

Cambridge Centre
for Housing &
Planning Research

Housing Digital Built Britain Network

Position paper 2: What is the role of off-site housing manufacture in a digital built Britain?

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September 2018



UNIVERSITY OF
CAMBRIDGE

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This project was funded by the Centre for Digital Built Britain.

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1. The question

What is the role of off-site housing manufacture in a digital built Britain?

2. What are the key issues and why is this important?

2.1 Lack of housing supply

The current consensus is that for many years the UK has built too few homes, and too few of them in high demand areas, to satisfy housing demand, resulting in high house prices and increased sharing. This is a critical national issue. Without an increase in supply, housing affordability will worsen, household formation will be constrained, inequality will grow and pressures on government to expand housing benefit expenditure will increase. The consensus estimate of new house building need is 300,000 for England alone, while total completions in 2016/17 were 217,000. Only 183,500 of these were newly built, with the remainder produced from conversions and changes of use. These totals are gross of demolitions: but with only around 10,000 demolitions each year, the existing housing stock of some 20m homes will have a future 'life' of an implausible 2,000 years.

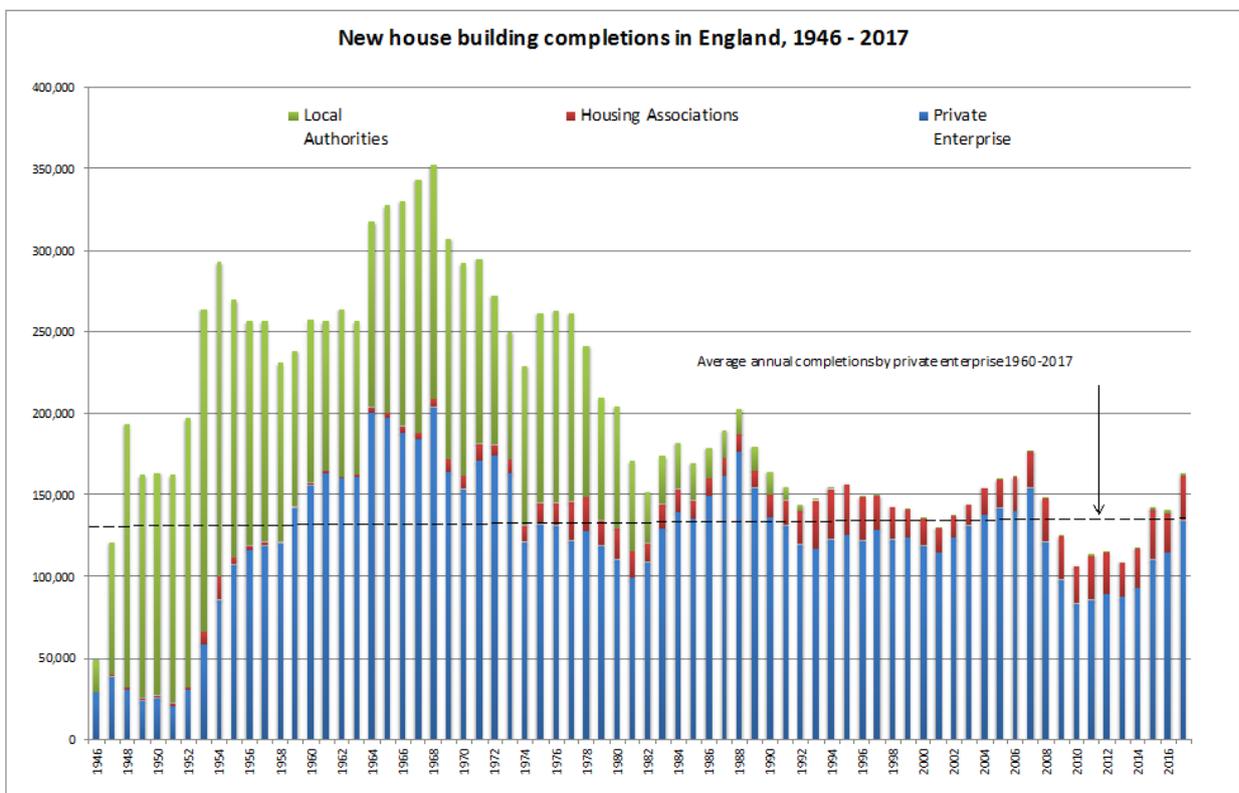


Figure 1 House building completions 1946-2017 (Source: MHCLG Live Table 244)

