BUILDINGS & CITIES

Understanding the embodied carbon credentials of modern methods of construction

RESEARCH

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ABSTRACT

This study assesses the embodied carbon credentials of modern methods of construction (MMC) by conducting a critical literature review and synthesis of the findings. While several studies have reviewed the broader impacts of MMC, no other study to date has comprehensively reviewed the embodied carbon credentials of this construction typology. Since MMC is not an internationally recognised term, the assessment is inclusive of other terminology used in different parts of the world – *e.g.* prefabrication, off-site construction and industrialised construction. The study captures 250 separate studies and distils these to a final sample set of 41 studies and a total of 82 case study comparisons. Although a general perception exists that the adoption of MMC results in embodied carbon savings, the evidence to support this claim is not robust. The results from individual case studies range significantly in both direction and magnitude, and, in the absence of a critical review, considerably different conclusions can be drawn. Upon critique and synthesis of the published studies, it is found that the adoption of MMC has no significant positive, or negative, impact on the embodied carbon of a building.

POLICY RELEVANCE

MMC have been widely cited as the answer to housing shortages and productivity issues in the construction industry more broadly. They have subsequently attracted political attention and implementation in many regions. Embodied carbon is another topic of continued debate in built environment policy. There is a somewhat hopeful assumption that the adoption of MMC will reduce embodied carbon. But, to date, the evidence to arrive at that assumption has been inconsistent. The literature that compares MMC with traditional construction varies considerably. It is found that there is no broad link between MMC and reduced embodied carbon. Reducing the embodied carbon of buildings requires assessment on a case-by-case basis.

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1. INTRODUCTION

The built environment is at a crossroads. There is a need to build more infrastructure and housing to address a global shortage of affordable housing (Galster & Ok Lee 2021). At the same time, nations are setting increasingly stringent climate-related targets (Net Zero Tracker 2024). But the consumption of more resources to build more and the reduction in the embodied environmental impacts of the built environment have opposing outcomes (O'Hegarty and Kinnane 2023). To address this issue, there is an increased effort to measure and reduce the embodied carbon of construction (that is, the greenhouse gas emissions associated with producing, constructing and maintaining buildings and their materials). This reduction effort includes recent requirements for embodied carbon disclosure in different regions, *e.g.* Europe's latest Energy Performance of Buildings Directive (EPBD 2024). Simultaneously, there are calls to enhance the productivity and increase the speed of construction using more modern methods of construction (MMC), which encompass off-site construction and prefabrication. Understanding the relationship between MMC and embodied carbon is therefore critical.

While there has been an increase in the number of studies that compare the embodied carbon of MMC with traditional construction applied to buildings, to date there has been no study that comprehensively captures all these studies, analyses their findings and interrogates the methodologies and assumptions in detail. This study aims to fill that gap by synthesising the emerging data from the literature. Several studies have reviewed the broad range of benefits of MMC (Aghasizadeh *et al.* 2022; Sánchez-Garrido *et al.* 2023), such as speed of construction, productivity and waste reduction. This research focuses specifically on the embodied carbon impact of MMC, and hence its feasibility as a decarbonisation solution for the construction sector. To address this question, the research conducts a critical review of the literature that compares the embodied carbon of buildings constructed using MMC with those applying more traditional methods.

For more context on the origins and definitions of MMC, readers are referred to this article's supplemental data online. In summary, there is some uncertainty surrounding the meaning of MMC, the categories of MMC and the percentage of a building that is 'MMC' or 'traditional'. Importantly, MMC is not an internationally recognised term, and therefore this study encompasses other terminology used such as prefabricated buildings, off-site construction and industrialised building systems (see Figure 2 for list of search terms). There are also several different categories of MMC, ranging from 3D modular construction to on-site labour reductions. This study includes any categories with a premanufacturing aspect. It is worth noting that only a portion of a building is typically MMC, so comparisons of a building constructed using 'MMC' or 'traditional' methods will inevitably be imperfect (Figure 1).

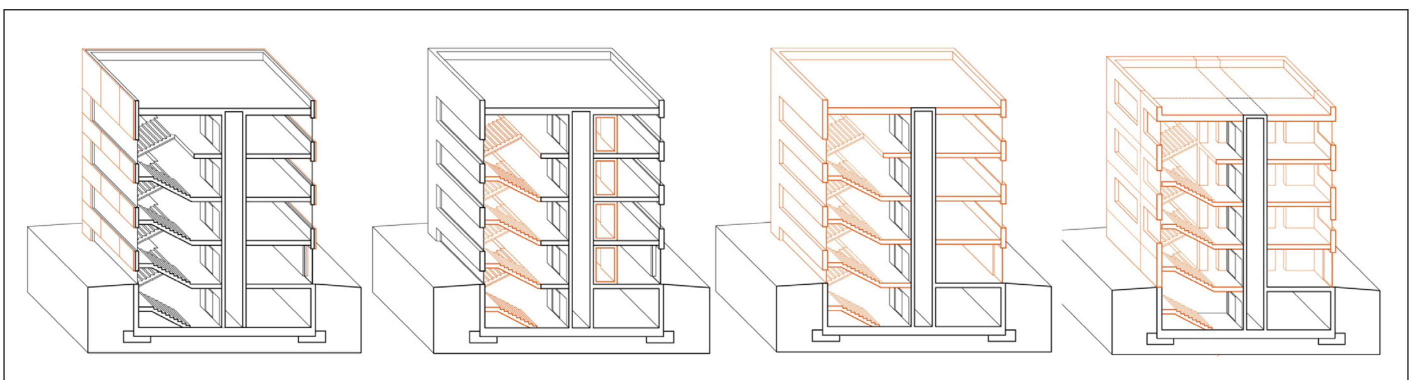


Figure 1: Conceptualisation of an increasing percentage of MMC by volume of material used. MMC is shown in orange.

