we have. [...] Our factory churn is quite stable. People quite like it because they're still working in construction but they're in one place, which is warm and dry, and they can work near their homes*' (RICS, 2018). As the CLC Smart construction guide for clients summarizes, '*It's not just productivity we need to be concerned about*' but housing innovations and evaluations should be driven by improving wellbeing and opportunities for both the workforce and the end-users (Construction Leadership Council, 2018b).

The Metrics audience

Challenges in evaluating housebuilding also arise from the large number of projects team members '*superimposing their own definition of value onto the project*' (Pasquire, Gibb, & Blismas, 2005). Principles of Lean which are based on the elimination of non-value-adding activity for the end user suggest that emphasis should be made on evaluating what the building does. Indicators such as sustainability, whole-life performance, quality, aesthetics or customization of dwellings may inform

the 'use value'. However, Oliveira (2017) reports that post occupancy studies of MMC homes have been overlooked and that little data exist on residents' preferences or expectations.

The economic constraints driving the current production strategies of private housebuilders, who deliver most new housing, appear to restrain change in assessing value of homes delivered (Lang et al., 2016). For example, Miles and Whitehouse (2013) report that there is no interest from housebuilders in faster build time or improved quality in the delivery of projects because production should be adapted first to suit sales rate and borrowing financial agendas. Whilst location and price are identified as main concerns for buyers, housebuilders have no '*commercial advantage in constructing new homes to a level of performance above the basic requirements set by Regulations*' or in improving levels of quality that would disrupt sales value of homes commonly set in comparison with neighbouring properties (Miles & Whitehouse, 2013). The first report of the AIMCH initiative reviewing productivity evaluation protocols also recommend caution on imposing a rigid set of performance metrics to stakeholders who might pursue different strategic objectives (Horner et al., 2019).

Cost is everything

The choice of a construction method is likely to be based on cost rather than technology and '*It is the price point that is all important to house-builders*' (Miles & Whitehouse, 2013). '*There continues to be a climate, within construction, of benefit evaluation based almost solely on cost. Non-monetary benefits and disbenefits of the construction process are merely alluded to, or disregarded*' (Blismas et al, 2006). The focus on costs rather than value consequently limits comparisons of traditional construction with OSM solutions that often come with higher upfront costs and broader benefits. Blismas (2006) details '*pure direct cost comparisons will favour traditional on-site operations that are costed on a rate-based system, with overheads, access, crantage, repairs and reworks hidden within preliminary costs. OSP costs are usually presented as all-inclusive amounts with a premium for off-site overheads.*' However, evaluating benefits of construction methods in monetary terms can be advantageous in enabling comparisons with further items in financial appraisals and overall profitability. Detailed evaluations of costs could also support in-depth assessments, such as insuring that savings from shifting activities to the factory outweigh logistics costs (Bertram et al., 2019) .

Overall, value assessments of construction methods for housing appear to require different approaches at industry and organizational levels, though the later seem to have been overlooked (Wei Pan, Gibb, & Dainty, 2012). On one hand, policy makers are supporting improved capacity and quality, whole life performances, health and safety, workforce training and resilience, sustainability, energy efficiency or net zero carbon agenda (UKGBC, 2019) whilst on the other hand, housebuilders are pushed to maintain current profitable practices that can accommodate market fluctuations as well as financial and legal constraints..

b. Construction metrics sets to assess offsite vs Trad'

OC benefits

Increase of predictability and pace, delivery of better quality & less defects, reduction of wastage and local disruption, improvement of health & safety and work conditions are some of the benefits of OC commonly reported (e.g. Miles and Whitehouse, 2013, RIBA, 2016, House of Lords, 2018). Advantages and disadvantages of OSM adoption in key literature have been summarized by Whitehead in Figure 2 (2018; in Pryce, 2019).

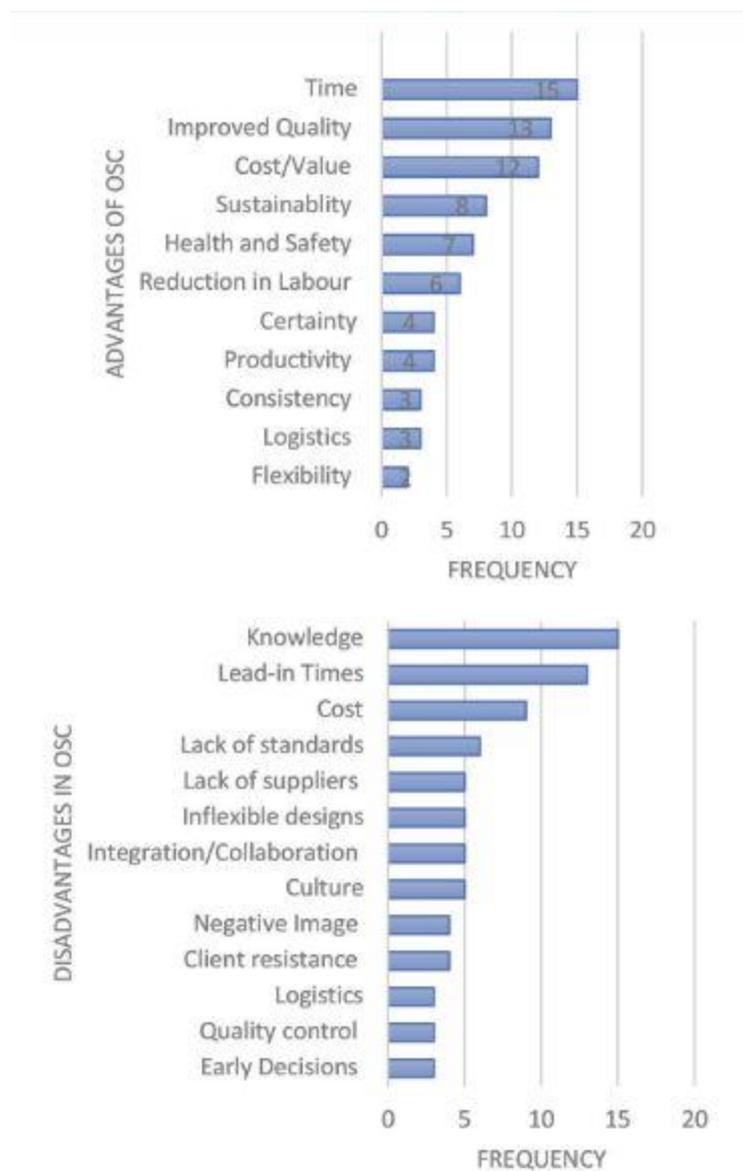


Figure 2: Advantages and disadvantages of Offsite Construction (from Whitehead,2018; in Goodier et al., 2019).

The diversity of potential benefits at either organizational or industry levels suggest challenges in the definition of standard assessment protocols. Whilst providing a straightforward set of KPIs for housebuilding projects, the Construction Leadership Council notes: *‘There are some areas such as risk, wellbeing design and circular economy where there are currently no quantitative measures in place and as a result are looked at on a qualitative level’* (2018a). Abundant and discordant literature on OC suggest difficulties in consistent quantitative assessments detached from projects circumstances and client perceptions.

Metrics sets on construction methods, offsite vs trad’

In *‘What you should really measure if you want to compare prefabrication with traditional construction’* (Pasquire et al., 2005), a framework for the measurement of risks and benefits of prefabrication is described as part of the decision making aid toolkit IMMREST, or Interactive Model for Measuring PRE-assembly and STandardisation. In total, 97 detailed items and considerations are referred to and classified into 6 main categories: Cost (49) / Time (6)/ quality (13) / health and safety (12)/ Sustainability (9) / site benefits (8). To address decision making still largely based on anecdotal evidence, the report identifies differentials between the data required and the data usually recorded as a driver for innovation on information management processes in housebuilding organizations.

Concise approaches to the evaluation of construction processes based on technology-blind outputs have also been developed to assess production against Government-led targets for housing in terms of *‘delivering the numbers required to the necessary timescale (time), in the right place and of the right quality (quality), at prices people can afford (cost)’* (NAO, 2007). The NAO described a strategic approach to evaluation focused on performances indicators that drives behaviour of decision makers and that builds on existing knowledge to ease partners engagement. More recently, a set of KPIs focused on tracking innovation in housing projects was developed by the Construction Leadership Council (2018a). to encourage organisations to participate in forming robust benchmarks on: Capital cost, speed, productivity, Pre-manufactured value, quality, Health and safety, Embodied carbon, In-use energy, Waste generated, number of homes completed.

Productivity

Labour productivity has been identified as a performance indicator relevant to the whole construction sector and defined as the value added by construction workers per hour of work or the ‘output in terms of structures created minus purchased materials’ (McKinsey Global Institute, 2017). The AIMCH (Advanced Industrialised Methods for the Construction of Homes) initiative led by a consortium of key industry partners identified productivity or the ‘ratio of output to input’ as critical in assessing OSM processes and commissioned a dedicated research on associated metrics. The report presents a review of numerous ways of recording productivity and recommend amongst other the use of:

- Output of physical units on total hours paid
- Output of physical units on available hours worked
- Output of physical units on productive hours worked

- Labour hours per plot.

Maybe as a sign that productivity can't be assessed in isolation, findings were complemented by an additional review of metrics on Safety / Productivity / Quality / Cost / Time / Predictability / Efficiency / Material waste. Notice was made of the metrics set published by the Construction Leadership Council (2018a) described as a reference document which refers to productivity in terms of £/man/hour.

There has been much discussion on how to measure OSM implementation for housing. Overall, difficulties in collecting data with high granularity whilst balancing circumstantial factors and embracing the diversity of components and systems in use appear to inhibit the development of a comprehensive systematic evaluation system (W. Pan, Gibb, & Dainty, 2008).

c. The degree of prefabrication

Whilst new offsite systems and propositions are emerging for the housing market, most buildings are delivered with some prefabricated components already. This supports evaluation strategies considering the degree of prefabrication of structures as weighty to compare a range of building systems may they be considered MMC or traditional.