The majority of new homes are built for sale by speculative house building firms, and over the seventy years from 1946 to 2016, house builders provided three out of every five (62%) homes built, as shown in Figure 1. The speculative house building industry currently builds around 120,000 homes per annum, Housing Associations build some 25,500 and local authorities around a further 1,500. The Figure clearly shows the highly cyclical nature of the speculative house building market

The majority of properties are built using 'traditional' construction techniques, usually with a brick outer skin and a lightweight blockwork inner skin, but there are a wide variety of construction methods, including timber (stick, panellised), steel and concrete. The vast majority of dwellings are assembled on site, in the open air, from large numbers of small modular components (bricks, blocks, tiles, window and door sets, etc.). The off-site manufacture of larger elements is relatively infrequent, although some of the larger volume house builders have their own factories for constructing timber framed wall and roof panels, although these appear to be used only on a proportion of their output (typically, on the social housing element mandated through S106 agreements). At the same time, there are a number of small manufacturers of modular elements, most commonly bathroom 'pods' or prefabricated modular homes for caravan or 'park home' sites. Bathroom pods have been widely used in the hotel and student housing markets, and to a lesser extent for high rise flatted developments. There is a long history of experiments with industrialised building systems in the UK, through early prefabricated experiments in social housing from 1900 onwards, postwar 'prefabs' and the industrialised building systems, mostly large panel concrete, of the 1960s.

The low output of the housing industry, concerns about its quality and extended construction times have led to a resurgence of interest in recent years in the prospect that digitisation and off-site manufacturing might offer solutions. Examples of this interest range from the '£60,000 house' challenge by the Deputy Prime Minister, John Prescott in 2004, to the recent investment of £55m by Legal & General in a factory to produce 3,000 modular homes per annum. The recent report by the House of Lords Science and Technology Select Committee, *Off-site manufacturing for construction: Building for change*, heard a wide variety of evidence on the prospects for off-site manufacturing. It highlighted how in the light of the current housing shortage, the Government has set ambitious targets for house building and announced further investment in the sector in its Construction Sector Deal, but the report also calls on the Government to specify what conditions it might attach to this investment to drive the use of off-site manufacture for residential housing. There are pressures on the industry to increase productivity, speed up delivery, reduce environmental impacts and improve quality whilst reducing costs. Innovation and digitisation through off-site housing

manufacture will be part of the solution to delivering housing in a digital built Britain, but there is currently little in terms of an evidence base.

2.2 Innovation and digitalisation: off-site manufacture

Farmer's 2016 review of the UK construction labour model was dramatically titled *Modernise or Die: Time to decide the industry's future*. The report was damning of the current situation, suggesting that if fundamental changes are not made, the construction industry will become "seriously debilitated" (Farmer, 2016, p.8). The perceived problems in the industry identified in the report included:

- Low productivity, due to not embracing the role of technology;
- Problems of future workforce capacity, due to an ageing workforce, a low level of new entrants, and deep and recurring recessions;
- A lack of collaboration and improvement culture, which prevents organisations from scaling up, sharing risks and creating more business plan certainty;
- Lack of R&D and investment in innovation.

