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Building time, cost and quality performance of modern methods of construction in a live research project.

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BUILDING TIME, COST AND QUALITY PERFORMANCE OF MODERN METHODS OF CONSTRUCTION IN A LIVE RESEARCH PROJECT

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The use of modern methods of construction (MMC) has been embraced by the construction sector of many countries, largely due to assertions that some MMC processes can be economically effective and efficient. MMC have been received as opportunities by governments to stimulate economies and support demands for new homes, and contractors to improve their profit margins. Although many studies have commented on the implications of using specific MMC, no evidence has been presented of the relative building time, cost, and quality performance of multiple MMC in one live house construction experiment. This paper presents an analysis of the value of turning to MMC including steel-based and timber-frame modular construction, light-gauge and panelised light-gauge steel frame construction and aerated concrete panelised construction methods. The findings presented here are likely to facilitate decision-making processes relating to these performance aspects of the MMC which were largely inferior to the traditional construction method discussed here and identify areas of improvement. Further advancements are required to improve the performance and desirability of these MMC.

Keywords: case studies; house building; live research; modern methods; performance

INTRODUCTION

The definition of modern methods of construction ('MMC') has been a subject to debate. It has been argued that, inter alia, (i) timber frames are not considered modern and thus do not fall within the definition of MMC and (ii) MMC make use of off-site manufacturing systems along with innovative materials, precision manufacturing techniques and digital technologies (Housing, Communities and Local Government Committee, 2019). The steel-based and timber-frame modular construction, light-gauge and panelised light-gauge steel frame construction and aerated concrete panelised construction methods discussed in this paper, fall within this definition.

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The use of MMC has been embraced by the residential building sectors in many countries over the past decades (Zhang *et al.,* 2021; Saad *et al.,* 2023). This is largely due to assertions that some of the construction processes involved in MMC can be relatively more economically effective and efficient. For example, it has been argued that MMC are (i) likely to produce buildings of comparatively higher quality and (ii) relatively more time efficient (e.g., see Lawson *et al.,* 2012). Furthermore, MMC have been received as an opportunity by (i) construction contractors to improve their profitability and (ii) governments to stimulate economies and satisfy demands for new homes (Mesároš and Mandičák, 2015; HM Government, 2017; Spišáková and Kozlovská, 2019; Meacham, 2022). For instance, the UK requires at least 260,000 new homes each year to keep up with this demand. However, this target has proven difficult to achieve (Home Builders Federation, 2014). In the UK 98% of the local councils were unable to meet the regional housing demands (Oliveira *et al.,* 2019). This has been attributed to, inter alia, a lack of effective strategies to address (i) planning constraints; (ii) inadequate efficiencies of some construction processes involved in MMC; (iii) the insufficient number of large housebuilding companies and (iv) unsatisfactory economies of scale. Specifically, it has been argued that (i) is the main root cause which impacts (ii to iv) and the viability of MMC (Barker, 2004; Home Builders Federation, 2006; HM Government, 2017).

Although many studies have commented on the performance of specific MMC and/or the key principles characterising MMC, no evidence has been presented of the relative time, cost, and quality performance of multiple MMC in one live construction experiment (Tam *et al.,* 2007; Lawson and Ogden, 2008; Blismas and Wakefield, 2009; Modular Building Institute, 2010; Pan and Sidwell, 2011; Lawson *et al.,* 2012; Jellen and Memari, 2013; Rahman, 2014; Farmer, 2016; Generalova *et al.,* 2016; Lopez and Froese, 2016). This paper contributes to the fulfilment of this research gap.

