Modern methods of construction (MMC) for net zero housing:

Implications from the social sciences and humanities

UKERC Working paper

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1. Introduction

The UK's construction industry has been struggling to meet the rising demand for housing since the 1960s. Currently, the housing deficit stands at 4.3 million homes (Watling and Breach, 2023). The deficit is far more pronounced for the social housing sector, as the UK needs 150,000 new social housing units every year to meet the demand (MHCLG, 2019). Meanwhile, the UK's construction industry also faces the most daunting challenge of reducing its greenhouse gas (GHG) emissions. The UK's building stock accounts for nearly 25% of total national emissions, an alarming figure considering that 80% of the total building stock of 2050 has already been built (EAC, 2022). With the UK pledging a net zero target by 2050, the industry must transform itself to rapidly deliver low-carbon buildings.

Modern Methods of Construction (MMC) have been promoted by the government as a solution to address both these challenges at scale. MMC[1] entail using prefabrication in environmentally controlled factories for between 75-95% of the constructed assets (Pan, Gibb and Dainty, 2007). MMC bring numerous benefits, including reduction of construction waste and environmental impacts, faster construction rates, higher quality assurance and control of buildings, lower requirements of maintenance or repair, reduction of the overall cost of construction and labour, and improved working conditions and health and safety of workers (Payne and Serin, 2023). Nevertheless, the uptake of MMC has been particularly low in the UK housebuilding industry, with only 8% of existing homes built using MMC (Savills, 2020). This can be linked to the absence of enabling regulations, the resistance of the industry towards adopting innovative methods and techniques, inertia within the business culture of housebuilding and insurance firms, poor awareness and perceptions of consumers regarding MMC, and the under-preparedness of the industry to deliver MMC projects (MHCLG, 2019; Payne and Serin, 2023). In particular, the confidence that clients have in MMC businesses is a critical factor that influences their decision on whether to employ MMC, which is often affected by the poor communication link between clients and the suppliers of MMC projects (Saad, Dulaimi and Zulu, 2023a).

In light of the above, this policy brief addresses the evidence base for the potential of MMC in helping transform the UK's construction industry towards greater efficiency and sustainability. To accomplish this, a scoping review has been conducted of relevant peer-reviewed scholarly and grey literature, primarily focused on the UK, and findings have been complemented by key knowledge insights from social sciences and humanities (SSH) perspectives in order to highlight implications for user behaviours, and energy poverty, governance and justice, with relation to low-carbon buildings in the UK, which are often absent under technical disciplines (Foulds and Robison, 2018). The brief concludes by offering recommendations for the building

[1] In the academic literature, multiple terms are often used synonymously with MMC, including off-site production/construction/manufacturing, modern methods of construction/manufacture in construction, prefabricated housing/building systems, modular integrated construction, etc, despite nuanced distinctions between each of the terms (Payne and Serin, 2023).

industry and the UK government for exploiting the advantages offered by MMC in meeting different sustainability and net zero targets and standards in the UK.

2. Modern methods of construction (MMC), a panacea? Investigating sustainability, scalability and safety

2.1 Environmental sustainability

The environmental impact and associated sustainability challenges of construction are the critical drivers of MMC in the construction industry. Consequently, evaluation of the sustainability of MMC projects has been one of the most prominent subjects of research in the field (Li et al., 2022), some of which will be discussed in this subsection.

2.1.1 Emission reduction

Most studies indicate that buildings using MMC generate lower amounts of GHGs than their conventional counterparts, even though these levels may vary from project to project (Chen et al., 2022; Li et al., 2022). In a recent study of two UK housing development programmes that produced a total of 879 dwellings using a modular approach, it was found that MMC reduced embodied carbon by almost half, amounting to 28,000 tonnes of carbon emissions avoided (Delahunty, 2022). Similarly, a report published by the Advanced Industrialised Methods for the Construction of Homes found that on a whole-life carbon basis, embodied emissions from an MMC-based project were up to 82% less than projects using traditional methods (AIMCH, 2022). However, not all projects using MMC techniques result in emissions savings (Hu and Chong, 2019). For instance, a two-story house constructed using MMC in the UK was found to have 2.3 times more embodied carbon than a house constructed using conventional techniques (Kalidoss and Mohammadpourkarbasi, 2022).