The report strongly advocates the uptake of off-site manufacturing to address the issues above. Farmer states that "now is the time to allow the opportunities from digitisation to offset the risks of continued reliance on labour intensive techniques" (ibid, p.5). Lloyds Bank's *Housebuilding Report 2018* gives a more positive picture of the uptake of innovation among house builders, suggesting that the housebuilding sector is "proving eager to adopt innovative new building techniques, which hold the potential to address challenges around the supply, quality and affordability of new homes, as well as boosting productivity and profitability" (Lloyds Bank, 2018, p.10). Lloyds Bank highlight modern techniques centred on building housing components off-site for delivery and assembly, and also cite futuristic techniques including robot bricklayers and 3D printed homes. Through their research, they found that the majority of building firms are investing in new building techniques, led by modular housing (68%). However, they noted that take-up has been slower among SMEs (firms with a turnover of less than £25m a year), which is likely down to the initial cost of investing proving a higher barrier to adoption (ibid).

3. What does current research and evidence tell us?

3.1 What is off-site housing manufacture?

Off-site manufacture for construction (OSM) is an umbrella term encompassing many different systems (House of Lords, 2018). It is an example of a modern method of construction (MMC) or smart construction, terms used by the sector to describe manufacturing methods that harness digital techniques and Building Information Modelling (BIM), and encompass methods other than off-site manufacture (ibid). Types of MMC which may be carried out off-site currently include:

- Volumetric construction - three-dimensional units which are fully fitted out off-site;
- Pods - used in conjunction with another construction method e.g. bathroom or kitchen pods;
- Panelised systems - panels with timber or light steel framing, structural insulated panels or cross-laminated timber;
- Sub-assemblies and components - larger components incorporated into new homes, including roof and floor cassettes, prefabricated chimneys, porches and dormers, and I-beams (NHBC, 2016, pg. 8).

According to the NHBC (2016), the majority of house builders and Housing Associations are using, or have considered, at least one MMC approach within their recent build programmes. Of the large and medium-sized house builders and Housing Associations surveyed by the NHBC (2016), only two said they had not used or considered at least one form of MMC in the last three years. The most used are sub-assemblies and components, installed by about three-quarters of the house builders and just under half of the housing associations in 2015, and panelised systems are the next most used MMC type (ibid). The NHBC found that very few have used full volumetric construction or pods in the three-year period 2013 to 2015. However, they identified that these are being considered for future use by over a third of organisations. By region, use of volumetric construction and pods has been almost entirely in London and the South East (ibid).

For the purposes of the House of Lords report, off-site manufacture was defined as any of the following methods:

- Components of the building manufactured off-site and then brought together onsite, such as columns, floor slabs and beams. This includes precast concrete;

- Two-dimensional panelised construction, where structures are designed and manufactured in wall and ceiling panels off-site then joined together onsite;
- Elements of buildings sub-assembled off-site. This is where essentials, such as bathroom pods, are manufactured in a factory;
- Buildings manufactured volumetrically or in modules, where whole segments of the buildings are manufactured three-dimensionally and assembled off-site and the completed modules are then fitted together onsite (House of Lords, 2018, pg. 9).

Miles and Whitehouse (2013) took a different approach to defining off-site construction focused 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..... [Offsite construction is] an approach to process in which the construction value added on-site is less than 40% of the final construction value at completion”.

(Miles and Whitehouse, 2013, pg. 20)

However, because off-site manufacture is a term that includes numerous different systems, the House of Lords report states that for the Government’s presumption in favour of off-site construction to be understood clearly, some taxonomy is required to help clarify it (2018).

3.2 How are digital tools and technologies being used in off-site housing manufacture?

The House of Lords report concluded that emerging digital technologies have the potential to transform off-site into a more viable alternative to on-site construction (2018), but the report did not identify any particular digital technologies. Whilst much has been written about off-site construction generally, there is little information about how digital technologies are used in off-site housing manufacture. For example, sophisticated digitalised information systems are required to facilitate a common data environment, and this is particularly important in housing projects manufactured off-site, but we know little about such developments. Digital technologies are important for information sharing/BIM in off-site manufacture for managing design, procurement and delivery, and generally in volumetric factory production, but we have few specific details.