LITERATURE REVIEW

Although the aim of this literature review is not to provide a comprehensive evaluation of all MMC, it offers an overview of key arguments (presented in the identified literature) related to the time, cost, and quality performance of (and some of the key principles characterising) the discussed in this paper MMC. Academics have argued that speed of construction is one of the main advantages of MMC over traditional construction methods (e.g., see Lawson and Ogden, 2008; Jellen and Memari, 2013; Sutrisna and Goulding, 2019). This advantage has been attributed to, inter alia, the ability to conduct simultaneous (i) off-site and on-site activities and (ii) construction and remediation efforts (Jellen and Memari, 2013). Lawson and Ogden (2008), Lawson *et al. (*2012) and Langston and Zhang (2021) argued that off-site manufacturing techniques can reduce the construction periods of modular buildings by up to 50%, but those efficiencies are greater in high-rise buildings as, inter alia, inadequate economies of scale and supply chains can cause time inefficiencies to low-rise buildings constructed with MMC. Modular construction methods offer another key advantage that is a simultaneous construction of building elements which should decrease on-site construction time (Modular Building Institute, 2010). Furthermore, construction periods can be reduced by applying (i) open panel and hybrid construction methods which can decrease construction time by around 25% and (ii) volumetric (or modular) construction methods which can reduce construction periods by approximately 60%. However, such construction time efficiencies are achievable only if the building designs are without flaws and finalised early in the construction project management process (National Audit Office, 2005; Ayinla *et al.,* 2022). In theory, this can be achieved by full integrations of the design, manufacturing, and construction teams (HM Government, 2013; Dowsett *et al.,* 2019). On the other hand, panelised, hybrid and volumetric construction methods typically require longer design periods (Oliveira *et al.,* 2019). To summarise the main arguments, although the application of MMC can contribute to construction time efficiencies; specifically, shorter on-site construction periods, it is unclear if meaningful overall time efficiencies have been achieved, or are likely to be achieved in the future, and how such efficiencies can be ensured in house building.

The identified literature centres on several aspects of the price and cost of MMC. Such costs typically include investments in production facilities, economies of scale, transport costs, minor repair costs and preliminaries (e.g., crane hire) The last two components are usually more cost efficient. This varies among the different building methods and contexts but impacts the desirability of all MMC (Sutrisna and Goulding, 2019). For example, modular construction methods can be more cost efficient than traditional construction approaches when used in high-rise buildings, poor soil conditions and restricted site workspace (National Audit Office, 2005; O'Connor *et al.,* 2014; Generalova *et al.,* 2016; Iuorio *et al.,* 2019). However, MMC incur significantly higher off-site manufacturing costs than traditional construction methods (Blismas and Wakefield, 2009; Pan and Sidwell, 2011; Lawson *et al.,* 2012). Furthermore, MMC can, at least in theory, reduce maintenance costs by improved precision of manufacturing of building components under factory conditions (Pan and Sidwell, 2011). However, studies suggest that further efficiencies are required to improve the affordability and viability of MMC; specifically, a 15% reduction in price which can be achieved by, inter alia, (i) increases in the volume of the construction works and a subsequent reduction in the start-up price (National Audit Office, 2005; Home Builders Federation, 2006; Rahman, 2014) and (ii) the use of off-site manufacturing techniques, but this mainly relates to high-rise buildings (Lawson and Ogden, 2008; Iuorio *et al.,* 2019). Lopez and Froese (2016) and Iuorio *et al.,* (2019) have provided cost analyses of some MMC, where the former concluded that the overall construction cost of modular high-rise buildings was 7% lower than the panel buildings. However, this study has significant limitations; specifically, the like for like comparison was impacted by many different building elements and construction site conditions and unavailability of detailed cost plans.

Construction quality includes three main components: durability, whole life costs and performance (National Audit Office, 2005). Leakage problems and perception issues relating to lightweight building elements, often used in MMC, are frequently perceived as indicators of low building quality which affects the desirability of such buildings (Tam *et al.,* 2007; Rahman, 2014). On the other hand, one of the main perceived advantages of off-site construction is achieving relatively higher construction quality by ensuring greater precision of manufacturing, quality control and management due to installations of building components under factory conditions by competent personnel (National Audit Office, 2005; Pan *et al.,* 2008; Blismas and Wakefield, 2009; Modular Building Institute, 2010; HM Government, 2013; Miles and Whitehouse, 2013). However, those advantages may prove difficult to realise due to, inter alia, inadequate competency of human resources (Yu *et al.,* 2019). Therefore, the primary argument is that the building quality of a particular MMC is influenced by the extent of off-site manufacturing used in that construction method and the competence of the human resources. For example, the degree of off-site manufacturing (and thus the quality management and building quality) is greater in volumetric construction systems than panelised construction methods (Lopez and Froese, 2016; Oliveira *et al.,* 2019). However, the identified literature does not provide comprehensive studies of the number and types of patent defects in homes built with the five MMC discussed here. This is one of the objectives of this study.