2. THE PERCEPTION OF MMC

The current perception of MMC as an embodied-carbon-saving strategy is assessed here by looking at both academic review papers and industry surveys.

2.1 THE ACADEMIC LITERATURE

Several studies have reviewed different aspects of MMC. Jin *et al.* (2018) review the literature on off-site construction and reported common research areas, while Kamali and Hewage (2016) review the benefits of modular MMC over conventional construction, concluding that, on average, the life cycle performance of modular MMC was better. Aghasizadeh *et al.* (2022) review the literature on MMC, focusing on highlighting gaps in assessing their environmental and economic performance. Ferdous *et al.* (2019) focus specifically on modular MMC multistorey buildings, concluding that MMC results in environmental benefits, such as reductions in on-site material waste, transport trips and embodied energy. Teng *et al.* (2018) report that, on average, prefabricated buildings resulted in a 15.6% reduction in embodied carbon compared to traditional construction, while Chen *et al.* (2022) review literature on embodied carbon of prefabricated buildings to conclude that the results are wide ranging (27–1644 $kgCO_2/m^2$). In probably the most comprehensive review of MMC's broader impacts, Sánchez-Garrido *et al.* (2023) conclude that 'MMCs offer a promising solution to the building sector's low productivity, labour shortages, cost control issues while reducing uncertainty, minimizing waste, and promoting sustainability'.

While these reviews are generally unanimous in their attribution of broad sustainability merits to MMC, the evidence referred to in these studies is fragmented with conclusions that do not report a high degree of confidence in its sustainability. As with many embodied carbon exercises, the outcome is highly sensitive to the assumptions made and hence requires further interrogation.

2.2 INDUSTRY SURVEYS

While observations across academia can be accessed via the published body of literature, perceptions among industry are also of interest.

A recent survey in the UK (Building Better 2024), completed by 57 housing associations (together responsible for 45% of all homes completed by housing associations in England) reported that, of six potential benefits of using MMC, the most significant benefit was environmental sustainability, with 66% of respondents ranking that as their first or second choice. In comparison, a 2016 telephone survey that gathered insights from 100 housebuilders and 35 housing associations across the UK found that achieving sustainability targets was the sixth most important reason for considering the use of MMC (when asked to rank 11 benefits of MMC) (NHBC 2016). A more recent survey on the perceptions of MMC's impact on embodied carbon published by the Institute of Structural Engineers found that 59% of the 218 respondents believed that MMC reduced embodied carbon (Morton and White 2024). In a report by Wang and McCrum (2024), 47 construction industry respondents from Ireland were surveyed and ranked the benefits of MMC according to their level of importance, in which sustainability came third. In a survey of 310 participants on the challenges confronting prefabricated building construction in Australia, reduced construction time was found to be the main perceived advantage of prefabricated construction over traditional construction, followed by quality control, reduced on-site noise and disruption and then reduced construction waste and CO_2 emissions (Navaratnam *et al.* 2022). In the USA, a 2019 survey by the Off-site Construction Council comprising 205 participants ranked meeting sustainability goals tenth out of 12 when asked about the advantages of off-site construction (NIBS 2019). Research by Razkenari *et al.* (2020) ranked MMC drivers in the following decreasing level of importance: reduction in construction time (highest driver), precision, shortage of skilled labour, improved productivity, improved quality, cost reduction and safer construction environment. In the above seven surveys, set in varying locations, sustainability received mixed rankings and was, interestingly, highly location-dependent. Overall, most studies consider MMC to be a more sustainable form of construction.

3. METHODOLOGY

A systematic literature review was conducted to compare MMC with traditional buildings where life cycle assessment (LCA) or embodied carbon calculation methodologies have been used. A keyword search for MMC- and LCA-related terms was first conducted using Scopus. Scopus was used as it is the most comprehensive database with a focus on high-quality publications. A snowballing process was used to capture other relevant high-quality studies that were not found through the Scopus search. The studies' titles, abstracts and keywords were searched using an automation process. The list of terms and process used is described in Figure 2. The initial article search yielded 250 results. These results underwent an initial screening where abstracts and conclusions of all 250 studies were manually reviewed and filtered for relevance based on the criteria below (Discard criteria – Stage 1), leading to 184 items being discarded from the assessment.

Discard criteria – Stage 1 – Relevance:

- Irrelevant i.e. studies captured by the similar terminology used outside the field of construction
- Illegible abstracts
- Studies only concerned with types of MMC
- Studies only concerned with carbon emissions from the operation of buildings