Proportion of prefabricated parts

Prefabricated parts are commonly used in the construction of homes and may include windows & door frame, cabinets sub-assemblies, or truss rafters for the delivery of pitched roof structures (Construction Leadership Council, 2018b; Greater London Authority, 2017; New London Architecture, 2018). Despite highlights on evolutions in the deployment of prefabricated components over the past 15 years, *'from building element (framing, panel and cladding) solutions to more complete volumetric solutions with an associated increase of premanufacture value'* (Zhang et al., 2019), there is limited quantitative evidence on the degree of prefabrication of projects. There is also confusion about the levels of assembly or sub-assembly appropriate for components to be assessed either as premanufactured or as a material listed in bills of quantities.

Pre-manufactured value (PMV)

The pre-manufactured value was promoted in the Farmer Review (2016) as a metric to quantify the extent of offsite construction in projects through a calculation aiming at *'measuring the proportion of a project made up of on-site labour, supervision, plant and temporary works'* (MHCLG, 2019). The PMV is now included in the industry standards described by the Construction Leadership Council (2018a) as: *'the value that is created as a result of completing work away from the site. It is calculated by taking the gross capital cost of the project and deducting the prelims - sometimes referred to as site overhead costs - and the site labour costs. The result of this is then divided by the capital cost and is reflected as a %'*. Therefore, many factors impact the percentage of PMV in projects. While data collections with

suitable granularity might be challenging, the metric can enable original analysis of the construction performances of projects with similar PMV to understand where OC delivers value with consistency.

D-fMA and Component-based evaluation

As an alternative to the evaluation of project outputs at completion, it appears interesting to acknowledge assessment tools available to AEC professionals to monitor and optimize both ease of manufacture and ease of assembly in the development of building systems. Laing O'Rourke has developed an approach to Design for Manufacture and Assembly (DfMA) to deliver high quality construction products such as concrete floor slabs elements, structural columns and modular plantrooms in their factory together with a dedicated set of metrics to track the degree of DfMA applied in projects (RICS, 2018). This 'Pre-assembly calculator' (PAC) allows evaluation against delivery targets of the firm described as *'70% of any given project is constructed using DfMA, leading to a 60% reduction of onsite labour and a 30% reduction in programme – all in comparison to a traditionally constructed alternative. It is also aiming for zero accidents and towards-zero carbon emissions'* (Ray O'Rourke et.al, 2013; RICS, 2018).

Examples of dedicated evaluation protocols for DfMA in large scale high-rise or infrastructure projects built with a component-led approach refer to criteria such as simplicity of design, number of components, standardization on elements and ease of handling (e.g. Purnomo Safaa, Utomo Dwi Hatmoko, & Purwanggono, 2019)(Gao, Jin, & Lu, 2019). The London high-rise landmark project 'Two Fifty One' described by Laing O'Rourke as a kit of 8436 prefabricated components, assembled to deliver the 36,554 m² gross internal area was monitored at component level to nurture perpetual improvement of systems (Banks, Kotecha, Curtis, & Al, 2018). Overall, component-based approaches to evaluation of the degree of prefabrication suggest that calculations correlating number of components with resources needed to manufacture and assemble them are to be complemented with significant qualitative data to make sense of it all.

Measuring the degree of prefabrication of systems appears critical to understand current building technologies developments, however the assertion of PMV as industry standard to generate big data with a suitable degree of granularity is yet to be evidenced.

2.4 Conclusion

The multiple definitions and classifications associated with the shift of building activities offsite have brought some confusion on the identification of benefits to be realized to address the poor productivity, labour shortages and lack of innovation often associated with the construction industry. In the past, prefabrication practices affirmed themselves as alternatives in moments of crisis but struggled to surpass this status in a housebuilding sector sometimes described as conservative and driven by the market & traditions.

Today recent progress in automation, digitalisation and data driven models however form new conditions for OC to be developed in parallel with new housebuilding business models and to embrace contemporary agendas on housing provision, sustainability or improvement of labour conditions. As the adoption of innovative building technologies integrating OSM in the housing sector is gradually progressing in the UK, the problem of evaluation of these new practices is pressing.

Existing value assessments of building technologies entail varied approaches at industry and organizational levels, and difficulties exist in collecting data on OSM with consistency whilst balancing circumstantial factors. Measuring the degree of prefabrication in projects appears critical in assessing construction systems impacts and perpetual improvements, however the use of Premanufacture Value (PMV) as an indicator does not provide much granularity or precise insights into OSM performances.

As a per to illustrate the conundrum of evaluating construction practices, Keith Waller, Programme director of the Construction Innovation Hub (CIH) comments: *“Yes, we should be designing for a modern delivery process consistent with digitally-enabled manufacturing and assembly. But we should also design for sustainability, for resilience, for whole-life performance; we should design to build in flexibility, accessibility, interoperability and security-mindedness; we should be supporting communities, building capability and opening opportunities for local business. We should use smarter, shareable data that drives performance and informs decision making. And much more. Therefore, we shouldn’t be designing just for manufacturing and assembly; we should be designing for all of the factors above, the sum of all of these parts – DfΣ”* (Waller, 2019).

3. Methodological approach

3.0 Introduction

The purpose of this chapter is to address the question of the comparison of performances of OSM building systems in low-rise housing projects. It presents methodological considerations related to the context of the research programme as well as the approach designed to collect and analyse data from the associated case study, i.e. the development of low-rise affordable housing on 6 small sites in Hertfordshire, UK.

3.1 Methodological approach rationale

Industry-led considerations specific to the study formed the context in which methodology was approached. Secondary data collection from a desk-based literature review covered earlier-on in this thesis (chapter 2) identified practices and knowledge on the evaluation of buildings' systems performances supporting a mixed-methods approach to address the research question.

Mixed methods approach to the evaluation of building systems performances

Consistency in the evaluation of building systems' performances presents inherent challenges due to the numerous factors at play during the phases of design and implementation. The varied contextual circumstances of reception of the data are also to be considered as mentioned in the previous chapter. The research programme carried out in parallel with a live housebuilding project was driven by the objective of informing the main client's strategy for future developments and appointments of contractors. This context weighted on the approach to research methods in order to link the specificities of this housing project with the development and testing of a theoretical evaluation model. As a result, both qualitative and quantitative data were thought relevant to the study.

Case study opportunity

The organisational structure of the case study project was defined by a single client working with a single manufacturer and a single main contractor to deliver different construction systems for 6 housing projects with similar programmes. The resulting reduction of variables permitted the focus on factors that could enable noteworthy comparison in between the 6 buildings. It was anticipated for example that data on groundwork by nature site-specific wouldn't allow meaningful analysis and that service-based components or appliances could be discarded if confirmed as identical in the detailed specifications. Consequently, both qualitative and quantitative data collection were to focus on the erection of superstructures only, including components such as windows, fit outs and finishes to be examined with regards to the detailed design specifications. As design work at planning stage did not integrate consideration for any specific building technologies, both qualitative and quantitative data collections were to disregard all activities prior the Technical Design phase (RIBA stage 4). Whilst defining metrics and methods of measurement, a degree of practicality had to be considered based on the resources and data thought to be available. Whilst analysing results, it must be noted that the case study project was initiated by the client as an experiment to trial building systems, and that the inherent risk involved for the project team members may be reflected in lower performances throughout the delivery programme.

Industry-led study

Despite being based on a main case study, data collections and analysis forming this research programme aimed at adding knowledge on the subject of the evaluation of building systems for housebuilding with a degree of prefabrication. It was therefore relevant to link the data collected with existing assessment protocols or industry metrics in order to add a supplementary opportunity for comparison with existing benchmarks and broaden the scope of analysis. The methodology adopted also reciprocally aimed at presenting data in a format that could be readily shared with industry stakeholders, including the housing association sponsoring this research. The review of existing literature focused on the identification of industry metrics in use and drivers for OSM adoption use was instrumental in this matter.

Ethical considerations

The arguments pursued in this research were underpinned by the objective of providing evidence to inform decision making on the construction of low-rise housing projects. Whilst it seemed meaningful to gather perspectives of project team members with experience in this field, it didn't appear necessary to name them neither individually nor through their company. It is understood that this information is accessible from other sources and therefore not confidential, however, the disclosure of anonymity of the project team members didn't support any insight in the data analysis. The University's ethics approval procedure was followed through the development of the questionnaire survey and all participants formally invited in participating were to be given a consent form for their consideration and full acceptance prior proceedings. Also, requests for data in the construction phases were to be submitted to the contractors, manufacturers and clients leaving disclosure at their discretion.

3.2 Methods for data generation

This section introduces the research methodology design and maps up the associated process for data collection throughout this study. It describes preferred qualitative and quantitative methods for the collection of primary data as well as practical alternatives involving secondary data.

Data generation process

The relevancy of combining a range of research methods such as questionnaires, interviews and case studies has been recognised (De Vaus, 2002). To address the question of the evaluation of the performances of building systems integrating OSM processes, research methods associated with the distinct objectives previously described were mixed.

- To Investigate the issues, characteristics, terms and considerations of using OSM systems in the UK housing sector, a desk-based literature review was conducted to collect secondary data supporting an analysis of OSM adoption drivers and housing key performance indicators (chapter2).

- To complement literature review findings on factors, indicators or benchmarks associated with the successful delivery of homes in the low-rise housing sub-sector (chapter 2), a survey was designed to collect perspectives from the professionals involved in the main case study on which this thesis is based (chapter 4) and support the development of a contextualised metrics set. As practicalities such as time and resources availability made face to face interviews impossible, an online questionnaire survey format was proposed. However, null results led to the adoption of an alternative approach to engagement with industry professionals at the end of the study in order to gather views on the evaluation model described in chapter 5.
- To describe and test a model dedicated to the evaluation of varied building technologies integrating OSM processes (chapter 5), findings from the literature review (chapter 2) were compiled as a framework. The model is designed to be applied and tested through the collection of primary data from the 6 building projects forming the main case study proposition, however an alternative testing method involving secondary data extracted from industry sources is also described. Results are to be discussed with a couple of experts/practitioners as per to validate the evaluation model outputs in comparison with the '*realisations of the reality*' (Fellows and Liu, 2008) and get feedback on the conditions of its application.