These conflicting results can be attributed to a number of factors that can affect embodied carbon emissions calculations, including the diverse calculation methodologies and criteria that are often used (Chen et al., 2022). Moreover, the carbon reduction potential of MMC also relies on the extent to which construction is conducted off-site. This suggests that there is a critical need for a proper and industry-wide agreed methodology to measure emissions from buildings, which will be crucial to understand the emission mitigation potential of MMC.

Currently, one of the greatest barriers to streamlining and standardising a methodology for measuring the emission reduction potential of MMC is the poor exchange of knowledge within and between different sectors involved in the value chain, which is often exacerbated by a tendency of those involved in the projects to gatekeep their emission quantification procedures (Chen et al., 2022). More importantly, methodological challenges require more than merely technical solutions. These need to be complemented by an accurate representation of the wider socioeconomic and political context within which MMC operates. SSH insights can play an important role in helping enhance the research-policy interface by shedding light on the feasibility of emission-curbing strategies. They can also explore how existing and available technologies are embedded in current building policies and industry behaviour, and evaluate the innovation potential in low-carbon buildings (see for example Killip, 2013). Therefore, while there is a crucial need for a widely agreed methodology to quantify emissions, it is also important to ensure that the methodology fits the context of the UK's building industry.

2.1.2 Energy efficiency

A key component of the British Energy Security Strategy is improving energy efficiency by lowering the amount of energy needed by homes and businesses (BEIS, 2022). The government recognises the energy efficiency of homes as a key response to rising energy prices, where it can bring down heating bills by 20% (BEIS, 2022). MMC can improve energy and resource performance at the industry level and throughout the building's life cycle due to their reliance on sustainable design techniques, environmentally friendly facilities and materials, and reuse strategies (Hu and Chong, 2019; Li et al., 2022). For example, Keepmoat Homes, a housebuilding company in the UK that provides private homes for sale, reported that 20-30% less energy is used to heat MMC homes in comparison to traditionally built new homes (MHCLG, 2019). Recent studies of building projects in other countries (e.g., Hu and Chong, 2019; Nguyen, Moon and Ahn, 2022) also show that 20-32% energy savings can be achieved using prefabrication techniques. Overall, MMC are widely recognised as having significant potential for high thermal and energy performance, although some studies do suggest that they can also cause an increase in energy consumption, again attributed to the method of calculation and calibration of energy-saving levels (Hu and Chong, 2019; Li et al., 2022).

Improving the energy efficiency potential of MMC-based projects is another important avenue where SSH can make significant contributions. Currently, research in low-carbon/energy-efficient buildings is primarily framed under technical, environmental, or even economic lenses. However, a significant amount of industry learning and skill development is required to deliver projects under MMC, as eventually, buildings become spaces where different occupants interact differently with energy facilities, affecting the energy consumption within them (Stevenson and Leaman, 2010). Due to a lack of integration of SSH knowledge about occupant behaviours when designing projects, buildings can end up failing to deliver on their desired ambitions to reduce emissions during the building's life-span, due to factors like 'rebound effects' or 'value-action' gaps (Gram-Hanssen, 2014). In the absence of contributions from different SSH disciplines, there is a risk of normalising purely quantitative and technical metric-based standards for efficiency, which end up perpetuating existing unsustainable patterns of energy demand (Shove, 2018).

2.2 Waste reduction

Construction processes, including demolition and excavation, generate more than half of the total waste in the UK (MHCLG, 2019) and any improvement in the recovery rate of waste within the construction industry has remained largely stagnant over the years. MMC can offer huge waste reduction capacities. Reduced material waste, decreased material loss or misplacement, and improved procedures are some aspects that contribute to waste reduction when using MMC (Li et al., 2022). Additionally, by increasing the ratio of recycling to reuse, such as with demountable and layered design and normative design standards, the amount of construction waste generated during the demolition stage can be decreased (Li et al., 2022). In contrast to traditional buildings, where material waste typically ranges between 18% and 22%, factories can be optimised to reduce material waste to under 1% of the total for the projects using MMC (MHCLG, 2019).