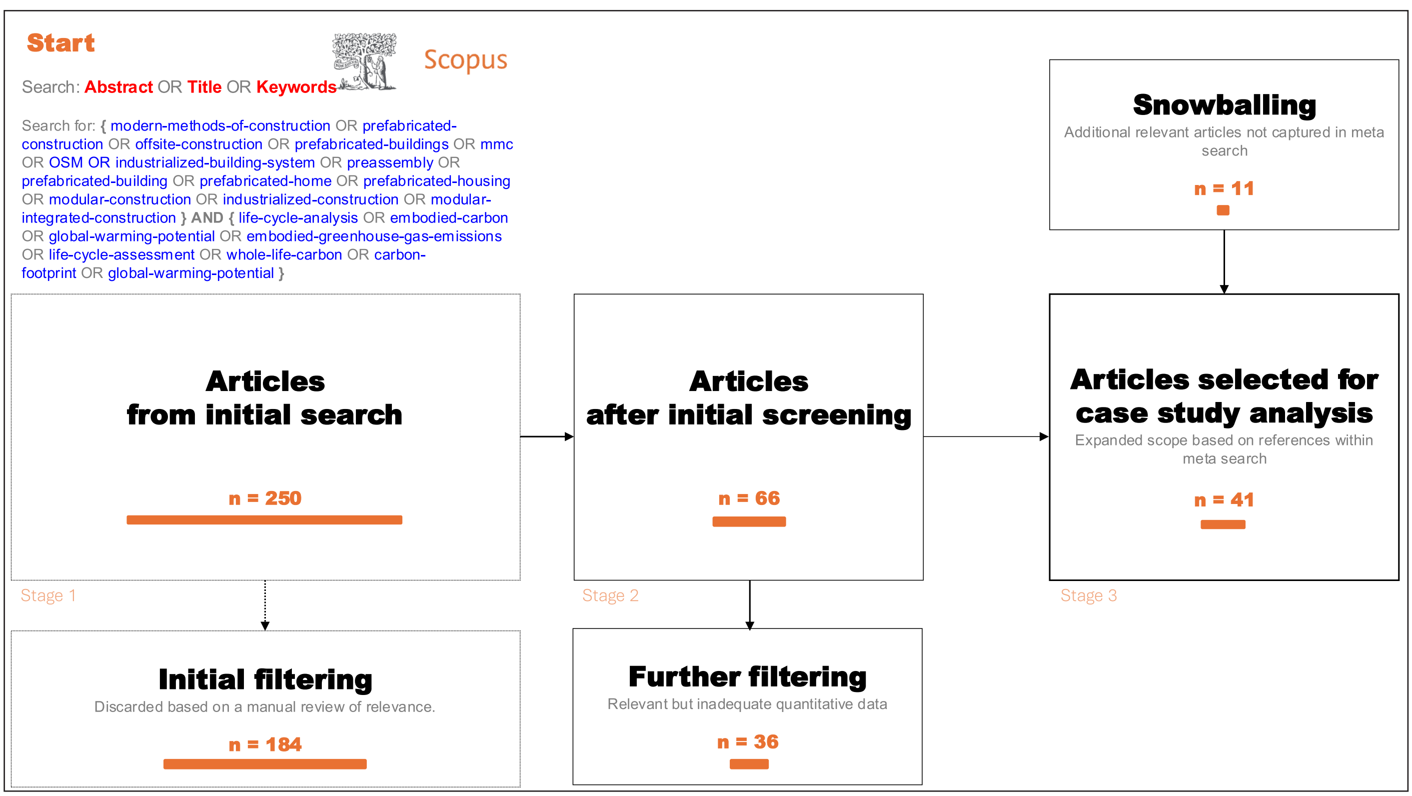
The remaining 66 studies were then fully reviewed, with a focus on data quality, resulting in a further filtering of 36 articles.

Discard criteria – Stage 2 – Data quality:

- Studies with no clear separation between operational and embodied impacts in the life cycle assessment
- Questionable, unconventional or untransparent methodologies used
- Studies that only provided a single MMC LCA case study without comparison to a traditional construction case study

In Stage 3 of the collection, a snowballing process was conducted to capture articles missing from the original search. This assessment resulted in including an additional 11 articles, bringing the final number of articles used for data analysis to 41.

Figure 2: PRISMA flow diagram of literature selection and screening process.