METHOD

Introduction to Case Studies

The data presented here was generated in a live research and construction project involving the building of over forty semidetached houses which were assembled on over twenty land plots (i.e., a "pair" of semidetached houses were assembled on each land plot) with six different construction methods. Each pair was assembled with one construction method. Therefore, each land plot corresponds to one construction method and one case study. All houses were similar, located on one construction site and were built at the same/similar time. Since a 'like for like' comparison is essential to accurately measure and evaluate the time, cost, and patent defect performance of those houses, the twelve most similar semidetached buildings were selected from that sample; specifically, the houses had identical/similar gross internal floor area, number of storeys, number of bedrooms and building fabric. Those twelve houses include two houses built with a traditional construction method (Case 1) and ten houses built with five MMC, namely the light-gauge concrete panelised construction (Case 2); the timber frame modular construction (Case 3); the light gauge steel frame modular construction (Case 4); the panelised light-gauge steel frame construction (Case 5) and the steel frame modular construction (Case 6) methods. Therefore, this study is based on an experimental approach where the data (a set of six case studies), provided by the organisations involved in the project, was filtered to ensure the most similar houses were compared. The names of the parties and some project features were anonymised to ensure their confidentiality. The project was completed before the start of the COVID-19 pandemic, Brexit and the war in Ukraine and thus was unaffected by high inflation and other external factors such as supply chain issues which might have impacted the research findings if the project was affected by those events.

The research approach includes three main stages, namely (i) reviews of the individual house designs to identify differences between building elements which could impact the research findings; (ii) interviews with site personnel; specifically, the main contractor's site manager and quantity surveyor, were conducted to identify further factors that impacted the performance of each MMC and (iii) analyses of the three sets of data required for the time, cost and patent defect comparisons were conducted.

Reviews of residential building designs
The main findings from those reviews include differences in (i) the number of bedrooms; (ii) the number of storeys; (iii) the size of the ground floor internal areas; (iv) the type of building fabrics; (v) the type of smart technologies and (vi) the type of heating and electrical systems used in those residential buildings. As noted above, those limitations were reduced by selective sampling of identical/similar houses.

Interviews of relevant construction personnel
The main findings from the interviews with the site manager and quantity surveyor were (i) the six factors noted above were likely to impact the time, cost and patent defect performance of those buildings; (ii) construction plant requirements and/or site logistics also impacted the performance of some MMC; specifically, delay was caused to the modular homes by deficient site logistics which impacted the use of cranes; (iii)

inadequate drainage designs and water board issues; (iv) problematic designs of modular buildings; specifically, the design and construction of two units were rectified after the units were delivered to site; (v) relatively small contractors constructed the modular buildings and (vi) the nature of some patent defects was unclear from the records, so the help of site personnel was required to categorise those defects.

Data requirements
The three sets of data required for the time, cost and patent defect comparison were (i) baseline programmes (which indicate the planned durations) and as built programmes and data (which indicate the actual design, manufacturing, and construction durations); (ii) cost value reports (CVR), final accounts and material costs which articulate the elemental cost of the buildings and (iii) reports specifying the patent defects conveyed by the residents.

Data collection

As noted above, construction time, cost and patent defect performance data were collected to fulfil the objectives of this study. The data collection is discussed next.

Construction time data
Since one of the objectives of this study is to measure and evaluate the planned and actual construction time performance of the five MMC discussed here and compare the findings to the relevant traditional construction method, the detailed baseline programmes (specifying the agreed by the specialist subcontractors, the main contractor, and the client planned activity durations) were used to measure the planned design, manufacturing, and construction durations. The programme updates and the as built records were used to measure the actual durations of the programme activities.

Construction cost data
As noted above, the cost data was recorded in a CVR and included two main components. Component **1(**Construction Costs) included the costs of supervision, plant, labour, materials, overheads and building elements. Component 2 was Preliminary Costs. Detailed elemental cost plans for the building substructures were provided. The main limitation of the elemental cost plans was that the modular plots were priced as lump sum costs which included most building superstructure elements. Therefore, those building elements were excluded from the detailed comparison.