3.3 Conclusion

To address the problem of the comparison of performances of OSM building systems in low-rise housing projects, the research programme was designed to develop an evaluation model to be tested through the primary data extracted from the main case study proposition and secondary data from exemplar industry cases. Literature review findings informed the development of a dedicated metrics set. Feedback from a couple construction practitioners nurtures a critical discussion of the research outputs.

4. Defining success for housebuilding, the case of a series of housing developments on small infill sites in Hertfordshire, UK

4.0 Introduction

The purpose of this chapter is to present the primary data collection proposed to gather views from project's team members on metrics for housebuilding and OSM processes. It also includes notes on the programme of the main case study proposition on which this thesis is based and context of data gathering.

4.1 Notes on the case study project

a. Case study project proposition

The case study proposition presented an opportunity to collect comparative data on the performances of a range of OSM processes to be analysed in relation to the specificities of infill residential development programmes on small sites.

Scope of the project

A local housing association (The client) purchased in April 2018 a series of six small former garage sites from Dacorum Borough Council, Hertfordshire, UK for a sum of ~£3M with the aim of developing affordable housing. A team of consultants including legal and planning consultants, surveyors, employers' agents, costs consultants and architects had been appointed to work on the project from early 2018. The first planning application for the delivery of 2 houses of 2 bedrooms designed for 4 persons (2 x 2b4p) on a site described as '*Cupid Lane*' was submitted in August 2018. In the Autumn 2018, a brief was developed to trial a range of Modern Methods of Construction (MMC) integrating OSM processes as a pilot project to inform the client 's future approach to construction and procurement.

A manufacturer was invited to tender as a technical supplier to undertake the manufacture, supply and installation of 2-dimensional timber based structural insulated panels (SIPs) with varied degrees of finishes and additional bathroom and kitchen volumetric pods. An agreement was drawn with the different partners involved to monitor varied building technologies, which included structural insulated panels (SIPs) on 2 of the sites, bathroom and kitchen pods as well as closed panels on another 2 and traditional brick & blocks for the 2 remaining sites in order to enable comparison.

Residential development programme description

This pilot project's programme consisted in the delivery of 34 low-rise affordable housing on six small infill sites described in Table1. Schedules of accommodation relative to these six distinct building

projects from 2 to 11 units however evolved through conversations with the local authority responsible for granting planning approval.

The case study project presented a great opportunity to gather tangible data on the performances of OC for a type of development that may not be the prime focus of the industry due to inherent challenges such as low repeatability of units & lack of economy of scale, access restrictions and complexity of urban context. Highlight on the relations between the specificities of the urban fabric and the performances of building systems are critical to support further construction projects in Hertfordshire and similar contexts.

Table 1: Presentation of the sites part of the main case study project, i.e. the development of low-rise affordable housing on 6 small sites in Hertfordshire, UK.

Location	Surface in hectares (ha)	View	Schedule of accommodation	Building system discussed	Planning status
Cupid Green Lane, HP2 7HH	0.037ha		2 x 2-beds/3 p houses	SIP Panels + bathroom pods	Application registered on 17/07/18, granted on 27/02/19 with loss of 1 bed space
Rucklers Lane, Kings Langley WD4 8BA	0.032ha		4 x 2-beds/4 p houses	Simple SIP to be compared with SIP+ (fitted windows) & pods	Application registered on 01/10/18; granted on 03/04/19
Hyde Meadows, Bovington HP3 0ER5	0.131ha		5 x 2-beds/4 p houses	SIP+ (fitted windows) & pods (bathroom and kitchen)	Application registered on 19/02/19; granted on 04/07/19
Pulleys Lane, HP1 2PZ2	0.144ha		2 x 2-beds/4 p houses	Traditional brick and block construction	Application registered on the 01/10/18; granted on the 14/01/19
Long Arrotts, HP1 3EY	0.161ha		4 bed bungalows & 6x2b flats	SIP Panels & pods	Application registered on 01/10/18; granted on 05/09/19
Wood View, HP1 3HT	0.172ha		5 x 2B/3p & 6 x 1B/2p	Traditional brick and block construction	Application registered on 04/03/19, no resolution at the date of completion of the research

b. Case study project delivery

The case study proposition formed progressively through a series of iterations of work on the project's viability, feasibility, design or procurement led by the client. Emerging constraints within this process impacted heavily on the initial brief and delivery timeframe of the project suggesting existing barriers to adoption of OC in housing developments on small infill sites.

Project delivery programme

The delivery programme as understood in early 2019 was set for work on site to start on the 7th of July 2019 as shown in Table 2. The commencement of the research programme in January 2019 coincided with the clients' involvement with a SIPs manufacturing company carrying out technical feasibility assessments alongside the ongoing work towards securing planning approvals for each of the 6 sites.

Table 2: Diagram of Initial case study project timeframe as understood in early 2019

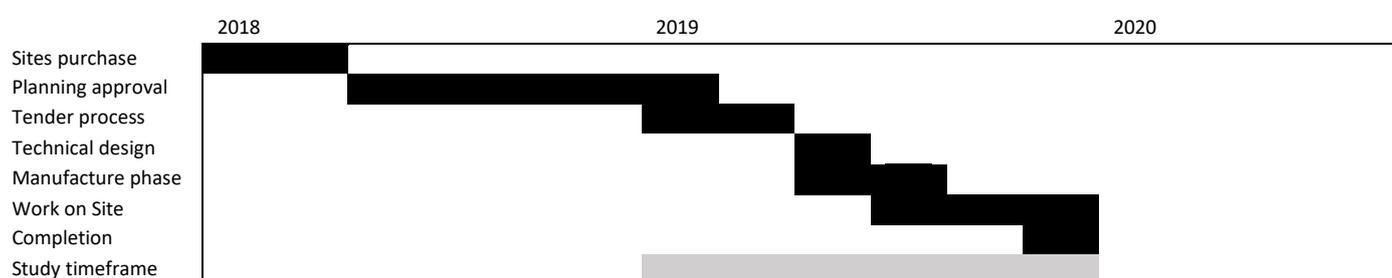
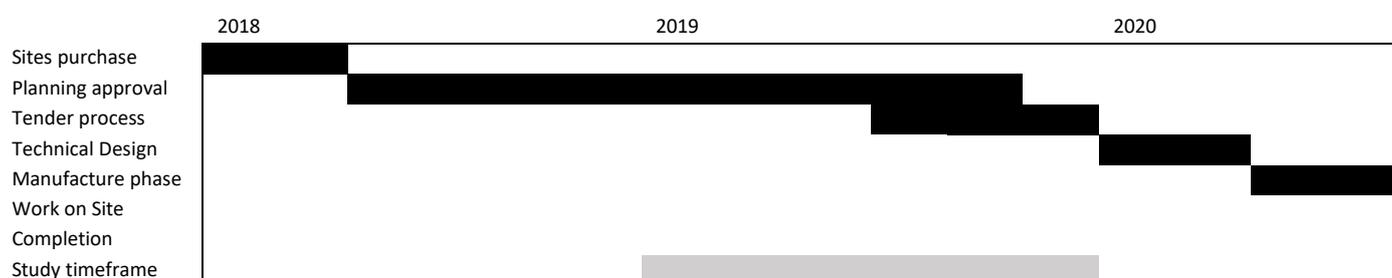


Table 3: Diagram of updated case study project timeframe as understood in early 2020



Delivery delays

The unsuccessful partnership with a first manufacturer in March 2019 together with difficulties regarding planning applications and procurement brought projects' team members to re assess, re-negotiate and re-work in details the terms of delivery of this pilot project causing extended delays as shown in Table 3. An initial inception meeting in mid-December 2019 marked the formal appointment of most projects' team members as well as the start of the Technical Design stage (RIBA 4). This was soon to be followed by the manufacture of components by an alternative company specializing in 2D closed and open timber framed panels.

Approach to procurement and appointment of consultants

Though the client approach to offsite construction procurement had been informed by in-house research and case study visits, multiple routes to MMC delivery were discussed and considered as the project progressed. Turnkey modular volumetric solutions had been discarded due to restricted access, lack of adaptability or economy of scale and the MMC category 2 appeared most relevant in addressing successfully the project brief's specificities.

As the client engaged in conversations with a first SIPs technical supplier based in the UK, work was ongoing to secure planning approval. This generated the need for re-work on internal layouts to integrate the constraints related to the manufacture and installation of standard bathroom and kitchen pods. Eventually, the tender process was unsuccessful due to the increased costs attributed to R&D work for the development of new pods products suggesting a lack of maturity of supply chains. A second technical supplier of open and closed panels with more experience in the low-rise affordable housing sub-sector was appointed as an alternative which resulted in the reduction of the scope of the pilot project, with less building technologies to be trialled and no pods at all. During the induction meeting prior to the Technical Design stage, project's team members mentioned potential forthcoming problems on the lack of compliance of the building system adopted with the thickness of floor plates described at planning stage. This could potentially result in the change of building heights and generate further re-work.

The multiple difficulties that emerged during the planning and procurement phases of the project constrained its progression and delivery. This suggests that projects of a similar nature may be more affected by good practices on planning and procurement than by the approaches to construction adopted. Existing guidance (e.g. Sinclair et al., 2016) that promotes the integration of manufacturing constraints and the engagement with manufacturers at a very early stage as a way to unlock some benefits of OC and mitigate the need for re-work may have been overlooked in this case. This confirms that the lack of knowledge may be one of the main disadvantages of OC (Goodier et al., 2019) together with a relative immaturity of the market.