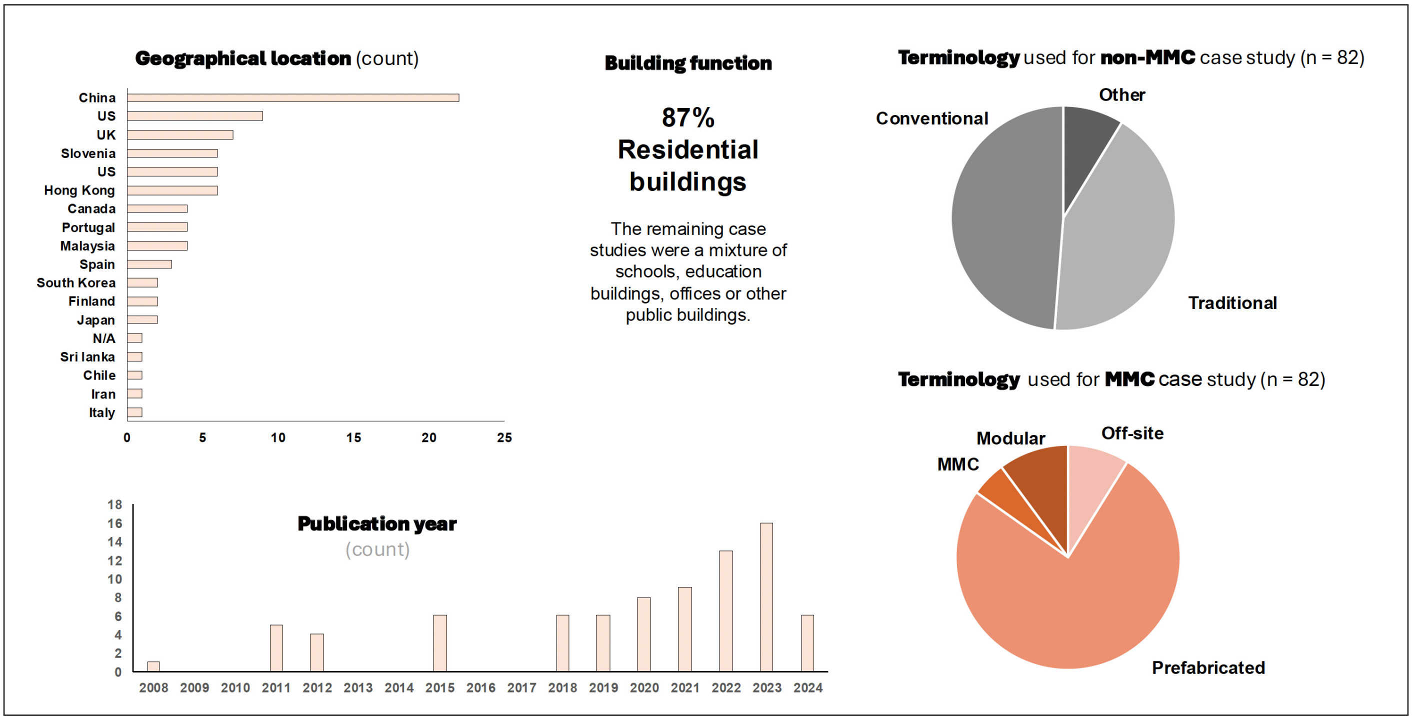


3.1 SAMPLE SET

The final sample set (41 articles) resulted in 82 case study comparisons, the breakdown of which is presented in Figure 3. The case study comparisons include any study that compared an MMC and traditional case study. Most articles presented just one case study comparison, while some included multiple MMC case studies with a 'traditional' benchmark. Full details on these comparisons is presented in Table 1. Of the 82 case study comparisons, 58 comparisons had data appropriate for quantitative analysis. Therefore, any quantitative result includes a maximum of 58 comparisons, while qualitative comparisons were extracted from the 82 comparisons.

In terms of building typology, 87% of the case studies were of residential buildings (including houses, apartments and high-rise blocks). Geographically, more than a quarter of studies were from China. The terminology used for the non-MMC cases was approximately a 50/50 split between 'conventional' and 'traditional', while the most common description for the MMC types was 'prefabricated'. The metric for floor area used across study comparisons was inconsistent (most used gross floor area (n = 29) or conditioned floor area (n = 27)) but comparisons made within each case study always used the same metrics.

Figure 3: Case study data representation.



3.2 FURTHER DATA FILTERING

Many studies compared different materials, while some compared different building sizes. In Section 4.4, an additional filtering process is implemented to compare studies where the same primary materials were used and where the difference in floor area was no greater than 50%, enabling a more like-for-like comparison. The number of comparisons resulting from this filtering process is 23.

4. RESULTS AND DISCUSSION

4.1 DATA COMPARABILITY

Different methodologies have been applied in the literature in terms of the tools used, boundaries covered and scope specified, as well as other assumptions about materials. Table 1 gives an overview of the different methodologies adopted across the case studies. Most studies covered the initial product and construction stages, i.e. LCA stages A1–A5 of EN 15978 (2011), while some just covered the product stage (A1–A3). Although A1–A3 boundaries cover most of the embodied

STUDY REFERENCE	DATA INCLUDED IN QUANTITATIVE ANALYSIS	A1–A3 (PRODUCT)	A4 (TRANSPORT TO SITE)	A5 (CONSTRUCTION)	B (USE)	C (END OF LIFE)	STRUCTURE	SKIN (FACADE AND ROOF)	PARTITIONS AND FINISHES	MEP SERVICES	GENERAL DESCRIPTION PROVIDED IN THE STUDY
Altan and Popovic-Larsen 2012		x	x	x							Traditional vs cold-form steel skeleton with cast *in situ*
Aye *et al.* 2012	x	x	x	x			x	x	x		Conventional concrete vs prefabricated modular steel
Aye *et al.* 2012	x	x	x	x			x	x	x		Conventional concrete vs prefabricated modular timber
Balasbaneh and Sher 2021	x	x	x	x		x	x	x	x	x	On-site concrete vs individual panel system
Balasbaneh and Sher 2021	x	x	x	x		x	x	x	x	x	On-site concrete vs prefabricated prefinished volumetric construction
Cai *et al.* 2023	x	x	x	x			x	x	x		Cast-in-place vs prefabricated light steel
Cao *et al.* 2015		x	x	x			x	x			Cast in-situ vs precast concrete
Chalotra 2022		x	x	x			x	x			Timber-concrete building vs existing-concrete building
Delnavaz *et al.* 2023	x	x					x	x	x		Cast in-situ structure vs precast concrete structure
Dong *et al.* 2015	x	x	x	x			x	x	x		Cast in-situ apartment a and h vs precast concrete apartments
Dong *et al.* 2015		x	x	x				x			Cast in-situ facade group vs precast concrete facade group
Dong *et al.* 2015		x	x	x				x			Precast concrete facade element vs cast *in situ* facade element
Du *et al.* 2019	x	x	x	x			x	x	x		Traditional vs prefab scenario
Du *et al.* 2019	x	x	x	x			x	x	x		Traditional vs prefab scenario
Du *et al.* 2019	x	x	x	x			x	x	x		Traditional vs prefab scenario
Filion *et al.* 2024	x	x					x	x	x		Concrete vs volumetric modular
Filion *et al.* 2024	x	x					x	x	x		Concrete vs cross-laminated timber and glulam columns
Gao *et al.* 2024	x	x	x	x			x	x			Cast-in-place concrete building materials case b vs prefabricated component case a
Greer and Horvath 2023	x	x	x	x			x	x	x		Timber traditional (2 storeys) vs steel container modular

(Contd.)