However, modular construction is still heavily siloed from maintenance and waste management in the UK – a missed opportunity to promote the circularity of prefabricated components (Iacovidou et al., 2021). Moreover, there are growing concerns that MMC might make it harder to reuse materials, particularly composite materials that are glued together (Lowe, 2022). Strict demarcations between the functioning of the construction and waste management sectors can inhibit the exchange of important information, which makes it difficult to anticipate the impacts of actions from one sector on another. Therefore, there is a gap, as well as an opportunity for cross-sectoral collaboration between the two sectors when it comes to tackling the issue of waste management from construction, which will not only help address these trade-offs, but also allow both sectors to successfully reach their net zero targets. Indeed, a circular economy focus is a pre-requisite for the UK's construction industry to achieve net zero, and solely by cutting the use of raw materials, emissions can be reduced by two-thirds within 12 years (Green Alliance, 2023). This is why circular economy principles are now increasingly being promoted in terms of reusing materials, especially for refurbishments in the UK.

2.2.1 Project management and implementation

When it comes to project implementation, the economics of MMC are a major priority for many stakeholders, as they seek to validate the on-ground benefits of MMC, such as enhanced productivity, quality, project duration, and cost effectiveness (Li et al., 2022). This sub-section critically discusses the impacts of MMC on some of these aspects.

2.2.2 Project duration and costs

MMC have been widely promoted to address the housing deficit in the UK. A fast turnaround between 'ground-breaking' and occupancy is a major advantage of modular construction, as both site preparation and building construction take place at the same time, and any likelihood of delays brought on by severe weather, vandalism, and site theft is significantly lowered (Kamali and Hewage, 2016). The National Audit Office found that volumetric MMC can reduce on-site construction time by 20-60% when compared to traditional homes (MHCLG, 2019). Indeed, one of the primary reasons contractors select MMC is due to their ability to deliver projects quickly (Pan, Gibb and Dainty, 2007; Payne and Serin, 2023). For example, the Portakabin Group's 99.7% completion rate for all projects, compared to the industry average of 40% for project time and 30.7% for project cost predictability, is proof that employing off-site solutions improves predictability (KPMG, 2016).

Nevertheless, a significant barrier that impedes the uptake of MMC is high initial investment. In order to set up production lines and machinery and train staff in new building techniques, industrial facilities that manufacture MMC modules require a sizable initial investment. Moreover, MMC fabrication facilities need large yards to build modules before they are installed on-site, resulting in higher operational costs (MHCLG, 2019). Currently, a lot of MMCs are experiencing major losses due to the general lack of demand for MMC projects, since existing supply business models are failing to communicate confidence to public client organisations (Payne and Serin, 2023; Saad, Dulaimi and Zulu, 2023b). Current models fail to account for how the overall project cost can be significantly lowered via off-site construction (Kamali and Hewage, 2016) through: (i) the bulk order of supplies and lower transportation costs for workers and machinery; (ii) on-site overhead reduction, avoidance of weather extreme exposures, standardisation of design, higher energy efficiency, and greater installation efficiency; and (iii) reduced workers on site, which relieves labour shortages and boosts craft production. In addition, a study by the UK government also demonstrates how off-site manufacturing is capable of producing a new home in a single day while also cutting the cost of an average home by at least 10% and increasing delivery predictability (KPMG, 2016). Overall, MMC can result in a 20-40% reduction in construction costs, as well as the potential for improved whole-life costs (MHCLG, 2019).

Lifting barriers imposed by poor awareness and perception of costs is integral to the widespread adoption of MMC in the UK. Providing better clarity regarding costs (Payne and Serin, 2023) by considering the entire project lifecycle, as well as the savings brought about by reduced project time, will be crucial to improve the appeal of MMC for housebuilders. SSH insights are also important to demonstrate the complexity and interconnectedness of markets, where prices, costs and values are created through the amalgamation of social, political, technical, institutional, cultural and economic factors (Lovell and Smith, 2010), in order to properly capture the real costs of MMC-based projects.

2.2.3 Project quality

There exists a legacy of questionable and subpar prefabrication techniques, particularly from the post-WWII era, which has eroded the industry's faith in MMC (Payne and Serin, 2023). The contemporary emphasis on quantity, or how MMC accelerates housing production, contributes to this stigma, and may undermine policy objectives focused on expanding the use of MMC. However, it has been demonstrated that contemporary MMC projects that are typical of today's industrial practice offer numerous advantages, including improved building quality and higher quality control (Payne and Serin, 2023). A greater level of product quality can be attained through automated equipment, and repetitive procedures and activities (Saad, Dulaimi and Lulu, 2023b). Moreover, less material exposure to inclement weather on the construction site can result in higher building quality (MHCLG, 2019).