Reported patent defects
The patent defects were reported by residents and recorded by the main contractor's customer care department for a twelve-month period after the construction completion date. This data was logged in a Microsoft Excel file and included address, the nature and location of the defect and the issue closure details. The data was filtered to ensure that only information relating to defects and design issues was identified. As noted above, some defects were categorised as miscellaneous. The site team's assistance was sought to establish the nature of those defects and categorise them. Only the building defects were included in this analysis (i.e., the defects in structures and areas such as gardens, fencing and sheds were excluded). As different electrical and heating systems were installed in the twelve houses, two sets of results were produced. The first data set shows the defects in those systems and the second one excludes them to improve the objectivity of the comparison. The defects in electrical and heating systems were likely to distort the research results because some heating and electrical systems generated significantly more patent defects than others.

Data analysis

The aim of this study is to identify, measure, analyse, synthesize, evaluate, and categorise the time, cost and patent defect performance of six construction methods used in a live research and residential construction project, including five MMC.

Construction time performance

Figure 1 illustrates a summary of the key findings from the relevant data analysis; specifically, it offers a comparison of the planned and actual construction durations.

Figure 1: Construction time performance

Time (per a pair of houses)						
Build Duration (Weeks)	Traditional	Modern Methods of Construction				
		Concrete Panel	Timber Frame Mod.	Light Gauge Steel	Steel Frame Mod. T1	Steel Frame Mod.T2
Planned duration	21	14.4	15.8	14.4	15.4	8.4
Percentage difference vs Traditional	0.00%	-31.43%	-24.76%	-31.43%	-26.67%	-60.00%
The actual duration	46.2	56.8	54.4	51	52.4	51.4
Percentage difference vs Traditional	0.00%	22.94%	17.75%	10.39%	13.42%	11.26%

The main research finding is that the planned time efficiencies did not materialise; specifically, (i) MMC should achieve, at least in theory, construction time efficiencies which are illustrated in Figure 1 by the shorter planned construction durations and (ii) the actual construction durations of all houses built with MMC were (between 10.39% and 22.94%) longer than the traditionally built dwellings.

Construction cost performance

Figure 2 shows a summary of the key findings from the data analysis; specifically, the cost of (i) substructures; (ii) superstructures; (iii) joinery; (iv) miscellaneous building elements (e.g., decoration, tiling, vinyl, and mastic sealant) and (v) preliminaries.

Figure 2: Construction cost performance

Cost (per pair of houses)	Traditional	Concrete Panel	Timber Frame Mod.	Light Gauge Steel	Steel Frame Mod. T1	Steel Frame Mod.T2
No. of buildings	2	2	2	2	2	2
No. of beds	2/3 bed	2/3 bed	2/2 bed	2/3 bed	2/2 bed	2/2 bed
Ground internal floor area (GIFA)	78/83	78/83	78/78	78/86	78/78	78/78
Substructures	£33,368.00	£33,473.00	£31,719.00	£34,724.00	£31,103.00	£34,646.00
Superstructures	£35,478.00	£69,409.00	£190,000.00	£71,940.00	£237,987.00	£187,685.66
Joinery	£14,846.00	£11,008.00	£0.00	£12,906.00	£0.00	£0.00
Miscellaneous	£45,059.11	£43,101.67	£0.00	£40,387.62	£0.00	£0.00
Prelims	£7,407.00	£14,415.50	£770.00	£12,060.00	£770.00	£770.00
Building TOTAL (per pair of houses)	**£136,158.11**	**£171,407.17**	**£222,489.00**	**£172,017.62**	**£269,860.00**	**£223,101.66**
Cost per m2	**£845.70**	**£1,064.64**	**£1,426.21**	**£1,048.89**	**£1,729.87**	**£1,430.14**
Percentage difference from Traditional	**0.00%**	**25.89%**	**68.64%**	**24.03%**	**104.55%**	**69.11%**
Adjust build cost (78m2)- Most Common G	**£65,964.80**	**£83,041.98**	**£111,244.50**	**£81,813.26**	**£134,930.00**	**£111,550.83**

The key finding from the cost comparison is that the cost of traditional construction was substantially lower than MMC; specifically, the cost per m2 of the traditionally built homes was from 25.89% to 104.55% lower than the properties built with MMC. The substructure cost of all six construction methods is comparable; however, the superstructure cost of the latter method was substantially higher than the former method. The use of modular construction methods generated insignificant preliminary cost efficiencies when compared to the higher construction costs of those methods.