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Greer and Horvath 2023	x	x	x	x			x	x	x		Timber traditional (2 storeys) vs timber modular
Greer and Horvath 2023	x	x	x	x			x	x	x		Timber traditional (2 storeys) vs steel modular
Greer and Horvath 2023	x	x	x	x			x	x	x		Timber traditional (3 storeys) vs steel container modular
Greer and Horvath 2023	x	x	x	x			x	x	x		Timber traditional (3 storeys) vs timber modular
Greer and Horvath 2023	x	x	x	x			x	x	x		Timber traditional (3 storeys) vs steel modular
Greer and Horvath 2023	x	x	x	x			x	x	x		Steel traditional vs steel container modular
Greer and Horvath 2023	x	x	x	x			x	x	x		Steel traditional vs timber modular
Greer and Horvath 2023	x	x	x	x			x	x	x		Steel traditional vs steel modular
Han *et al.* 2022	x	x	x	x			x	x	x		Traditional cast *in situ*. vs prefabricated building
Han *et al.* 2022	x	x	x	x			x	x	x		Traditional cast *in situ*. vs prefabricated building
Han *et al.* 2022	x	x	x	x			x	x	x		Traditional cast *in situ*. vs prefabricated building
Hernández *et al.* 2023	x	x	x	x			x	x	x		Traditional masonry and concrete vs mmc (VAP system)
Jang *et al.* 2022	x	x					x	x	x		Reinforced concrete conventional vs modular steel structures
Jang *et al.* 2022	x	x					x	x	x		Conventional construction vs modular steel
Jayawardana *et al.* 2023	x	x	x	x			x	x	x		Reinforced concrete, *in situ* vs off-site prefabricated
Jia Wen *et al.* 2015	x		x	x			x	x	x		Industrialised building system vs conventional cast *in situ*
Jia Wen *et al.* 2015	x	x					x	x	x		Industrialised building system vs conventional cast *in situ*

(Contd.)

STUDY REFERENCE	DATA INCLUDED IN QUANTITATIVE ANALYSIS	A1–A3 (PRODUCT)	A4 (TRANSPORT TO SITE)	A5 (CONSTRUCTION)	B (USE)	C (END OF LIFE)	STRUCTURE	SKIN (FACADE AND ROOF)	PARTITIONS AND FINISHES	MEP SERVICES	GENERAL DESCRIPTION PROVIDED IN THE STUDY
Kamali *et al.* 2019		x	x				x	x			Conventional construction method vs modular building
Kamali *et al.* 2019		x	x				x	x			Conventional construction method vs modular building
Kechidi and Banks 2023		x	x	x			x	x	x	x	Steel-framed modular vs a referenced 'traditionally built' house
Kim 2008	x	x	x	x			x	x	x		Conventional home vs prefabricated modular home
Li *et al.* 2022		x	x	x	x	x	x	x		x	Prefabricated concrete building vs cast-in-place building
Li *et al.* 2022		x	x	x	x	x	x	x	x	x	Prefabricated concrete building vs cast-in-place building
Li *et al.* 2022		x	x	x	x	x	x	x		x	Prefabricated concrete building vs cast-in-place building
Li *et al.* 2022		x	x	x	x	x	x	x		x	Prefabricated concrete building vs cast-in-place building
Li *et al.* 2022		x	x	x	x	x	x	x		x	Prefabricated concrete building vs cast-in-place building
Loo *et al.* 2023		x	x	x			x	x			Cast *in situ* vs modular integrated construction
Lukić *et al.* 2020	x	x					x	x			Masonry vs cross-laminated timber
Lukić *et al.* 2020	x	x						x			Reinforced concrete vs cross-laminated timber
Lukić *et al.* 2020	x	x					x	x			Reinforced concrete vs cross-laminated timber
Lukić *et al.* 2020	x	x						x			Masonry vs cross-laminated timber
Lukić *et al.* 2020	x	x					x				Masonry vs cross-laminated timber
Lukić *et al.* 2020	x	x					x				Reinforced concrete vs cross-laminated timber
Mao *et al.* 2013	x	x					x	x	x		Conventional construction vs Semi-prefab
Mao *et al.* 2013	x	x	x	x			x	x	x		Conventional construction vs Semi-prefab

(Contd.)