Abanda et al. (2017) argue that emerging BIM provides opportunities to leverage the benefits of off-site manufacturing, that the biggest growth in construction productivity will come from automated off-site activities facilitated by BIM, but also note that studies about the impacts of BIM on off-site manufacturing are scarce. Their review found some studies looking at: how BIM can be used in modelling and managing off-site manufactured buildings; how different BIM software systems have been used in the modelling of a prefabricated house in the different phases of the construction life cycle; how BIM can be used to guide how the prefabricated components should be put together to form a building; and some studies focusing on the ease of incorporation of off-site manufacturing and collaboration early on in the design and construction process using BIM (Abanda et al. 2017). They argue that BIM can facilitate off-site manufacturing in different ways, for example:

- BIM allows greater precision in specifying material requirements, which can reduce over-ordering and thus decrease construction site waste.
- BIM can assist fabricators and contractors by providing a 3D model of element positions.
- BIM technologies can accurately represent geometry, behaviour and properties of individual building components/objects and can facilitate their incorporation into standardised building elements or volumes and made available digitally.
- The information contained within or linked to BIM models allows the possibility for direct interfacing between designers, suppliers, manufacturers and users. (Abanda et al., 2017, pg. 92)

3.3 What are the potential benefits of off-site housing manufacture?

Krug and Miles (2013) define sustainability as “the simultaneous pursuit of economic prosperity, environmental quality and social equity. Sustainable construction needs to perform not against a single, financial bottom line but against this triple bottom line”, and argue that off-site construction “stands up well when tested against this definition” (pg. 4). The House of Lords Select Committee states that the benefits of off-site manufacture for construction in general are:

- Better quality buildings and infrastructure;
- Enhanced client experience;
- Fewer labourers and increased productivity;
- Creating more regional jobs away from large conurbations;
- Improved health and safety for workers;
- Offering building safety advantages - making it easier to ensure buildings meet quality assurance standards;
- Improved sustainability of buildings and infrastructure; and

- Reduced disruption to the local community during construction (House of Lords, 2018, pg. 15)

The NHBC surveyed house builders and found that the main reason for considering use of MMC was to achieve a faster build programme, other reasons included improving build quality, tackling the skills shortage, improving health and safety, achieving a fast weathertight envelope, reducing costs and improving site efficiencies (NHBC, 2016). Housing Associations were motivated by the need to deliver homes quickly and cost effectively (ibid). Similarly, MacFarlane (2018) identified that the interest in off-site manufacturing stems from:

- Its potential to improve speed and sustainability. The start-to-completion time can be reduced because building can start at the same time as site preparation, with both taking place in parallel;
- Off-site manufacturing is argued to be less affected by building delays caused by poor weather and staff shortages;
- Defects are fewer if fabrication takes place in a factory and it is possible to manufacture with millimetre precision;
- Off-site manufacturing's economies of scale and increased opportunities for automation offer cost advantages compared to traditional building methods.

The National Audit Office (NAO) suggested that using modern methods of construction should make it possible to build up to four times as many homes with the same on-site labour, and that on-site construction time can be reduced by over a half (NAO, 2005), but data on this has not yet been collected.

3.4 What is the policy background?

There has been a recent policy drive to promote off-site construction. The Government's Construction Sector Deal, and its stated 'presumption in favour' of OSM, have shown a strong commitment to investing in this area (House of Lords, 2018).

In the 2018 Autumn Budget speech, it was announced that Government is to prioritise use of off-site manufacturing and other modern methods of construction by adopting a presumption in favour of offsite manufacturing across suitable capital programmes, where it represents best value for money. In the light of the current housing shortage, the Government has set ambitious targets for house building and announced further investment in the housing sector in its Construction Sector Deal (House of Lords, 2018). The Construction Sector Deal (2018) argues that off-site manufacturing technologies will help to minimise the wastage, inefficiencies and delays that affect onsite construction, and enable

production to happen in parallel with site preparation – speeding up construction and reducing disruption.