Nevertheless, pre-project planning and engineering are considerable hurdles for prefabrication, preassembly and modularisation. Modular architecture differs greatly from traditional architecture. In addition to the complexity of the design of the modules themselves, additional considerations are required for the integration of various components within a module, as well as for the lifting, transportation, placement and joining of modules to create the building at the final project site (Kamali and Hewage, 2016). Since complex modules result in complicated interconnections, additional engineering design is required. Skill shortage, both among architects and developers and workers, has consistently stood as a major barrier to the uptake of MMC in the UK (Payne and Serin, 2023). The success of MMC, therefore, depends on upskilling in the industry to help it better prepare for delivering MMC projects.

There is also much to be done regarding the poor consumer perception of MMC-based projects. In order to tackle the hangover of poor quality of projects left by old MMC practices, any regulation or policies related to MMC should include increasing the quality of housing by providing codes and standards, rather than simply promoting MMC as a booster for increasing the number of new build houses in the UK (Payne and Serin, 2023). The perception of consumers also needs to be addressed by improving the line of communication between the MMC supply sector and clients' demands (Saad, Dulaimi and Zulu, 2023a). One way to achieve this is by adopting hybrid strategies, as undertaken by some UK housebuilders, in their bid to overcome the negative public reception of prefabricated buildings. An example of this is building prefabricated houses in a way that appears to be similar to those built using masonry methods, such as by lining the houses with a brick outer layer, which strives for 'alignment rather than distinction' (cited in Payne and Serin, 2023) in order to make MMC projects look more like traditional buildings.

2.2.4 Workers' occupational health and safety

The social benefits of MMC are largely ignored in research, despite being substantial, especially for workers (Li et al., 2022). For instance, due to the use of multiple pieces of construction equipment, not only do MMC improve the automation of the construction process, they also subsequently create a safer working environment for construction workers (Kamali and Hewage, 2016; Li et al., 2022). Since about 85% of the work is completed off-site, modular construction is safer, avoiding the constantly changing nature of on-site work (MHCLG, 2019). Transferring the bulk of the construction work to factories with simpler and highly repetitive site operations can reduce workplace accidents, the need for working at heights, congestion and exposure of workers to harsh weather, dangerous activities and nearby construction operations (Kamali and Hewage, 2016; PBC Today, 2019). On-site reportable incidents could be decreased by 80% when using MMC (Kamali and Hewage, 2016), and because the task is simpler, prefabrication and modular construction require less trained labour on site, thereby cutting labour needs by up to 75% (MHCLG, 2019). Moreover, the highly organised processes, the potential for improved supervision, shorter time gaps between different trades and workforce stability all contribute to higher productivity in modular projects (Kamali and Hewage, 2016). MMC also have the potential to upskill and strengthen the UK manufacturing industry through high-tech manufacturing and new supply chain opportunities, while increasing overall export potential (Payne and Serin, 2023). Moreover, due to an increased proportion of factory-based work, standardised hours and potential for localisation of factories, areas with high rates of unemployment can be targeted to generate employment opportunities in the construction sector, especially for underrepresented groups, such as women (MHCLG, 2019). In doing so, MMC can also be used as a vehicle to promote a more inclusive labour workforce.

2.2.5 Securing insurance

Over the years, rising rates and shrinking capacities of the UK's insurance markets have caused insurers in the UK to be less willing to take on risks. Such risk aversion can act as a barrier to the uptake of MMC due to the insurers' relative lack of familiarity with techniques, particularly at the operational phase, where real-world data on how MMC buildings fare in fire and situations of large escapes of water remain scant (Desmond and Fitzgibbon, 2022). Ultimately, any risks and supply chain concerns would need to be significantly outweighed by the benefits of using MMC, such as lower risks of project delays and extreme weather, lower requirement of manpower and safer working environments. Construction firms and their brokers will have to provide insurers with evidence of their expertise in MMC, robust quality assurance and control regimes, contractual arrangements between contractors and suppliers, and risk allocation strategies, as well as detailed plans for laydown areas and off-site storage (Desmond and Fitzgibbon, 2022). Overall, the rise of MMC in the construction industry points to the expectation and need for insurers to collaborate on insuring such risks through public-private partnerships. The public sector in the UK especially is playing a crucial role in establishing procurement standards and promoting the adoption of MMC. New modes of governance that draw upon the advantages of collaboration between public and private sectors can help drive innovation in the construction sector

(HM Treasury, 2012), thus helping scale up MMC, and consequently appear more attractive to insurers.