STUDY REFERENCE	DATA INCLUDED IN QUANTITATIVE ANALYSIS	A1–A3 (PRODUCT)	A4 (TRANSPORT TO SITE)	A5 (CONSTRUCTION)	B (USE)	C (END OF LIFE)	STRUCTURE	SKIN (FACADE AND ROOF)	PARTITIONS AND FINISHES	MEP SERVICES	GENERAL DESCRIPTION PROVIDED IN THE STUDY
Monahan and Powell 2011	x	x	x	x			x	x	x		Conventional masonry cavity wall scenario vs MMC timber-frame brick veneer
Monahan and Powell 2011	x	x	x	x			x	x	x		MMC timber-frame larch cladding vs conventional masonry cavity wall
Morton and White 2024	x	x	x	x			x				*In situ* reinforced concrete flat-slab vs precast concrete
Morton and White 2024	x	x	x	x			x				*In situ* reinforced concrete flat-slab vs steel modular
Morton and White 2024	x	x	x	x			x				*In situ* reinforced concrete flat-slab vs engineered timber
Pan *et al*. 2018	x	x	x	x			x	x	x		Base case vs precast cross-wall panels
Pan *et al*. 2018	x	x	x	x			x	x	x		Base case vs precast cross-wall panels
Pons and Wadel 2011	x	x	x	x			x	x	x	x	Cast in-situ (non-prefabricated) vs industrialised steel technologies
Pons and Wadel 2011	x	x	x	x			x	x	x	x	Cast in-situ (non-prefabricated) vs precast concrete
Pons and Wadel 2011	x	x	x	x			x	x	x	x	Cast in-situ (non-prefabricated) vs industrialised timber technologies
Quale *et al*. 2012	x	x	x	x			x	x	x		Conventional vs two-story modular residence, of a four-module residential building
Rinne *et al*. 2022		x					x	x	x	x	Traditional reinforced concrete vs hybrid building
Rinne *et al*. 2022		x					x	x	x	x	Traditional reinforced concrete vs timber building
Sandanayake *et al*. 2019	x	x	x	x			x	x			Cast in-situ concrete vs prefabricated except roof
Smith *et al*. 2018		x					x				Stick-built on-site construction vs panelised timber
Smith *et al*. 2018		x									Stick-built on-site construction vs modular

(Contd.)

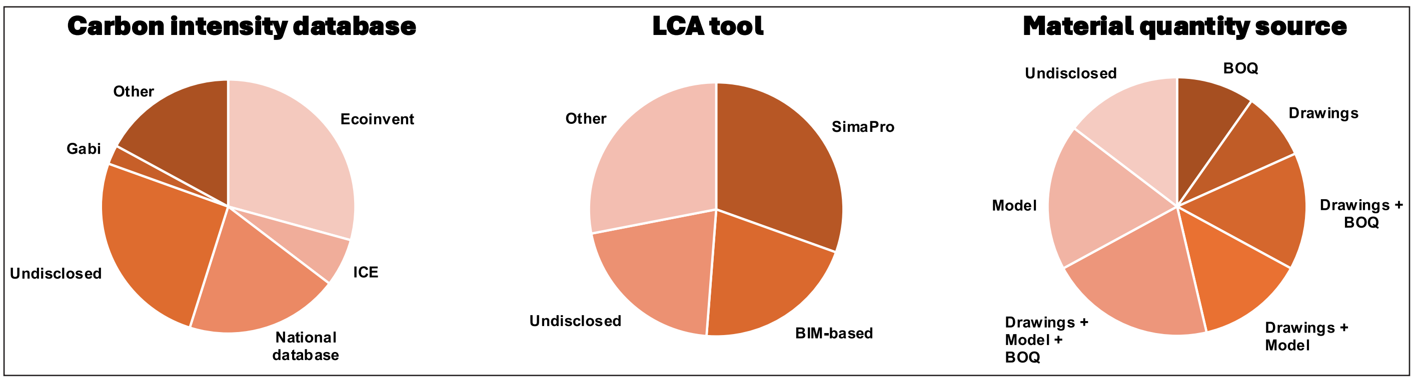
STUDY REFERENCE	DATA INCLUDED IN QUANTITATIVE ANALYSIS	A1–A3 (PRODUCT)	A4 (TRANSPORT TO SITE)	A5 (CONSTRUCTION)	B (USE)	C (END OF LIFE)	STRUCTURE	SKIN (FACADE AND ROOF)	PARTITIONS AND FINISHES	MEP SERVICES	GENERAL DESCRIPTION PROVIDED IN THE STUDY
Tavares *et al.* 2021	x	x	x	x			x	x	x		Conventional reinforced concrete vs light steel framing
Tavares *et al.* 2021	x	x	x	x			x	x	x		Conventional reinforced concrete vs wooden frame
Tavares *et al.* 2021	x	x	x	x			x	x	x		Conventional reinforced concrete vs light steel framing
Tavares *et al.* 2021	x	x	x	x			x	x	x		Conventional reinforced concrete vs wooden frame
Teng *et al.* 2018		x	x	x			x				Traditional base cases vs prefabricated building
Tian and Spatari 2022	x	x	x	x			x	x	x		Traditional construction vs prefabricated
Vitale *et al.* 2018	x	x	x	x	x	x	x	x			Conventional reinforced concrete with brick walls vs cold formed steel
Wang *et al.* 2020		x	x	x			x	x	x	x	Traditional vs prefabricated
Wang *et al.* 2020		x	x	x	x	x	x	x	x	x	Traditional vs prefabricated
Xu and Liu 2021		x	x	x			x	x	x		Cast-in-place building vs prefabricated concrete building
Zhou 2021		x					x	x	x		Prefabricated building
Zhou *et al.* 2023			x				x	x	x	x	Cast *in situ* building vs prefabricated building

Table 1: Comparison of the LCA stage and elemental scope coverage in case studies assessed

carbon of a building, the omission of the A4 and A5 LCA stages (covering transport to site and on-site construction processes) can be problematic when comparing traditional construction to MMC, which aims to move efforts from construction stage to the product/manufacturing stage. There were also studies that specifically looked at the A4 and A5 boundaries. Zhou *et al.* (2023), for example, analyse emissions by LCA module, concluding minor improvements in the MMC case study compared to traditional construction. There was also a selection of studies that included different scenarios for the use (LCA module B) and end-of-life (LCA module C) stages (Li *et al.* 2022; Vitale *et al.* 2018; Wang *et al.* 2020). In terms of component coverage, as shown in Table 1, almost all studies covered the structure, while most covered the skin and internal partitions and finishes. A select few studies went beyond this scope and captured mechanical, electrical and plumbing (MEP) services.