4.2 Primary data collection: questionnaire survey

a. Survey design

To complement literature review findings on factors, indicators or benchmarks associated with the successful delivery of homes in the low-rise housing sub-sector (chapter 2), a survey was designed to collect perspectives from the professionals involved in the main case study on which this thesis is based (chapter 4) and support the development of a contextualised metrics set.

Aims of the questionnaire survey

Questionnaire surveys have been defined as a research instrument intended to measure something within a defined population being studied which may include behaviour, beliefs, knowledge, attitudes and attributes of respondents (De Vaus, 2002). In this research, the questionnaire survey format was adopted to collect perspectives from case study project stakeholders on metrics for housebuilding and establish the potential impacts of the decisions about building systems onto their respective roles. The choice of the data collection was supported by practical aspects, including the straightforwardness of digital format administration that is also cost effective and that respondents can engage with in their own time, as opposed to one-to-one interviews meetings. The questionnaire format also enables some balance in between flexibility of 'open ended' questions allowing a range of inputs from professionals of different backgrounds and provision for structure in the analysis through frequencies, averages and/or percentages.

Identification of the participants

The questionnaire survey was destined to project team members participating in the project from the Technical Design stage (RIBA 4) onwards and was to be carried out from the moment of their formal appointment by the client. The project's team members identified by their roles included:

- Client / developer (Group Managing Director, Project Managers, Head of Assets & Compliance)
- Employer's agents / Project Management consultants
- Main contractor
- Sub-contractors
- Specialist suppliers
- Manufacturer
- Architects, Principal designer
- Engineers (foundations, drainage...)
- Consultants (surveyors, QS, services, transport, ground investigation, trees, landscape...)
- OSM Warranty liaison
- Building control liaison

Though the inclusion of future residents in the study appeared meaningful to understand aspects of output value with regards to Lean principles as mentioned in the literature review in chapter 2, it was not possible to integrate post occupancy study elements in the timeframe of the research programme.

Benefits realisation management

The design of the questionnaire was driven by the objective of identifying evaluation metrics relative to the differential in between the desired outcomes and the actual outputs of the project from the diverse project team members perspectives. This resonates with 'Benefits Realisation' assessments defined by the Association for Project Management (APM) as *'the practice of ensuring that benefits are derived from outputs and outcomes'* (<https://www.apm.org.uk/resources/what-is-project-management/what-is-benefits-management-and-project-success/>). The Infrastructure and Projects Authority reports on the definition of 'benefit' from the Cabinet Office as *"the measurable improvement resulting from an outcome perceived as an advantage by one or more stakeholders, which contributes towards one or more organizational objectives"* (IPA, 2017). It describes benefits cycle practices as comprising 6 main steps: Define success / Identify and quantify / Value and appraise / Plan to realise / Work to realise / Review performance (IPA, 2017). As an instrument to understand stakeholders wants and needs, and facilitate the formation of clear objectives in complex projects to support evaluation protocol, 'Benefit Realisation' assessment types were used in the design of the questionnaire survey through reference to the two initial steps: Define success / Identify and quantify.

Survey Structure

The first set of questions was designed to bring clarity to the nature and extent of the involvement of each team member in the project as well as their organisation. It aimed at capturing the circumstances of project partners engagement with OSM in relation to their business model as well as their desired outcomes for the case study project delivery. A few questions were grouped under headings: *A. ROLE / B. DESIRED OUTCOMES*.

The second set of questions aimed at identifying relevant indicators and metrics in use to assess the delivery of affordable housing as well as performances of different modes of construction. It also included requests for benchmarks in order to quantify level of benefits that could realistically be realised in the case study proposition through the implementation of OSM processes. A few questions were grouped under headings: *A. INDUSTRY HOUSING METRICS / B. CONSTRUCTION PERFORMANCES*.

Questionnaire content

See appendix A.

Through inviting the project's team members to share their views on metrics for housebuilding and on the impacts of OSM implementation on their specific role, the first data collection proposed aimed at supporting an assessment of building technologies based on the outputs and value added for stakeholders. This approach was developed to reveal the benefits of OC for the parties involved in the project in a holistic manner, to highlight metrics and benchmarks in use and to inform the design of an evaluation model (chapter 5).

b. Survey data collection

In order to proceed with the data collection based on a questionnaire survey as described, an invitation to complete a digital form was shared with the client in August 2019 and forwarded to professionals thought to be or to become active team members in the case study project.

Data collection timeframe

The requests for participation in the survey were initially left unanswered which suggested that it was necessary to delay the data collection to the time of formal appointment of respective projects' team members. The lengthy delays in the case study project progress resulted in an increase pressure on stakeholders that didn't favour their participation in the survey proposed. In mid-December 2019, an inception meeting was organised with attendance of all projects' team members to mark the start of the Technical Design phase and the collaborative planning of the construction work to come. As the research came to its term, it was not possible to proceed with the questionnaire survey and no data was collected.

The failure in the data collection through questionnaire survey reflected the general struggles in the development and progression of the case study project. It also suggested that the initial brief for the research agenda did not take into consideration a risk mitigation strategy and that the research programme was wrongly foreseen. The limitations in engaging with project stakeholders consequently restricted the development of an evaluation model based on tangible evidence.

4.3 Conclusion

The case study project presented a great opportunity to gather tangible data on the performances of OC for small infill residential development types that may not be the prime focus of the industry. However, the multiple difficulties that emerged during the development of the project in the planning and procurement phases caused great delays and constrained the engagement and participation of projects team members in the research programme. This suggests that the planning and procurement stages are likely to have more impact on project delivery than the approach to construction adopted. It also reinforces the relevancy of literature review findings on the need to increase upfront planning and engage with manufacturers at an early stage in order to unlock the benefits of OC.

5. Development of a speculative model for the comparison of building systems performances integrating OSM processes in low-rise housing projects.

5.0 Introduction

The purpose of this chapter is to present the principles underpinning the development of an evaluation model dedicated to the comparison of performances of building systems with OSM components as well as the details of associated metrics and data points. As part of the research methodology proposed, two methods are described to test and validate the evaluation model including data collection from either the main case study proposition or alternative secondary sources. Results are discussed with a couple of experts/practitioners to question further the relevancy and conditions of application of the model developed.

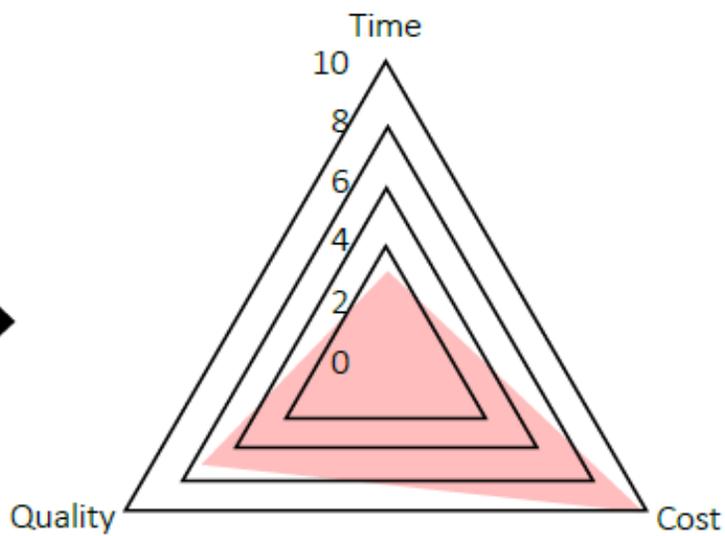
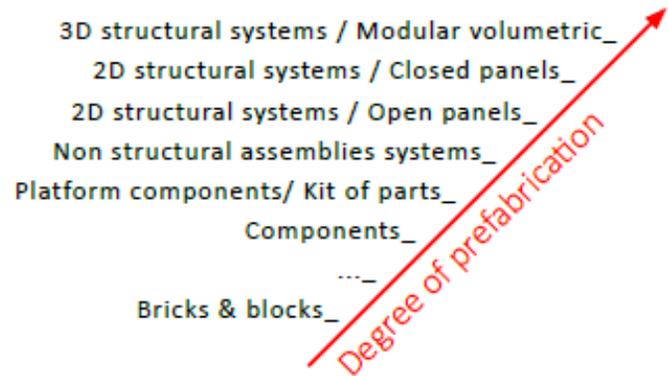
5.1 Model development

a. Approach

Literature findings highlighted the relevancy of revealing the impacts of the implementation of OSM processes on the homes completed. This led to the description of an evaluation model in two parts: a concise metrics set to assess housebuilding outputs on one side, and an assessment of the degree of prefabrication of systems through 3 different calculation methods on the other.

On the relation of building systems to housing delivery

With regard to case study proposition's context, it appeared relevant to describe a model enabling a straightforward assessment of the OSM building technologies available on the market in order to inform the client strategies in appointing future suppliers and contractors. As mentioned in previous chapters, the difficulties in collecting data with high granularity whilst balancing circumstantial factors and embracing the diversity of components and systems in use constitute a challenge for the development of a comprehensive systematic evaluation system (W. Pan et al., 2008). The inherent complexity of such task where circumstances weight heavily on decision making supported a holistic approach to the evaluation of building technologies. Rather than presenting a lengthy description of benefits and barriers to the adoption of a specific solution, it was proposed to focus on revealing the impacts of OSM processes on homes delivery performances.



Assessment of completed low-rise (<5 storeys) affordable housing

Figure 3: Diagram of the approach to the development of the evaluation model

b. Measuring housebuilding

Two main references highlighted in the literature review are used to support the formulation of a metrics set for housing projects focused on conciseness, technology-blind outputs, and practicality. Associated measurements in compliance with industry standards can enable then a supplementary opportunity for comparison of building systems performances with existing benchmarks in order to broaden the scope of analysis.