2.3 The way forward

2.3.1 Bridging gaps in sustainability outcomes: Improved decision-making

Improving the sustainability of MMC involves improving the scope of effective decision-making. Decision-making often includes accounting for many uncertainties, which can affect the potential of MMC to deliver buildings sustainably. Information theory and advanced technologies such as building information modelling (BIM), radio frequency identification devices (RFID) and the Internet of Things (IoT) are gradually being used to support decision-making to reduce uncertainty in construction and manufacture (Li et al., 2022; Nguyen, Moon and Ahn, 2022).

Numerous synergistic policies related to such technologies that have been implemented in the UK are encouraging the adoption of MMC. For instance, as a result of the UK government's 2016 mandate that made proficiency in BIM Level 2 a requirement for all state-run projects costing over £2 million, the adoption of BIM grew to 73% across the industry in 2020 (National Building Survey, 2020). Moreover, by maximising planning, design, building, maintenance and demolition operations, BIM can demonstrate significant potential for the advancement of project life-cycle sustainability (cited in Hu and Chong, 2019). Finally, using BIM software can entail maintaining a database that keeps track of the building from the time of its conception until it is occupied. This data is accessible to stakeholders; therefore, it has the potential to increase their trust in the system (MHCLG, 2019).

Information technologies such as sensors and IoT are also increasingly being used to track the environmental pollution impact of MMC, ranging from the quantification of GHG emissions to measuring the levels of dust, water and noise pollution (Li et al., 2022). These tools can help design projects to achieve energy efficiency, emissions reduction, waste reduction, scheduling optimisation and labour-friendly operations simultaneously. In addition, real-time data mining, an IoT-based application, may be able to contribute to MMC in the early stages of a project, and during construction and into operation, through real-time site monitoring and data collecting on building performance (Nguyen, Moon and Ahn, 2022). The knowledge produced could benefit construction partners, particularly architects and engineers, by helping gather, filter, analyse, interpret and store performance data for prediction, as well as the optimisation of building structures and designs for their next projects (Nguyen, Moon and Ahn, 2022). Understanding the expectations of stakeholders and using information technologies to develop projects that respond to multiple interests is key to increasing the uptake and acceptability of MMC projects.

However, the success and sustainability of any project relies on the type and quality of data collected, as only purely quantitative metrics and data cannot improve decision-making. The building industry in the UK is still lagging far behind compared to other European countries in terms of performance and policies; one of the major reasons for this is the failure to understand the role of occupants, variations in behaviours, practices and lifestyles, and their distributional implications in building design and planning. Furthermore, such large-scale quantitative metrics also serve to hide socioeconomic inequalities and their role in, for example, inducing energy poverty (Petrova and Simcock, 2019). In particular, post-occupancy evaluation (POE) – a form of building performance evaluation (BPE) which has been recognised to improve occupancy performance and reduce environmental impact throughout Europe – is yet to take root in practice in the UK due to poor leadership and collaboration and high costs (Stevenson, 2019). Social scientific research methods and more in-depth qualitative approaches, especially those that investigate themes of equity and justice, will need to be adopted to free the current practice lock-ins and improve the POE of buildings. As MMC scales up in the UK, learning the lessons of what works well and what does not is key in designing buildings that perform better.