In terms of the software used (LCA tools) and data sources, a range of approaches was adopted throughout the literature (see Figure 4). The most common database used for carbon intensity factors was *Ecoinvent*, while the most popular LCA tool was *SimaPro*. The sources of the data used in the various studies to prepare material quantities were more dispersed, with most studies using a combination of sources: 2D drawings and/or 3D models and/or bills of quantities. Additionally, several studies did not disclose this information.

Figure 4: Range of tools and data sources across the different case studies.



4.2 OVERALL FINDINGS

The embodied carbon results for all case study comparisons are presented in Figure 5, showing the estimated figures for the 'traditional' and 'MMC' case study buildings. The data presented is from 58 case study comparisons, with declared data in $kgCO_2/m^2$. In Figure 5, only a slight difference between the two sets of data can be observed in the box plots, indicating how, on average, MMC buildings perform marginally better than traditional construction. The results also show the broad range in both the traditional and MMC data sets. Given the marginal difference between the MMC and traditional case studies and the general broad range of results, no significant conclusions regarding the two construction methods can be made and a more detailed analysis of individual studies is required.

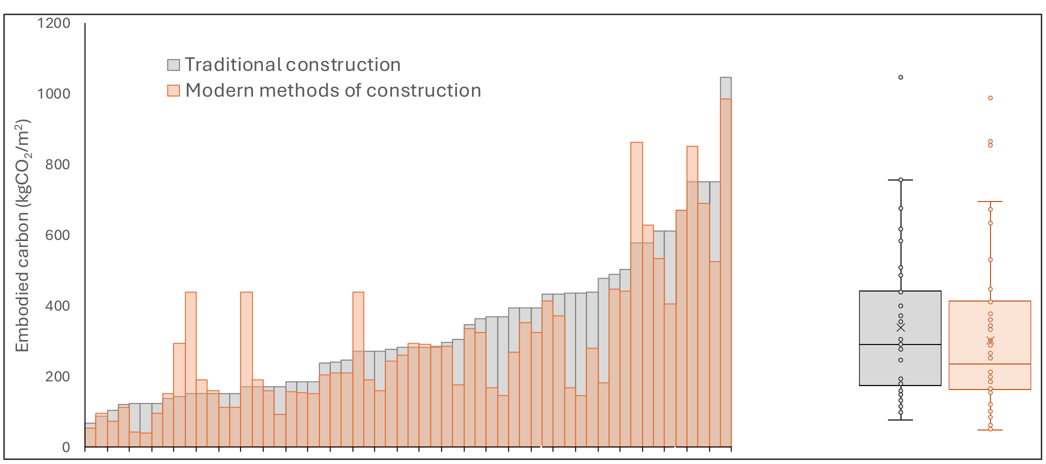


Figure 5: Embodied carbon result comparison of traditional and MMC constructed buildings.

4.3 IN-DEPTH ANALYSIS OF CASE STUDIES

For comparison purposes, the differences in embodied carbon between the MMC and traditional buildings are presented and arranged in order in Figure 6. The results show that in 71% of the case studies there was a difference of less than 100 $kgCO_2/m^2$ in embodied carbon between the two types of construction. Additionally, in 52% of the case studies, the difference was less than 50 $kgCO_2/m^2$ and could therefore swing either way by an assumption change in the embodied carbon figures of, for example, the underlying materials. The average difference across the 82 case study comparisons was 32 $kgCO_2/m^2$ (or 7% as a relative comparison of the traditional construction figure) lower for the MMC buildings. There are also a few studies at both ends of the figure where the difference was greater than 100 $kgCO_2/m^2$. These significant[1] figures on each side are perhaps most concerning in that the absence of a critical review could result in intentional and/or unintentional selective referencing of studies to fit a particular narrative. They are therefore, reviewed in detail in the subsequent section.

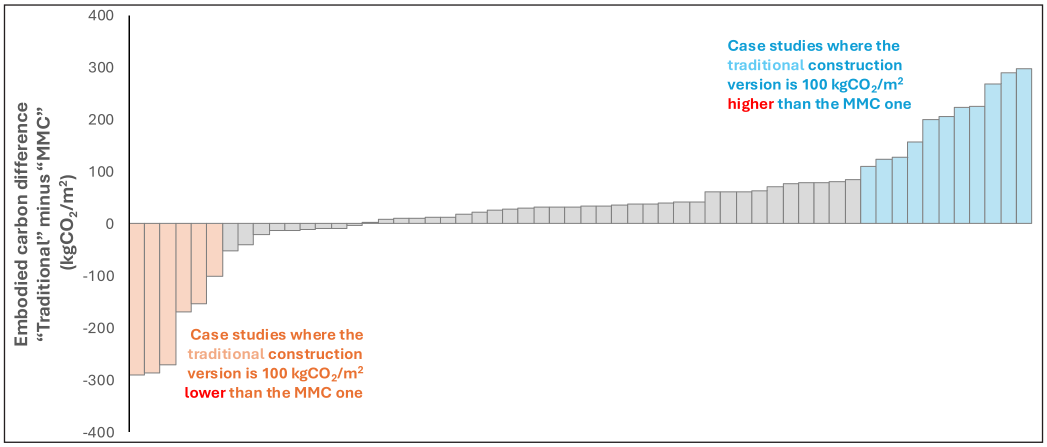


Figure 6: The embodied carbon difference between traditional and MMC buildings.