Reference reports on housebuilding evaluation practices

Concise approaches to housebuilding evaluation based on technology-blind outputs have been developed in the past order to assess production against Government-led targets for housing in terms of ‘*delivering the numbers required to the necessary timescale (time), in the right place and of the right quality (quality), at prices people can afford (cost)*’ (NAO, 2007). The National Audit Office report ‘*Homebuilding: Measuring Construction Performance*’ published in 2007 aimed at defining MMCs in terms of performance and outputs rather than in terms of specific building products and techniques. Through contributions of key stakeholders’ organisations, a set of performance indicators was identified as vital in driving behaviour of decision-makers regardless of construction technique chosen (Figure 5).

	Construction stage	Completed property
Time	<ul style="list-style-type: none"> ■ Duration of Construction – Predictability and Actual 	<ul style="list-style-type: none"> ■ Defect resolution ■ Life span – Predicted
Cost	<ul style="list-style-type: none"> ■ Construction Cost – Predictability and Actual 	<ul style="list-style-type: none"> ■ Whole life costs – Predicted
Quality	<ul style="list-style-type: none"> ■ Number of defects ■ Health and Safety ■ Environmental efficiency 	<ul style="list-style-type: none"> ■ Quality of workmanship ■ Customer satisfaction ■ Environmental impact

Figure 4: Performance indicators for assessing construction techniques (NAO, 2007)

More recently, a set of Key Performance Indicators (KPIs) was proposed by the Construction Leadership Council to track innovation in housing projects (CLC, 2018a). This set composed of 13 KPIs is complemented by associated case studies and benchmarks as well as a ‘Metrics Management Dashboard Web page’ to ease the engagement of industry partners and encourage ‘big data’ gathering. This industry

standard therefore provides a robust UpToDate reference for metrics calculation methods and data collection protocols.

Metrics sets comparison

The two metric sets and associated calculations above introduced are compared in Table 4 to highlight similarities in metrics themes. Commonalities informed the formulation of an updated set of metrics focused on conciseness, compliance with industry standards and practicality of data collection with ambition to reflect decision makers' priorities.

Table 4: NAO and CLC KPIs sets comparison with metrics adopted in yellow

Metrics described in 'Homebuilding: Measuring Construction Performance' (NAO, 2007)	Calculation	Metrics described in 'Innovation In Buildings Workstream Housing Industry Metrics' (CLC,2018a)	Calculation
Predictability/ actual duration	Actual Time – Estimated Time x 100% on Estimated Time	Time on site	Elapsed time spent on site/gross internal floor space in m2 (days/m2)
Predictability/ Actual costs	Actual Cost/m2 – Predicted/Estimated Cost/m2 x 100% on Estimated Cost/m2	Capital costs	Capital cost associated with construction of buildings/gross internal floor space in m2
Defects	Survey on completion using a 0–10 scale	Quality rating	(1-(cost of post-completion defects/total build cost))*100
Health and Safety	_Reportable accidents per 100,000 employed per year on-site for the Main Contractor's company _Reportable accidents per 100,000 employed per year off-site for the Main Contractor's company _Reportable accidents per 100,000 employed per year for the portfolio of new build projects carried out by the Commissioning Client.	Safety	(Injuries (per year)/(hours worked per year))*100
Environmental efficiency, waste	waste removed from site (m3/£100,000) + waste removed from the factory (m3/£100,000)	Waste generated	m3/£100K project value total + m3/£100k project value construction + tonnes/£100k project value
Environmental efficiency, Carbon emissions	CO2 emissions caused by the energy used on site during the construction process per £100,000 of project value (kg CO2/£100,000) + CO2 emissions caused by the energy used during the offsite fabrication process per £100,000 of project value (kg CO2/£100,000)	Embodied carbon	Amount of embodied carbon associated with production and transport of materials used in construction/gross internal floor space in m2 (kgCO2e/m2)
Environmental efficiency, Road miles	_number of road-miles travelled by on-site operatives during the construction process per £100,000 of project value. _number of road-miles travelled by off-site operatives delivering to and from the site during the construction process per £100,000 of project value.		
Defect resolution	Survey conducted three months following completion using 0-10 scale		
Lifespan-predicted	Estimate (in years) supplied by developer/builder		
Whole life costs	value of Predicted/Estimated Whole Life Cost per square metre at Construction Completed/Available for Use		

Workmanship, number of defects /warranty claims	Surveys conducted of the new home three months after the end of both the defects resolution and warranty periods using a 0-10 scale		
Customer Satisfaction	Survey questionnaire with the purchaser/commissioning client at handover; with the occupier three months following the end of the defect's resolution period. The		
Environmental impact, energy efficiency	Rating to be calculated by the homebuilder	EPC rating	Average value calculated by giving a value 1-7 to A-G ratings respectively, calculating an average score from these and rounding to the nearest whole figure
Environmental impact, waste	Rating to be calculated by the homebuilder		
Environmental impact, sustainable	Rating to be calculated by the homebuilder		
		Homes completed/year	Number of homes completed per year
		Productivity	Capital cost associated with construction of buildings/total man hours (£/man hour)
		Pre- manufactured value	% ((Gross capital cost-preliminaries-site labour cost)/capital cost)*100
		BIM Level 2	BIM level 2 accreditation
		Firms ISO 9001 accredited	ISO 9001 accreditation
		Prelims cost per home built	(Cost of preliminaries/total capital cost)*100

Proposed Metrics set #1

The set of metrics proposed summarized in Table 5 derived from a definition of MMC in homebuilding (NAO, 2005) focused on outputs structured in 3 main themes: Time /cost /quality. These included measurements on the pace and cost associated with projects delivery together with additional metrics on programmes certainty. A supplementary theme was also included as per to monitor potential safety and sustainability dysfunction in construction management, though this was expected to be secondary in the analysis of the data gathered from the case study proposition due to its procurement structure with a single main contractor.

Table 5: Summary of metrics proposed to assess housebuilding project delivery performance showing essential measurements in yellow as well as optional.

Theme	Metric	Calculation
Time	Duration of construction	Elapsed and predicted time spent on site/gross internal floor space in m ² (days/m ²)
	Predictability	Actual Time – Estimated Time x 100% on Estimated Time
Costs	Actual costs	Capital cost associated with construction of buildings/gross internal floor space in m ²
	Predicted costs	Actual Cost/m ² – Predicted/Estimated Cost/m ² x 100% on Estimated Cost/m ²
Quality	Quality rating	(1-(cost of post-completion defects/total build cost))*100
	Customer satisfaction (Optional for practical reasons)	Data could be captured through questionnaire surveys with purchaser/commissioning client at handover
Impacts (Optional)	Safety	RIDDOR, (Injuries (per year)/ (hours worked per year) *100
	Embodied carbon	Amount of embodied carbon associated with production and transport of materials used in construction/gross internal floor space in m ² (kgCO ₂ e/m ²)
	Waste generated	m ³ /£100K project value total + m ³ /£100k project value construction + tons/£100k project value

A concise set of metrics to evaluate housebuilding performances was developed from two main references including ‘*Innovation In Buildings Workstream Housing Industry Metrics*’ from the Construction Leadership Council (2018a) understood as a current main standard in use. The data collection protocol proposed included updated calculations to enable the comparison of performances of projects evaluated with existing industry benchmarks.

c. Measuring the degree of prefabrication of building systems

An assessment of the degree of prefabrication of systems is described as part of the evaluation model proposed through 3 different calculations methods. This includes the pre-manufacture value (PMV) industry standard metric as well as alternative methods referring to practices from other sectors to scrutinise further the nature and performances of OSM processes.

Pre-manufacture value

The pre-manufactured value (PMV) was promoted in the Farmer Review (2016) as a metric to quantify the extent to which OC is applied in projects through *'measuring the proportion of a project made up of on-site labour, supervision, plant and temporary works'* (MHCLG, 2019). The PMV is now included in the industry standards described by the Construction Leadership Council (2018a) as: *'the value that is created as a result of completing work away from the site. It is calculated by taking the gross capital cost of the project and deducting the prelims - sometimes referred to as site overhead costs - and the site labour costs. The result of this is then divided by the capital cost and is reflected as a %'*. (CLC, 2018a). Many factors are therefore to impact the percentage of PMV in projects. Whilst data collections with suitable granularity appear challenging, the metric may enable original analysis of the performances of building projects with similar PMV to understand where OC delivers value with consistency.

Knowledge based assessment on OSM processes

The case study proposition presented the opportunity to monitor in details the delivery of offsite components across the varied stages of Design for Manufacture and Assembly (DfMA) excluding post-occupancy for practical reasons associated with the research programme timeframe but including:

- Design
- Manufacture
- Logistics
- Site Integration

As per to address the findings of the literature review which suggested that labour shortages and lack of productivity are amongst the main drivers for change to happen at industry level, it is proposed to monitor the nature and quantity of labour as well as the nature of tooling deployed with details on levels of automation and digitalisation for each of the DfMA stages mentioned above. Summary reports are to form deliverables to enable qualitative comparison for each of the building projects evaluated.

DfMA component-based evaluation

With references to DfMA evaluation practices in other sectors highlighted in the literature review (e.g. Purnomo Safaa, Utomo Dwi Hatmoko, & Purwanggono, 2019) (Banks et al., 2018)(Ray O'Rourke et.al, 2013; Royal Institute of Chartered Surveyors, 2018), it appeared relevant to monitor projects at component level in order to understand the relations of the number of components with both ease

manufacture and ease of handling/integration. As part of this assessment, it is proposed to capture data on each of the sub-assembly components used in the edification of superstructures in order to calculate an index described as: *components fabrication + transport costs sum / assembly labour + logistic costs sum*.

As traditional construction commonly uses some components made offsite such as windows & door frame, cabinets sub-assemblies, or truss rafters for the delivery of pitched roof structures (Council Construction Leadership, 2018b; Greater London Authority, 2017), it was envisioned that this approach would enable all building systems implemented in the case study proposition to be assessed as kit of parts to some extent.