The Home Building Fund (2016), administered by the Homes and Communities Agency (HCA) on behalf of government, provides development and infrastructure finance, and is intended to support innovation, including off-site manufacturing. The Homes and Communities Agency's Accelerated Construction £2bn programme involves taking direct action to build homes on surplus public sector land to increase the pace of housebuilding and diversifying the market by supporting smaller builders and modern methods of construction (HCA, 2017).

3.5 Recent developments in the industry

There have been recent entrants into the off-site housing market, the Chartered Institute of Building's BIM+ identified:

- Laing O'Rourke has announced a "game-changing" offsite partnership with developer Stanhope and housing association Network Homes to deliver hundreds of dwellings across the south east, providing £104m for a factory in Worksop;
- Urban Splash bought the offsite construction business from materials giant SIG;
- Berkeley Group (a volume house builder) has the go-ahead to build a modular homes factory in Ebbsfleet (Chevin, 2018).

In addition, MacFarlane (2018) reported that Croydon Council has recently granted planning consent for the world's tallest modular buildings, comprising 44-storey and 38-storey build to rent towers that will accommodate 546 homes, where the developer, Tide Construction, has already built Europe's tallest modular tower, a 29-storey student accommodation scheme in north London. L&G, a major player in the build to rent sector, invested £55m in a large facility in Leeds (ibid). Countryside Properties plans to build its own modular housing factory and announced its intention to invest £6m in a new timber frame factory in Warrington, which is expected to build around 1,500 homes a year, to particularly support the business in its focus on building homes for rent (Curry, 2018). The first houses from ilke Homes are being produced "the British modular homes business specialising in the latest off-site manufacturing techniques. Set up to operate at scale, ilke Homes is on track to deliver 2,000 modular homes a year from its Yorkshire factory" (ilke Homes, 2018).

Home Group is one of the biggest Housing Associations in the UK with a turnover of over £350m and one of the UK's largest providers of new homes and houses for affordable rent. Home Group are building a new village of 35 modular houses, using five different house

types, alongside six traditional, bricks and mortar homes. Gateshead Innovation Village is a live research project to test a range of modern methods of construction products, including modular houses, green and smart technology on one site (Home Group, 2018). Swan Housing Association's NU factory aims to produce 300-400 "precision engineered" modular homes per year, made of sustainable Cross Laminated Timber. For the homes for sale in the private market, buyers will be able to "use our online configurator software to design their new home" (Swan, no date).

However, despite optimism in the housing sector, there have been setbacks. For example, there have been delays in the first L&G factory homes being produced, which were originally planned for completion in 2016 (Chevin, 2018). Your Housing Group announced in 2016 a partnership with WElink, a renewable energy business backed by China's National Building Material Group, to fund six modular housing factories in the UK to build 25,000 homes across the UK over five years. However, Your Housing Group withdrew from the joint venture in early 2018 (Place North West, 2018). Student accommodation specialist Unite shut its pod manufacturing business at a cost of £21m in 2012 because dealing with fluctuations in demand proved too costly for a fixed-cost factory (Morby, 2012).

3.6 Why has take-up of off-site housing construction been limited?

Construction 2025, the government's 2025 industrial strategy, identified five main barriers that prevent innovation in the construction sector:

1. The nature of construction procurement frequently restricts collaboration between client and supply chain, particularly at an early enough stage to fully explore options for innovation;
2. Companies are not confident that innovation will be commercially rewarding, with particular concerns about levels of demand for innovative products and services;
3. Companies that do want to innovate find that the necessary finance is too expensive and/or difficult to access, that the approach to risk and insurance of works deters innovation, and that some of the Government support available to the industry is not sufficiently visible;
4. There is a failure to capture learning from successful innovations and take this forward to future projects; and

5. Collaboration between industry, academia and research organisations is patchy, which limits effective knowledge transfer (HM Government, 2013).