Reported patent defects

Figure 3 illustrates a summary of the key findings from the data analysis; specifically, the number of reported issues with snagging items (or minor defects/outstanding work) per category, including (i) structural cracks; (ii) flooring; (iii) render cladding; (iv) brickwork; (v) decoration; (vi) plastering; (vii) damp; (viii) joinery; (ix) plumbing; (x) roof; (xi) screed; (xii) sealant and (xiii) windows and doors.

As noted above, various innovative smart technologies, electrical and heating systems were tested in the houses which were excluded from the comparison because this data distorted the overall findings. The main discovery was that overall, save for the houses constructed with the light steel gauge construction method, the average patent defect rate of houses built with MMC was higher than the traditionally built dwellings. Furthermore, the concrete panel systems averaged more defects than the three modular construction methods.

Figure 3: Reported patent defects

Average defects for all construction types (excluding heating and electrics)														
Type	Structural cracks	Flooring	Render Cladding	Brickwork	Decoration	Plastering	Damp	Joinery	Plumbing	Roof	Screed	Sealant	Windows doors	TOTAL
Traditional	0	0	0	0	0	0.17	0	0.83	0.83	0.33	0.17	0.17	1.67	4.5
Concrete panel	0	0	0	0	0	0.5	1	1	2	1.25	0	0	2.75	8.5
Timber Frame Modular	0	0	0	0	0	0	0	0	2.5	1	0	0	0.5	5
Light Gauge Steel	0.07	0.07	0.07	0	0	0	0.13	0.67	1.4	0.4	0	0.07	1.07	4.07
Steel Frame Modular Type 1	0.13	0.38	0.13	1	0.38	0.38	0	0.63	2.38	0.25	0	0	2.25	8.38
Steel Frame Modular Type 2	0	0	0.17	0.17	0	0	0	0.5	1.5	0.33	0	0.17	2	4.83
Average defects when all modern methods of construction are combined compared to traditional construction														
MMC	0.06	0.11	0.09	0.26	0.09	0.14	0.17	0.63	1.77	0.49	0	0.06	1.66	5.74
Traditional	0	0	0	0	0	0.17	0	0.83	0.83	0.33	0.17	0.17	1.67	4.5

The reported issues include dampness in the homes built with the light steel gauge and concrete panel building methods. Since the main construction difference between those two MMC and traditional construction is the inner leaf assembly, this could be the reason for the damp issues.

CONCLUSIONS

The discussion and conclusions centre on the relative time, cost, and patent defect performance of the five MMC examined here. The main finding is the relatively inferior time, cost, and quality performance of those MMC. This verifies previous arguments that some offsite approaches do not offer many real improvements compared with their onsite counterparts (Ayinla *et al.,* 2022). The areas of further advancement, include early detection of design and site issues, enhanced economies of scale, standardisation, and competence of human resources (e.g., see Yu *et al.,* 2019).

Construction Time Performance

The data presented here highlights some of the disadvantages of the modular construction methods; specifically, the impact of site and design issues on their construction time performance. For example, the inability to rectify design issues quickly on site means that the modules must be carried back to the manufacturing plant to be repaired and brought back again once the issues have been resolved which resulted in inadvertent delays. This suggests that, inter alia, the arguments made by (i) the National Audit Office (2005) claiming that modular construction methods are likely to produce time efficiencies of up to 400% when compared to traditional construction methods and (ii) Lawson and Ogden (2008) and Iuorio *et al.,* (2019) who suggested that some MMC can generate construction time efficiencies of 30-50% , are very optimistic theoretical estimates that can be significantly influenced by such time performance factors and may be difficult to achieve without further improvements. Therefore, the use of MMC does not guarantee actual construction time savings, unless such construction site and design issues are reduced. Furthermore, the specialist MMC contractors were relatively smaller which may have impacted the construction time performance of those MMC. Consequently, (i) the time efficiencies associated with, inter alia, simultaneous off-site and on-site activities (and contemporaneous construction and remediation efforts) can be offset by design and site issues and (ii) it may be unrealistic to use MMC to increase the number of homes built, which is a target of many governments, unless effective, efficient, and viable solutions to the issues presented here are applied.