Proposed Metrics set #2: 3 methods to capture the degree of prefabrication of building systems

1. **Pre-manufactured value (PVM)**, as a % calculated by taking the gross capital cost of the project and deducting the prelims and the site labour costs.
2. **Knowledge based assessment on OSM processes:** Technical supplier design / Manufacture / Logistics / Integration to capture work achieved offsite in relation to detailed design specifications
3. **DfMA component-based evaluation as an index:** components fabrication + transport costs sum / assembly labour + logistic costs sum; to understand whether *‘savings of shifting activities to plant outweigh logistic cost’*

Table 6: Summary of metrics to assess the degrees of prefabrication of building systems showing essential measurements in yellow and optional.

Metric	Calculation	Comments
Pre-manufactured value (PMV)	% calculated by taking the gross capital cost of the project and deducting the prelims and the site labour costs	Industry standard aiming at measuring <i>‘the value that is created as a result of completing work away from the site’</i> (CLC 2018)
Work processes deployed (Focus on superstructures only)	Knowledge based narrative (Summary reports)	As per to address the findings of the literature review which suggested that labour shortages and lack of productivity are amongst the main drivers for change to happen at industry level, it was proposed to monitor the nature of labour qualitatively as well as the tooling deployed with details on levels of adoption of automation/digitalisation through the stages of design for manufacture and assembly (DfMA) described as design / Manufacture / Logistics / Site Integration
component-based index (Focus on superstructures)	components fabrication + transport costs sum / assembly labour +	To understand whether savings of shifting activities to plant outweigh logistic cost and with reference to practices in other sectors, it was proposed to assess the components’ ease

<p>only) (Optional for practical reasons)</p>	<p>logistic operation costs sum;</p>	<p>manufacture in relation to the ease of handling/integration. Note 1: As traditional construction commonly uses some components made offsite such as windows & door frame, cabinets sub-assemblies, or truss rafters for the delivery of pitched roof structures (Council Construction Leadership, 2018b), the approach appeared relevant to all building systems understood as kit of parts to some extent. Note 2: the assessment proposed was suited to the original case study initially involving a single OSM manufacturer to deploy different components and specifications options to be compared, however it might lack relevance at industry level.</p>
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The adoption of OC and the associated increase in the degrees of prefabrication of building systems identified as critical to support innovation at industry level point to the relevancy of dedicated evaluation protocols. However, the pre-manufacture value (PMV) presented in multiple reports as industry standard enable only low granularity. This suggests gaps in the knowledge applied to the evaluation of OC that cross sector learning may help to address.

5.2 Testing and validation

a. Model testing

Approach to model testing

As part of the research methodology proposed, two methods are described to test the evaluation model including data collection from either the main case study proposition or alternative secondary sources. As reported in chapter 4.2, the lengthy delays in the progression of the main case study proposition impacted consequently the research programme and it was not possible to collect primary data as preferred. As an alternative, data was extracted from 2 exemplar cases with reference to industry benchmarks as per to form basis of speculative analysis. The selection of exemplars was constrained by the limited availability of data on the PMV metric only recently introduced as well as the nature of information needed on homes delivery performances sometimes described as ‘commercially sensible’. A few cases were identified from grey literature and industry reports, however none of the associated data sets was wide enough to cover all of the model requirements. The series of case studies linked to the activities of the Construction Leadership Council (CLC) on promoting innovation in housebuilding presented opportunities to relate at least one of the measurements proposed to assess the degree of prefabrication of systems with indicators on homes delivery performances. It was also beneficial to refer to associated up-to-date industry benchmarks described by the CLC. Results of the comparison of 2

exemplars and benchmarks were then discussed with a couple of experts/practitioners as per to validate the evaluation model outputs and get feedback on the conditions of its application.

Data generation

Secondary data was extracted from exemplar cases described as follow:

- EXEMPLAR #1: PLACE LADYWELL (2014-2016)

'Rogers Stirk Harbour + Partners' partnership with Lewisham Council to create a deployable residential development using a volumetric construction method [...] responds to the high demand for housing in the Borough by offering a short-term solution. It is constructed as 64 individual fully finished units (24 dwellings) stacked in a 4-storey arrangement, all manufactured in a factory in Nottinghamshire.' (<https://www.rsh-p.com/projects/place-ladywell/>)

'Balconies and lift/stair cores were also manufactured and installed on site as separate components. The units were manufactured from standard timber components using simple technologies and fully fitted out with bathroom, kitchen, flooring and all finishes in the factory [...] before being transported by road to site and lifted into place.' (<https://www.constructionleadershipcouncil.co.uk/wp-content/uploads/2018/10/>)

- EXEMPLAR #2: AIMC4, PRESTON PANS SITE (2009-2013)

'The AIMC4 project has designed, trialled and used a range of solutions to improve sustainability in a cost-effective way thanks to the collaborative work of developers, advisory groups and suppliers. The 17 resulting homes demonstrate improvements in energy efficiency, supply chain effectiveness and reduced build costs through offsite construction, innovative material use and solution technologies such as waste-water heat recovery.' (<https://www.constructionleadershipcouncil.co.uk/wp-content/uploads/2018/10/181022-CLC-Casestudy-AIMC4.pdf>)

Stewart Milne Group built AIMC4 specification homes on three sites in 8 weeks including a terrace of three 2- and 3-bedroom homes built in Athena Grange, Prestonpans, East Lothian near Edinburgh using proprietary Sigma II Build System (closed-panel timber frame) and single skin party wall.

(<https://www.hhcelcon.co.uk/sites/default/files/attachments/IP9-13-1.pdf>) (https://www.specifiedby.com/stewart-milne-timber-systems/sigma-ii-build-system/Milne-Timber_SIGMA-II-BUILD-SYSTEM_Brochures_Brochure.pdf)

- EXEMPLAR #3: CLC Dashboard benchmarks

In October 2018, the Construction Leadership Council published a mature set of 'Housing Industry Metrics' to track the impact of innovation in buildings workstream (Construction Leadership Council, 2018a) with additional reference benchmarks to be updated in 2019 (CLC, 2019). It provided a basis to speculate on performances of traditional construction in current practices.

Results

The data collected from 2 exemplar cases described above is compared in table 6 with industry benchmarks. Results are then visualised to illustrate differentials diagrammatically (figure 1 and 2).

Table 7: Summary of secondary data collection

Metrics	Modular volumetric: PLACE Ladywell	Panellised: Aimc4 Prestonpans	Traditional: CLC benchmark 2019
Duration of construction	estimated at 0.07 day/m ² or '45% reduction compare to traditional'	Estimated 0.16/m ² (3 terraces block in 8 weeks)	0.18/m ²
Predictability	-	-	-
Actual construction costs	Estimated at 1666/m ²	Estimated at 1151/m ²	£1101/m ² (result of applying indices of construction costs for 2016*)
Predicted costs	-	'volume extra-over costs of £3000-£3700 respectively'	-
Quality rating	-	'the homes are of better quality with less defects'	99.4%
Pre-manufactured value (PMV)	Estimated at 68% **	Circa 55% ***	40%
Work processes deployed for the superstructure	Technical Design stage including automation/digitalization-based processes? (Y/N + list)	N Bespoke design	-
	Manufacture	N Low skilled labor, standard timber components, simple technologies	Y Closed panels fully fitted with windows and cladding in factory on assembly line with 'some' automation
	Logistics	N Standard transport/just in time delivery of modules managed by operation team	N
	Integration	N traditional craneage, assembly based on sites operatives labor	N
component-based index (Focus on superstructures only)	Modules: - volumetric modules (2 per flat), no detailed information - Balconies, no detailed information - lift/ stair core, no detailed information	Modules: - timber-frame closed-panel timber-frame, no detailed information	n/a

*<https://opendatacommunities.org/resource?uri=http%3A%2F%2Fopendatacommunities.org%2Fdata%2Fhouse-building%2Fconstruction%2Fcosts%2Findices%2F2016-01%2FK02000001%2Fnewhousing-materialprices>

**https://www.aecom.com/without-limits/wp-content/uploads/2017/05/LM00092_Modular_CM_0417_v3.pdf

*** (https://www.bregroup.com/wp-content/uploads/2018/04/Offsite-Construction-BRE_26.04.18_MMC-Working-Group_Mark-Farmer-MHCLG.pdf)