Krug and Miles (2013) identified that whilst off-site construction has a wide range of sustainability benefits, some of which are coupled with significant financial benefits, in some cases the “benefits arising from the sustainability case bring no direct advantage to the developer or the building contractor” (pg. 17), which inhibits wider take up of off-site construction. They also found that many of the financial benefits are relatively small when measured as a fraction of the construction value so their degree of influence over the choice of construction method is therefore unlikely to be significant (ibid). Similarly, Miles and Whitehouse caution:

“House-builders are risk averse and typically will not adopt the use of novel technology unless there are powerful commercial arguments that justify taking on that risk. We need to bear in mind that the cost of materials used in the construction of new homes represents only a small proportion of the overall cost of new homes and any savings from the introduction of new solutions or processes are likely to be modest.”(2013, pg. 9)

Twelve house builders surveyed by the NHBC had used volumetric construction at least once in the last three years and their experiences were mixed (NHBC, 2016). They did not all encounter the expected benefits, and their experience highlighted the importance of paying detailed attention to co-ordination and planning well in advance of construction starting on-site and during construction (ibid). Cost remains one of the barriers to the wider uptake of off-site housing construction. Whilst cost ranges may be comparable depending on specific project circumstances, they are higher on average when MMC are used (NAO, 2005). Manchester City Council has been exploring the potential of modular housing as a solution to lack of supply, however, Joanne Roney, chief executive of Manchester City Council, found that:

“As with all things far too good to be true, the challenges of modular are greater than hoped”.

She said that, for Manchester City Council, the biggest barrier is finding a product that allows them to use their available land, regardless of size, and still beat the price points of traditional build methods, and described how it became obvious that modular manufacturers were going to struggle to beat traditional build costs for affordable two-storey family homes at lower density sites (Roney, 2018). Volumetric off-site housing production needs large upfront investment e.g. in developing a factory. However, these upfront costs do not take into

account the lifetime operating costs of housing and so do not account for the potential of more efficient management of housing assets once handed over to owners.

Existing evidence suggests that there are a range of issues which may be constraining the development and success of off-site construction that are not related to engineering, architecture and design (DCLG, 2008; Calcutt, 2007; CML, 2002). There are challenges around the structure of the house building industry, where market homes are brought forward at a rate of around one a week, with multiple diverse sites active across the country, and the few larger house builders each having developed their own range of standard house types. The Calcutt Review noted that those sceptical about off-site methods feel that “it requires considerable up-front investment in manufacturing plant which offsets the savings from faster construction times, and is likely to leave MMC as an uncompetitive option until demand has greatly increased” (pg. 29). The review identifies that house builders need to manage the pace of build-out to maximise profits from a site and so sheer speed is relatively less important (Calcutt, 2007). Attitudes of prospective buyers are also important and “house buyers have traditionally been resistant to MMC, possibly influenced by memories of post-war prefabs and the system build houses of the 1960s” (ibid, pg. 31). Mortgage lenders have been reluctant to provide finance for homes built using unfamiliar forms of modern construction. Current house builder business models may also be a constraint on the wider use of off-site construction. These models:

“Require the flexibility to cope with the wide range of conditions at the project level. They cope well with the differences and vagaries of site conditions, demand patterns, construction approval processes and design requirements. That present models work so well is because they have been optimised for current conditions. But it is these very vagaries that can create a barrier to the adoption of the new processes that MMC demands”. (Barker 33 Cross-Industry Group, 2006, pg. 7)

Miles and Whitehouse (2013) noted that the batch-production model of the current house building sector is not an easy fit with large scale off-site manufacture and “it will require considerable efforts by off-site suppliers to understand how the house-building industry operates in order that it can better meet the project needs of the market” (ibid, pg. 8). They suggested that some off-site suppliers were:

“Operating manufacturing practices that make it hard to provide for the cost effective delivery of small batch production runs capable of meeting the development practices of the house-building industry as it exists today. Currently the opportunities to apply economies of scale through mass-production techniques to reduce unit

price do not exist in the domestic house-building for private sale market". (Miles and Whitehouse, 2013, pg. 8)

The use of off-site construction also does not necessarily tackle the challenges of land supply, constraints in the planning system, or NIMBY-ism and opposition to new housing development. For example, existing planning and land constraints may restrict investment in off-site:

"The implications of current planning and approval delays, uncertainties (including differences between local policies) and the supply of land with planning permission necessarily affect the climate for development. They adversely affect both the risks associated with investment in innovation and the ease with which economies of scale for product-based methods of construction can be achieved". (Barker 33 Cross-Industry Group, 2006, pg. 7)

Modern methods of construction, including off-site, change the risk profiles of house building projects and some risks become more significant, such as unpredictable planning decisions and designs that are not suited to the construction method (NAO, 2005). Risks increase in the early stages of a project before on-site work starts (ibid), and such risks may inhibit a shift away from traditional construction methods. Risks identified by the NAO included late design changes; loss of factory production slot/production capacity; inaccurate or unsuitable foundations; suppliers failing to deliver on time; and manufacturer insolvency (NAO, 2005, pg. 21).

The House of Lords reported concern that the UK lags significantly behind other countries in use of off-site housing manufacture in the low-rise residential sector and said there will be challenges in developing the off-site sector:

"Much of the evidence we received painted a picture of a construction sector which is fragmented and lacking in trust. The current business models and the traditional model of financing and cash flow in the construction sector make it difficult to deliver the benefits of off-site manufacture for construction". (House of Lords, 2018, pg. 4)

Not only will business and finance models need to change, but new skills will need to be developed in the industry:

"While OSM could lessen the labour shortage, the different skills required for manufacturing are currently lacking in the UK labour market and must be developed. OSM will require a combination of skills involving site implementation, digital and

procurement. The Government must therefore ensure that young people entering the workplace are equipped with the digital skills needed for modern methods of construction, including off-site manufacture.” (House of Lords, 2018)

Miles and Whitehouse (2013) found that the view of off-site suppliers was that the house building industry “will at some point undergo a sea-change that will see off-site components increasingly being used in place of traditional site-based construction methods”. However, given the constraints identified in using off-site methods to build low-rise residential housing in particular, it is not clear what the specific drivers of such a “sea-change” might be.

4. What are the gaps in knowledge?

This rapid review of the literature and discussion at the first Network event has identified several areas in which further research is needed.

- **What do we mean by off-site housing manufacture?**

Whilst much has been written about off-site construction generally, there is little information about how digital technologies are used in off-site manufacture. As identified by the House of Lords, off-site manufacture encompasses many different systems, and for the Government’s presumption in favour of off-site construction to be understood and responded to, some taxonomy is required to help clarify it (2018).

- **What are key issues in the housing market and housing supply chain that off-site housing manufacture and digitisation might be expected to address?**

Emerging digital technologies might have the potential to transform off-site into a more viable alternative to on-site construction, but it is not clear in what specific ways this will happen. More research is needed to identify the particular issues and problems that off-site might realistically solve. For example, there have been suggestions that off-site housing manufacture and digitisation might reduce housing costs long-term. However, it is not clear if these lower costs would improve housing affordability, or if the savings would result in higher payments to landowners and/or higher returns to house builders and their shareholders. Whilst off-site may solve some of the labour shortages in the industry, new digital skills will be required for the off-site sector to flourish.

- **How are digital tools and technologies being used to develop off-site housing manufacture?**

Some forms of off-site housing construction have been used for many years. More work is needed to identify innovation and new developments in housing construction, and to identify where and how data and digital technologies play a role. For example, will the innovation come through BIM, new forms of factory production, or the robot bricklayers and 3D printed homes noted by Lloyds Bank?

- **What is the nature and scale of the current provision of off-site housing manufacture?**

We do not have a comprehensive picture of the current market, who the existing providers of different types of off-site housing are, who is investing in new technologies, what types of digital tools and technologies they use, how many units they produce or aim to produce, and who purchases, or is expected to purchase, them. More work is needed to explore which areas of the housing market are currently most engaged with digital manufacturing and off-site production, for example, this might be the student housing developers, apartment construction, or production of bathroom pods, and which actors are driving this innovation forward. Many Housing Associations have been experimenting with new forms of off-site and modular homes, as have some volume house builders. Assessing the current market and its scale would be an important first step.