2.3.2 Improving the scalability of MMC via standardisation

In the UK, many construction firms still rely on bricks-and-mortar construction, and are discouraged by MMC's dependence on mass production and huge investment costs. Mortgage lenders in the UK have also generally been averse to supporting prefabricated design methods (Payne and Serin, 2023). To make sure that MMC products are scalable, profitable and more mortgageable, there has been a call for more attention towards industry-wide standardisation in MMC practices, designs and technologies to improve economic and environmental efficiencies (Atkinson, 2021). Standardisation is also important for the methodologies used to quantify environmental impacts, namely the emission contributions and energy efficiency of MMC projects, which can be aided by the use of BIM, as well as SSH practices that facilitate interdisciplinary collaboration, such as between energy modellers, architects and behavioural scientists. Additionally, standardisation would give the industry better protection by helping insurers and suppliers gain more clarity regarding the projects, as there would be more uniformity in the materials and methods used (Atkinson, 2021). Social science research, such as conducted under psychology, sociology, or political ecology disciplines, is particularly important to understand the overall industry landscape (Killip, 2013), including its scope, scalability and expertise, and therefore to help develop standards that are more feasible and likely to be adopted widely. Currently, there is a clear absence of regulatory action and policies in terms of promoting sustainable buildings in the UK (Payne and Serin, 2023). In a policy context where the transition to low-carbon buildings is slow, transition intermediaries have an important role to play as stakeholders who can positively affect sustainability transition processes by reconciling diverse actors, activities, skills, resources and expectations (Kivimaa, 2014). In the UK, architects, consultants, builders, housing developers, council sustainability officers and charities are among the actors who can serve as transition intermediaries, with strong motivations to promote innovation in the construction sector (Martiskainen and Kivimaa, 2018), and also help to establish standards for MMC.

Standardisation of products and processes using MMC may prove to be less complicated since contemporary construction procedures frequently take place in regulated factory environments and use industrialised, lean and systematised approaches (Payne and Serin, 2023). For mainstream volume developers, MMC has the propensity to produce a relatively homogeneous style of housing, which would mean that they are more likely to embrace such techniques. Nevertheless, case studies from the US and Japan illustrate that a high degree of customisation is still possible through MMC, ensuring the collaboration and engagement of future users in project planning (Payne and Serin, 2023). In MMC projects, consumers are able to select finishes from a specification menu, such as face material, floor coverings, internal arrangements and additional bedrooms (MHCLG, 2019). This opens up numerous opportunities for participatory approaches in building design, which are in line with global efforts to develop and promote sustainable buildings, while also ensuring high levels of comfort, well-being, health and productivity for occupants (Chwieduk, 2003). Therefore, MMC offers the unique advantage of responding to the needs of multiple stakeholders.

2.3.3 Green building certifications for MMC

There is a growing understanding of the necessity to create new sustainability evaluation tools for MMC-based projects. However, the question regarding the use of present green building grading methods for assessment arises from the low efficacy of the rating systems in use (Nguyen, Moon and Ahn, 2022). The most well-known green building rating systems, including Leadership in Energy and Environmental Design (LEED), Building Research Establishment Environmental Assessment Method (BREEAM), and Green Mark, may potentially be used for MMC projects in a variety of structural forms, from prefabricated building sections and components to entire building units (Li et al., 2022; Nguyen, Moon and Ahn, 2022). However, not only have MMC-based projects scarcely been evaluated using these standards, but also such standards do not reflect metrics beyond whole-life or operational carbon emissions. There is a crucial need to step away from purely quantitative building performance standards and evaluation systems, as these are unable to capture the wider social dimensions of building performance (Stevenson, 2019). Overall, many of these assessment methods at their current stage are not suitable to fully assess projects built using MMC, particularly as they tend to overlook wider socio-cultural and political dimensions. Therefore, more research is required in order to construct a socio-technical green building rating system that specifically caters to MMC-based projects.

3. Conclusions and recommendations

The UK's construction industry is currently experiencing the unique challenge of meeting escalating housing demand in a quick and sustainable way. This brief has attempted to synthesise the growing evidence base on the potential of MMC in delivering projects efficiently and lowering environmental damage to encourage uptake, while drawing from SSH insights to delve into discussions of how the sustainability and scalability of MMC can be improved. The key insights from the literature are as follows:

- **GHG emissions:** MMC have been shown to have strong potential in the UK for lowering GHG emissions (up to 82%), provided that the right methodologies and criteria for calculations and measurements are used. To support the use of MMC as a strategy for achieving net zero, there needs to be a better understanding of suitable metrics, mainstreaming of uniform and accepted standardisation, and improved knowledge exchange between different stakeholders in the value chain.
- **Energy efficiency:** MMC can, on average, bring about 30% of energy savings relative to traditional methods. However, to achieve this, building designs need to consider how users may behave and interact with different energy technologies in the building. SSH research is crucial to integrate such considerations to improve industry learning regarding occupant-building interface and mitigate risks of rebound effects that perpetuate existing energy consumption patterns.
- **Waste reduction:** MMC has the potential to eliminate waste production and GHG emissions by promoting principles of the circular economy. To optimise the waste reduction potential of MMC, the waste management and construction sectors in the UK must work together and coordinate to share capacities, resources and knowledge, so that MMC projects are designed using products and processes that make it easy to reuse materials.
- **Project duration and cost:** MMC significantly cuts down time and costs by allowing for bulk orders and transportation of supplies, avoiding on-site overheads and exposure to weather extremes, greater installation efficiency and lower reliance on on-site labour, resulting in a nearly 50% reduction in construction costs, as well as the potential for improved whole-life costs. To overcome the hurdle of high initial investment costs and to win over prospective clients, it is essential to make costs clear throughout the project life-cycle by using a socioeconomic lens to highlight market complexity and accurately reflect the costs of MMC-based projects.
- **Project quality:** Greater building quality and high-quality control can be achieved via MMC due to automation and less material exposure to inclement weather. However, this also means that project planning and coordination are considerably more complicated. Upskilling the industry and improving consumer perception are essential to MMC's success in delivering sustainable buildings. Instead of simply pushing MMC as a boost for new homes, regulations and policies should put emphasis on enhancing housing quality.
- **Workers' health and safety:** MMC ensures that on-site workers are less likely to be exposed to dangerous situations or adverse weather conditions – up to 80% of

on-site reportable incidents can be reduced. Moreover, it offers the advantage of recruiting workers with less training for on-site work, while also leading to the upskilling in the manufacturing industry through new supply chain opportunities. MMC projects can also be used to improve inclusivity and equality in the labour workforce in the UK by strategically targeting high unemployment areas and regions with low representation of women in construction to build factories for the projects.

- **Securing insurance:** Insurers currently lack confidence and knowledge regarding MMC. To properly communicate the advantages of MMC, construction firms must demonstrate their experience and expertise in such projects, quality assurance strategies, contract agreements, risk distribution with suppliers and storage plans to insurers. With the public sector in the UK increasingly embracing MMC, public-private partnerships that help reduce project uncertainties and improve collaboration by promoting the exchange of information knowledge are crucial to expanding insurers' appetite to cover MMC projects.

For the UK building industry to achieve net zero while meeting housing demands, the following recommendations are made:

- **A socio-technical approach to evaluating MMC projects***:* The government and industry must work towards a more focused utilisation of RFID, BIM and other information tools when pursuing MMC, which can help projects be more environmentally sustainable, while also being cost-effective. Sensors and IoT, for instance, can also be used to properly assess and mitigate the environmental impacts of projects employing MMC. Moreover, data mining allows for real-time site monitoring and data collection on building performance, thereby improving decision-making and optimisation. However, there also needs to be a shift beyond merely technical methods and technologies. In order to improve building performance, social scientific research methods that bring in the 'human' dimensions in building designs are needed to improve POE, which can help shed light on what kind of sustainable design and construction elements do and do not work.
- **Ensuring holistic methodologies and standards:** The government and the industry need to work towards greater standardisation of MMC practices, designs and technologies to improve scalability and promote insurance coverage. Moreover, they must also collectively agree upon a methodology for the assessment of the environmental impacts of MMC, particularly the way in which emission contribution is measured. The push for standardisation can emerge from intermediaries, both from industry and government organisations, which have the incentive to advance the sustainability transition processes. However, standardisation should not be achieved through a purely top-down, techno-centric approach, since SSH is needed to properly understand the overall industry landscape, such as market forces, and preparedness in terms of expertise. It must also not only speak to volume builders – it ought to create opportunities for customisation to open up the scope for participatory building design, not only to improve the comfort of occupants, but also their perceptions regarding MMC.

- **Interdisciplinary research and development in green certifications for MMC:** Research and development of green building certifications need to be facilitated by the government and industry to assess the sustainability of projects that have used MMC to ensure that sustainability targets are met. Existing standards often tend to overlook social dimensions, necessitating a shift from quantitative standards to capturing broader social dimensions of building performance, such as understanding occupants' and end-user practices. Therefore, there is a need for multidisciplinary research with collaborations between STEM and SSH researchers to ensure that knowledge gaps in green certifications are addressed.

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