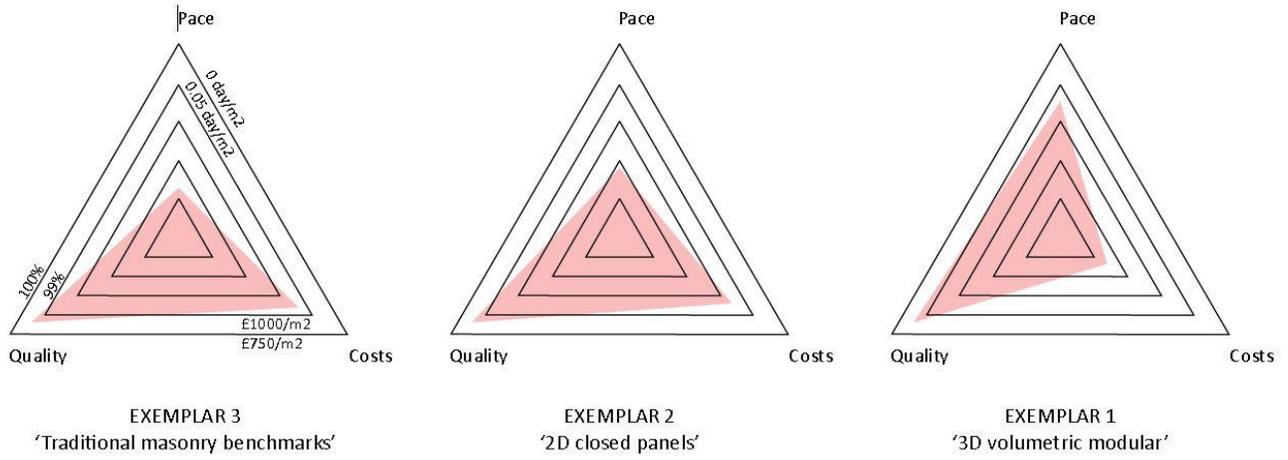


Figure 5: Quality/Pace/Costs relations observed in different exemplars

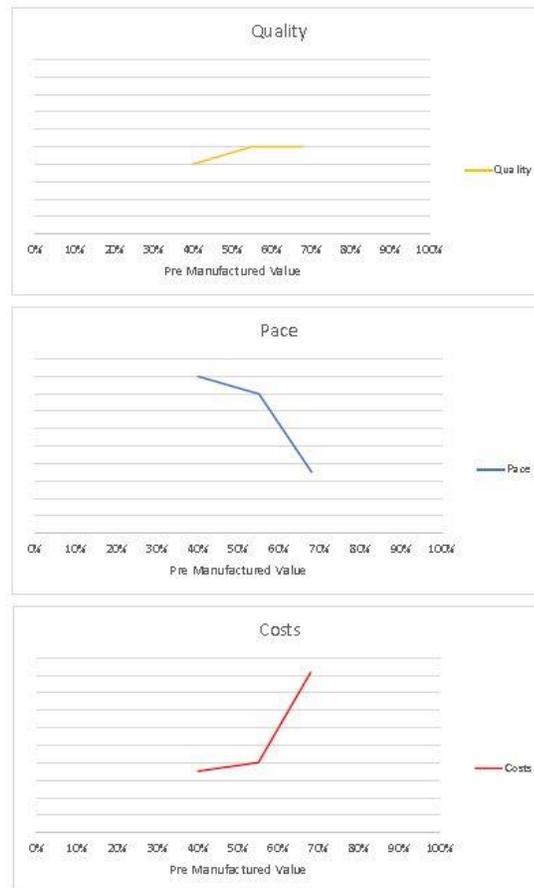


Figure 6: Variations of Quality/Pace/Costs results in relation to Pre manufacture Value (%)

b. Model validation

Discussion

The application of the proposed model on 2 exemplars cases and industry benchmarks showed some potential in describing relations in between the housebuilding projects performances metrics and the pre-manufacture values. Eventually, the results may be extrapolated as ‘trendlines’ to inform building systems assessment for decision makers. However, the level of information available from the secondary sources selected was insufficient to proceed with proposed assessment of the work processes, the nature of labour and the engagement with automation and digitalisation despite being identified as industry ‘game changer’. The lack of alternative to the Pre-Manufactured Value PMV to assess the degree of prefabrication of systems restricted analysis related to OSM implementation.

Further problems lie in the data collection itself:

- The projects were of different scales and delivered 3 years apart in different geographic areas, which might lead to discrepancies in performances comparisons.
- The exemplars sample was reduced, and projects specific circumstances may be far too prevalent to conclude on housebuilding and systems performances. A much larger data set would be necessary to support the accurate description of trends. Also, a more diverse data set that may include open panels system/ closed panels systems would have enabled deeper analysis of OC impacts.
- It was not possible to verify all metrics’ calculation methods and some of the results were based on estimations only, limiting the scope for comparison.

Feedback on the model development and potential applications

Through a workshop, comments on the results presented were gathered from both academic and industry professionals respectively involved in the evaluation of sustainability in OC and in the promotion of MMC in the UK. Threads of comments and discussions may be reported in the few main points structured as follow:

- ‘Need for OC Big data’: the test of the model showed that consistency in measurements methods and size of the projects sample is critical to support an assessment of building systems that may inform decision making in small housing projects’ delivery. Both the conciseness of the model and the low level of granularity of the PMV suggests the need for ‘big data’ collection in order to reach conclusions. Diverse projects involving both academia and industry are underway to collect large sets of data on housebuilding in the UK through digital tools.
- ‘Net zero carbon agenda’: the concise and material-agnostic assessment of homes delivery performances proposed described wider ‘impacts’ only as secondary, which might represent a miss opportunity with regards to the Net zero carbon agenda of the UK government. Indicators such as embodied carbon, waste and safety are pivotal in the current understanding of construction performances. The reduction of the model variables is useful to bring clarity and better communicate results to non-specialists as shown in the diagrammatic visualisation of

performances, however this could be supplemented by impacts RAG (Red/Amber/Green) assessments in relation to appropriate scales as shown below (figure 6).

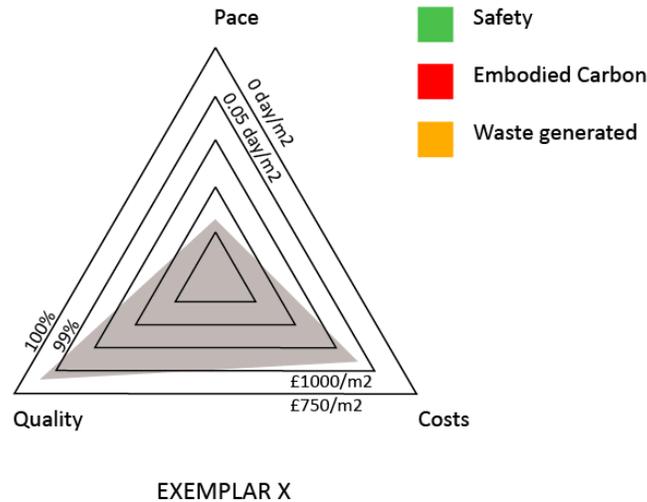


Figure 7: Evaluation model proposed with visualisation of impacts RAG assessment

- 'Application to knowledge gap': the pilot project described as main case study proposition presented a unique opportunity to compare performances of components specifications with high granularity due to the reduction of variables. This is a miss-opportunity; however, the straightforwardness of the model and associated visualisations makes it a potential support to communicate better OC performances to small developers and contractors. It may participate then in bridging the knowledge gap that has been described as one of the main barriers to OC adoption.
- 'Evidences on automation and digitalisation: qualitative data on work processes involved in OC as well as impacts on automation and digitalisation are critical to both academia and industry efforts to understand further how to tackle labour shortages and to support innovation. In the future, the combination of qualitative and quantitative data described in the model should be highlighted further. Quantifying value added through offsite processes and technologies in comparison to traditional may nurture some analysis accounting for factory overheads and needs for economies of scale to conclude on the accessibility of OC for small developers.

5.3 Conclusion

An evaluation model for the assessment of low-rise housebuilding projects delivered with OSM processes was developed solely from the findings of the literature review (chapter 2) as a result of the extended

delays in the progression of the main case study project and the failure in engaging with project's team members. The confrontation of a concise assessment of homes delivery performances with the degree of prefabrication of systems measured through three distinct calculation methods to be trialled formed the basis of the model. This was thought to enable an analysis of the impacts of varied OSM processes understood as an input on housebuilding performances understood as an output. As extended delays in the progression of the case study project didn't permit to proceed with primary data collection as initially described in the research methodology, secondary data was extracted from industry sources to test the model and exemplify applications. Discussions on the results through a workshop with experts highlighted the importance of integrating further wider impacts and qualitative data as well as the potential of the model's visualisations to become an efficient communication tool if applied at scale. However, the compromised nature of the secondary data used in testing the model limited opportunities for analysis and conclusions on the scope for its deployment.

6. Conclusion

The purpose of this chapter is to report on the findings and limitations of the research programme and associated case study proposition on which this thesis is based. It reflects on the implications of implementation of offsite construction in housing projects on small infill sites and concludes with recommendations for future research.

Summary of the research

OSM is described as contributing to increase productivity and to tackle labour shortages in the housing sector. Whilst a range of OSM building processes are already used for the construction of homes, few evidence-based studies report on the evaluation of associated performances beyond the circumstantial conditions of project delivery. This study adopts the perspective of a local housing provider seeking to encourage the adoption of OSM processes in housebuilding projects in Hertfordshire, UK. An evaluation model to compare performances of projects integrating varied OSM components was developed to gather tangible data on the performances of offsite construction (OC) for housing built on small infill sites that may not be the prime focus of the industry. Secondary data was used to test and exemplify the model which showed potential in describing relations between the degree of prefabrication of systems and homes delivery performances. Associated diagrammatic visualisations could also support better communication of OC performances to a wider audience to address identified 'knowledge gap'.

Contribution to knowledge

The research added new knowledge on the problem of the evaluation of OSM processes' impacts on completed homes in the low-rise housing sub-sector. The definitions and main concepts underpinning the implementation of OSM in the housing sector were clarified and summaries of historical, political and technical contexts of OSM adoption were formulated. A methodology was designed to support the development of an evaluation model dedicated to the comparison of performances of building technologies integrating OSM components that included a dedicated questionnaire survey focused on benefits realization management. Three different data collections protocols to capture the degree of prefabrication of building systems with varied granularity were described. Patterns of relations between homes delivery performances and degree of prefabrication of building systems were suggested.

Limitation of the study

Despite the great opportunity presented by the case study proposition to gather tangible data on the performances of offsite construction (OC) for small infill residential development as described in chapter 4.1, the lengthy delays in the progression of the project didn't permit the collection of data as planned in the research programme. It was therefore not possible to either engage with the professionals involved in the construction phase of the case study project to inform the development of a dedicated evaluation model. It was not possible to proceed with primary data collection as initially described in the research

methodology and the compromised nature of the secondary data used in testing the model limited opportunities for analysis and conclusions on the scope for its deployment. Alternative opportunities for data collection would be necessary to support similar approaches to the evaluation of housebuilding projects delivered with OSM processes.