- **What is the evidence of the outcomes of such housing to date?**

Useful research would be to explore the experiences of the construction firms who have been investing in and using digital technologies to develop off-site housing of various kinds (what the market is like, technical developments, digital innovations, scale and nature of production etc.), the experiences of purchasers e.g. Housing Associations (why go for this type of off-site, costs, benefits, challenges of data sharing, delivery and installation etc.), and the experiences of residents living in such homes (are the homes different, what are they like to live in, etc.). An important issue to explore is costs, analysing not just upfront costs of housing produced off-site but also the operating costs over the lifetime of housing assets, and the wider potential benefits of asset management, particularly for organisations such as Housing Associations with large housing portfolios.

- **What are the non-digital issues that need to be considered in the development of the off-site housing sector?**

As described earlier, there are a range of issues which may constrain the development and success of off-site construction that are not related to digital technologies, engineering,

architecture and design. There are issues around the structure of the house building industry, land supply, the planning system, finance, regulation and mortgage lending. Research is needed to analyse what challenges these issues in the housing supply chain pose for the expansion of digitised off-site housing development, and to explore what policy and practice solutions might be needed to remove the constraints on the off-site sector.

- **Why has take-up of off-site housing been greater in other countries?**

The House of Lords reported concern that the UK lags significantly behind other countries in use of off-site housing manufacture in the low-rise residential sector. The UK has been slow compared to countries such as Sweden, Germany and the US in its adoption of off-site manufacturing. Research is needed to review the reasons for this faster progress in other countries, and to analyse what lessons the UK might learn to stimulate wider uptake of off-site housing construction.

- **Learning from experience - why did prefabrication/industrialised building fail in the past? What can be learnt from previous experiments? Are we condemned to repeat the same errors because we are losing the institutional/industry knowledge?**

The UK construction industry has experimented with off-site methods before but these efforts have been widely criticised for the low quality of the building materials and the poor workmanship of this form of construction during the post-WW2 period (O'Neill and Organ, 2016). The UK should therefore learn from its previous mistakes to avoid repeating the same social and economic problems (e.g. lost identity, poor quality of design and construction materials, dullness and lack of variety in the products etc.) of the last century (Hashemi, 2013). It is important to review the lessons of previous attempts to expand the off-site housing sector and ensure that learning is taken from this experience.

- **What size and tenure of housing unit should be produced using new digital tools and technologies? What are the demand side factors that will shape what housing meets peoples' needs into the future?**

Technological and digital knowledge alone is not sufficient to develop the off-site housing sector. More data is needed about demographic and socio-economic changes over the next generations in order to assess what size and tenure of housing unit should be produced using new digital tools and technologies. For example, home ownership is declining and over 20% of the UK population now lives in the private rented sector, set to rise further over the next decade. In 2017, the build to rent market attracted £2.4bn in investment and it is forecast to grow by a further 180% over the next six years. These wider changes in housing tenure, incomes, aspirations and housing need must be taken into account in developing the

market for off-site housing. Will people want to live in such homes? Public attitudes towards modular and 'prefabricated' housing are currently quite negative. This is likely to be because of the failures of prefabricated homes in the decades post-war, and because of little knowledge about modern off-site methods and house styles. How might such attitudes be shaped? Where does greatest potential in the market lie, for example, will affordable/social housing and the build to rent market be where greatest uptake occurs first?

- **How should the outcomes of such housing be evidenced? How should the value of off-site housing be measured?**

There is very little evidence of the outcomes of off-site housing. This includes information about build costs, running and maintenance costs and requirements, energy efficiency, and the experience of living in them, for example. We also do not have a conceptual framework for measuring the value of off-site housing. For example, how do we consider the multiple stakeholders who might be affected by not just benefits but also costs? What will the economic impact be of wider take-up of off-site housing? How might it impact upon small and medium house builders, for example, if the preference becomes for volumetric factory housing production?

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