Construction Cost Performance

The main finding is unrealised potential and/or unrealistic assessments of the potential cost advantages of using MMC in house building. For example, previous studies suggest that (i) off-site manufacturing could lead to cost savings of between 10 and

20% (Lawson and Ogden, 2008) and (ii) 15% cost reduction could ensure the viability of some MMC (National Audit Office, 2005). However, (i) one is unlikely to be achieved in low-rise home building, unless significant cost improvements are attained in the future and (ii) a cost reduction of around 25% (not 15%) may improve the viability of the concrete panel and light gauge steel construction methods as their costs were respectively 25.89% and 24.03% higher than the traditionally built houses. Therefore, a smaller (than 25%) cost reduction is likely to improve the viability of those two MMC if, among other things, the quality, desirability, and speed of construction provide advantages that offset the higher overall costs. For example, the planned construction durations indicate that, at least in theory, speed of construction is still a viable advantage of those two MMC. The two MMCs resulted in more reported patent defects. Consequently, the desirability of those two MMC is unlikely to increase based on their actual time, cost, and patent defect performance.

The data presented here corroborates the higher overall MMC costs than traditional building; specifically, the greater costs of the building superstructures which is attributable to, inter alia, greater manufacturing and set up costs (Lawson *et al.,* 2012). Therefore, the higher overall construction cost is indeed one of the main barriers to the use of MMC (Pan and Sidwell, 2011; Sutrisna and Goulding, 2019). Moreover, this study confirms that the MMC have lower anticipated (or theoretical) preliminary costs than traditional building (Lawson *et al.,* 2012). However, (i) the actual preliminary costs of the concrete panel and light steel gauge construction methods was higher and (ii) even if the planned preliminary costs materialised, this would not have made a significant impact on the overall cost performance as using MMC in home building was significantly more expensive than applying the traditional construction method because of the higher superstructure costs. This study also verifies that the costs advantages of using MMC in home building vary. For example, the concrete panel and light gauge steel houses were around 25% more expensive than their traditionally built counterparts whilst some other MMC (see Figure 2) were between 68% and 104% more costly than the traditionally built houses. Therefore, the construction sector has not moved further forward over the last two decades as MMC are still relatively economically inefficient which could have been impacted by, inter alia, the lack of (i) adequate planning and governmental support (Mesároš and Mandičák, 2015); (ii) a significant increase in MMC demand (Home Builders Federation, 2006; Rahman, 2014) and (iii) standardisation (Generalova *et al.,* 2016).

Reported Patent Defects

It has been claimed that the relatively higher quality and durability of MMC are one of the greatest advantages of off-site construction (Miles and Whitehouse, 2013; Yu *et al.,* 2019). Although the data presented here is limited to patent defects and design issues, the analysis of the findings suggests that, save for the light steel gauge construction method, the traditional construction method still outperforms the MMC discussed here. This data also verifies study findings suggesting that panelised systems generally result in more defects than full modular systems; specifically, defects associated with drylining, joinery, mechanical and electrical works (e.g., see Lopez and Froese, 2016). Furthermore, this study contradicts claims that the fixing methods used in buildings constructed with MMC cause leakage problems (Tam *et al.,* 2007). There were no reported damp issues in any of the modular buildings. This finding indicates that quality improvements in MMC are possible which is an important revelation as this can, in theory, improve the desirability of MMC. The limitations and mitigation measures of this study are discussed in the Methodology and Data Collection section. Future research should focus on improving the time, cost and patent defect performance of the five MMC discussed here by, inter alia, minimising the identified here issues and applying the offered solutions.

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