Implications

The multiple difficulties that emerged through the main case study project on which this thesis is based suggest that the management of the planning and procurement phases is likely to have more impact on homes delivery performances than the approach to construction adopted. This resonates with existing analysis on housebuilders activities described as constrained by framework or without much impact on the quality of what is to be built (Miles & Whitehouse, 2013). Overall, the adoption of OSM in the case study proposition generated an increase of risk and lateness of executive choices which points to the need to simplify procurement and secure supply through integrated production capacity or exclusive partnerships with manufacturers (Wei Pan et al., 2012). The struggles encountered also highlight the challenges in working with partners at a local level on the development of innovative projects that might present complex and intricate contexts as well as a lack of economy of scale. This also reinforces the relevancy of literature review findings on the lack of knowledge as being one of the main disadvantages of OC (Goodier et al., 2019) together with a relative immaturity of the market.

Recommendation for future work

Future research may address the problem of evaluation of the degree of prefabrication of building technologies with different granularity. Additional detailed knowledge on the nature and impacts of digitalization and automation practices deployed in OC would enable AEC professionals to share good practices and support innovation at scale. Understanding further alternatives to housebuilding business models with vertically integrated manufacturing capabilities which seem to prevail in mitigating the financial risks of operating OSM factories would be beneficial to support OC adoption in small projects. Opportunities may lie in investigating emerging Platform approaches to Design for Manufacture and Assembly (P-DfMA) identified as potentially enabling both mass production and mass customisation in the delivery of assets through catalysing new flexible supply chain networks (Bryden Wood, 2017). In the housing sector, this could result in an exponential adoption of OSM driving down build costs for all and unlocking the delivery of mass customisation by self-organisation, with opportunities for local stakeholders to develop bespoke configurations of standard components to unlock the viability of complex sites at cost, and support a 'make it local, make it bespoke' approach to housing supply.

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Appendix A

Questionnaire / survey

Metrics to compare building systems for affordable housing

PARTICIPANTS INFORMATION

You are being invited to take part in a study.

Before you decide whether to do so, it is important that you understand the study that is being undertaken and what your involvement will include. Please take the time to read the following information carefully and discuss it with others if you wish. Do not hesitate to ask us anything that is not clear or for any further information you would like to help you make your decision. Please do take your time to decide whether or not you wish to take part. Hertfordshire University's regulation, UPR RE01, 'Studies Involving the Use of Human Participants' can be accessed via this link:

<https://www.herts.ac.uk/about-us/governance/university-policies-and-regulations-uprs/uprs>

(after accessing this website, scroll down to Letter S where you will find the regulation)

The purpose of the study is to collect data about affordable housing Key Performance Indicators (KPI's) and building systems performance metrics in use.

It is completely up to you whether or not you decide to take part in this survey. You are free to withdraw at any stage without giving a reason. The questionnaire is destined professionals from the housing and construction industries without age restrictions.

The questionnaire focus on the role of the participants in the project and your details will be kept confidential. The final case study report will reference to anonymous professional roles. Audio recording might be used through interviews to ease the transcript of the conversation in writing. The data will be anonymised prior storage in a password protected environment and deleted at the end of the research planned for December 2019. The data will not be used in any further studies.

This study has been reviewed by:

The University of Hertfordshire Health, Science, Engineering and Technology Ethics Committee with Delegated Authority

Laure Ledard

Architect/MSc by Research student

Although we hope it is not the case, if you have any complaints or concerns about any aspect of the way you have been approached or treated during the course of this study, please write to the University's Secretary and Registrar at the following address:

Secretary and Registrar
University of Hertfordshire
College Lane
Hatfield
Herts
AL10 9AB

Thank you for reading this.

Questionnaire / survey

Metrics to compare building systems for affordable housing

Case study Project : Dacorum Borough Council former garages sites affordable housing developments

1_DEFINE SUCCESS

The first set of questions aims at identifying the role of the participants in the project as well as their desired outcomes for its delivery.

A_ROLE

- What is your role in the project? When did you first get involved?

.....
.....
.....

- What is the nature and core values of your organisation?

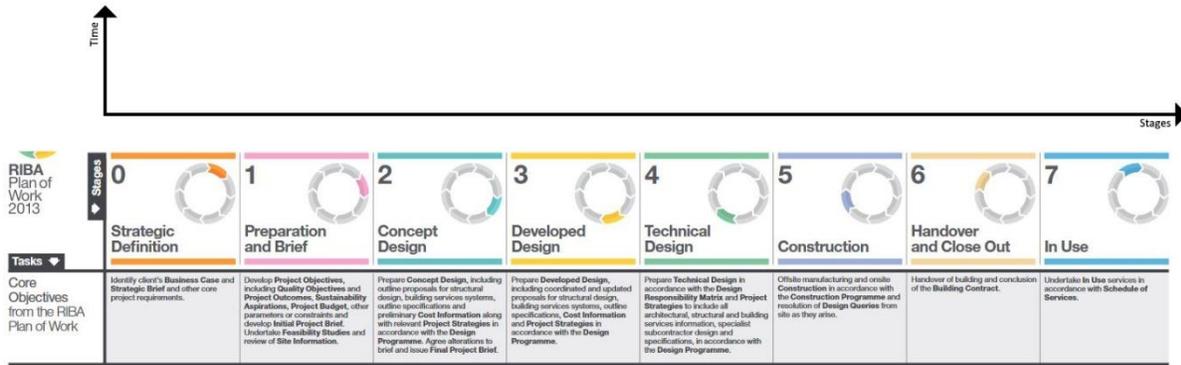
.....
.....
.....

- What are the main strategic objectives of your organisation? What are the strategic objectives specific to the case study project?

.....
.....
.....

- What stages of the case study project are you/ will you be involved with? Please describe roles in relation to RIBA plan of work?

.....
.....
.....



RIBA Plan of Work, *Designing for Manufacture and Assembly*, 2016

B_DESIRED OUTCOMES

- Define success for any affordable housing project your organisation is involved with? What are the desired outcomes?

.....

.....

.....

- Define success for the case study project? What are your desired outcomes?

.....

.....

.....

From the list below, which benefits would be most relevant to your role in the project and to your business strategic objectives? Please rate their level of importance from 1 to 5

	Not important 1	2	3	4	Very beneficial 5
Overall project time reduction					
Construction time reduction (Offsite activities, On site activities)					
Higher Predictability of programme duration					
Cost reduction of the whole process (design, construction, tendering, etc.)					
Construction and manufacturing costs reduction (Materials, Labour, Plant, Access, Complex costs)					
Project life cycle costs reduction (operation costs, maintenance costs)					
Cost certainty					
Higher Construction quality (Level of quality, defects)					

Life cycle quality increase (functionality, warranty claims, formal insurance claims, defects)					
Higher Customer satisfaction rating					
Environmental performance, energy efficiency improved, EPC rating					
Environment performance, water efficiency improved (bills)					
Health and safety					
Embodied carbon reduction					
Waste reduction					

2_ QUANTIFY SUCCESS

The second set of questions aims at identifying relevant indicators and metrics in use to assess the delivery of affordable housing as well as performances of different modes of construction and to quantify the level of benefits that could realistically be realised through off site Manufacture construction.

A_ HOUSING INDUSTRY METRICS

- What performance indicators are in use in your organisation to assess the delivery of housing projects? Please describe their nature and the collection protocol.
.....
.....
.....
- How do you approach the assessment of an affordable housing project in terms of quality? Cost? Time?
.....
.....
.....
- Are the standard Key Performance Indicators (KPI's) from the list below in use in your organisation to assess affordable housing projects? Please provide available benchmark figures accordingly as well as collection protocol details if applicable.

Housing Industry Metrics	Definitions	In use? (Yes/No) Details about collection protocol?	Benchmark for affordable housing
<i>Capital cost/m2</i>	<i>Cost associated with construction of building per metre square of gross internal floor space</i>		
<i>Embodied Carbon</i>	<i>Amount of embodied carbon associated with the production and transport of materials used in the construction of homes per metre square of gross internal floor space</i>		

<i>Days on site/m2</i>	<i>Elapsed time spent on site per metre square of gross internal floor space</i>		
<i>Homes completed</i>	<i>Number of homes completed per year</i>		
<i>Productivity</i>	<i>Productivity is the efficiency at which a building is being constructed looking at the ratio of capital cost to man hours recorded on site. It is reflected as £ / man hour.</i>		
<i>Pre-manufactured value</i>	<i>Pre-manufactured value captures the value that is created as a result of completing work away from the site. It is calculated by taking the gross capital cost of the project and deducting the prelims - sometimes referred to as site overhead costs - and the site labour costs. The result of this is then divided by the capital cost and is reflected as a %</i>		
<i>EPC Rating</i>	<i>Energy Performance Certificates record how energy efficient a property is and what its environmental impact is, using A-G ratings (A – being the most efficient/environmentally friendly and G – the least)</i>		
<i>Quality rating</i>	<i>Quality of homes is captured by looking at the cost of post-completion defects of a building as set out by the NHBC over the total capital cost. In short it is calculated as 1 minus the cost of post-completion defects over the total build cost, reflected as a %</i>		
<i>Waste generated</i>	<i>This measure looks at the ratio of volume of construction phase waste that has been generated in the construction of the home represented for every £100k of the capital cost</i>		
<i>RIDDOR</i>	<i>The frequency rate is the number of people injured over a year for each million hours worked by a group of employees or workers</i>		
<i>Prelims cost per home built</i>	<i>divided by the total cost per home built reflected as a percentage</i>		

B_CONSTRUCTION PERFORMANCES

- Are you or your organisation involved in the Technical Design phase of the case study project? Did you have any major requirement in terms of construction specifications? Please describe.
.....
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- Are you or your organisation involved in the Construction phase of the case study project? Which aspects of the construction process are being monitored up to completion and at handover? Please direct to appropriate standards if relevant.

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- Will your organisation be involved in the Maintenance phase of the case study project? What metrics or indicators are in use in your organisation to assess the life cycle of a build asset?

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- Is there anything you wish to be monitored during this case study? Do you have any comments about metrics to assess affordable Housing projects or Design for Manufacture and Assembly (DfMA)?

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