Note: Negative values indicate those where the traditional case study had a lower embodied carbon figure than the MMC case study.

4.3.1 Traditional construction with significantly lower embodied carbon

On the traditional-is-lower-carbon end of the spectrum (left side of Figure 6), the first notable trend is that the top five case study caparisons with the most significant differences are cases where volumetric construction was used. In the most extreme case, a traditional timber-frame construction (150 $kgCO_2/m^2$) was compared with that of a steel shipping container module (440 $kgCO_2/m^2$) (Greer and Horvath 2023) – showing a difference of −290 $kgCO_2/m^2$. Further comparisons between timber (170 $kgCO_2/m^2$) and steel frame (270 $kgCO_2/m^2$) construction and this shipping container module (440 $kgCO_2/m^2$) made up two more out of the top five case studies. A more like-for-like comparison was also made in the same study, which compared two timber options and showed a slight increase in embodied carbon with the modular timber option (190 $kgCO_2/m^2$) versus the traditional timber option (170 $kgCO_2/m^2$).

The next case study with the biggest difference (−286 $kgCO_2/m^2$) in favour of traditional construction was a comparison of a cast *in situ* concrete construction (578 $kgCO_2/m^2$) with a prefabricated modular steel construction (864 $kgCO_2/m^2$) (Aye *et al.* 2012). The same study also reported 630 $kgCO_2/m^2$ for a prefabricated timber building – also higher than the standard concrete frame. Nonetheless, despite these embodied carbon results, the authors concluded that, owing to the reuse potential of the steel and its lower weight per square metre of floor area, the steel modular construction had 'the potential to contribute significantly toward improved sustainability'.

Fifth on this side of the list, with a difference of −153 $kgCO_2/m^2$, was another comparison between an *in situ* concrete frame (142 $kgCO_2/m^2$) and a steel modular construction (295 $kgCO_2/m^2$) (Morton and White 2024). The authors of this work add insight to their findings, highlighting how the motive behind modular construction was to optimise speed by manufacturing similar products, and how this consequently limited the number of options available for buildings, resulting in a sub-optimal design. The same authors also compared a precast concrete option (150 $kgCO_2/m^2$) with an *in situ* option (138 $kgCO_2/m^2$), concluding in this case that there was a negligible difference between the two options. The smaller overall figures in this study compared to industry-average figures for the embodied carbon of buildings (usually above 400 $kgCO_2/m^2$) was due to the scope of the study, which was concerned only with the structural frames.

In an LCA study of four schools in Catalonia, Pons and Wadel (2011) showed that a 'non-prefabricated' case study resulted in 100 $kgCO_2/m^2$ less than a prefabricated steel version (852 $kgCO_2/m^2$). The same study, however, also reported figures for a prefabricated concrete (690 $kgCO_2/m^2$) and timber (526 $kgCO_2/m^2$) solution, both of which performed better than the *in situ* concrete case study.

4.3.2 MMC with significantly lower embodied carbon

On the other end of the spectrum (right side of Figure 6, with MMC as the significantly lower embodied carbon option) there was another comparison between *in situ* concrete and modular steel (+298 $kgCO_2/m^2$). Interestingly, this is the opposite result of the previously cited case studies, emphasising the issue with simply citing one case study as evidence of a broader conclusion, even within specific subcategories of MMC. The methodology used in this study is quite opaque, but some explanation might be found in the assumed material intensity figures. This study, of a school building in South Korea, used a national life cycle inventory database and reported an embodied carbon figure for steel of 404 $kgCO_2$/tonne, a figure that is almost one-third that of the average global figure for electric arc furnace steel (1370 $kgCO_2$/tonne) and a fifth the footprint of global average blast furnace steel (2330 $kgCO_2$/tonne) (World Steel Association 2023). The calculation for the concrete case study is not clear but it is possible that the findings are skewed by the assumption of particularly low embodied carbon steel.

Four of the next six case studies at this end of the chart (right side of Figure 6) compared a timber-frame construction with that of an *in situ* concrete one. Tavares *et al.* (2021) compared both a light-steel-frame (167 $kgCO_2/m^2$) and a timber-frame (145 $kgCO_2/m^2$) single family house (249 m^2) with two conventional reinforced concrete (RC) base cases – one with embodied carbon of 436 $kgCO_2/m^2$, the other with embodied carbon of 368 $kgCO_2/m^2$. An explanation for the considerable difference is not obvious but might be found in the table of quantities, which shows the weight of the RC case studies (approximately 1 tonne/m^2) compared to the other examples, which are both approximately 0.2 tonnes per m^2. It appears that the prefabricated case studies were optimised while the RC case studies were not. The studies' list of material quantities is clear and replicable and, while the carbon intensities of the major materials are not presented, the study refers to the use of *SimaPro V8.0* and *Ecoinvent V3*. This study alone accounts for four out of 11 of the comparisons where there was a difference of more than 100 $kgCO_2/m^2$ in MMC as the lower embodied carbon option.

Another residential comparison conducted by Monahan and Powell (2011) compared two timber-frame options, one with larch cladding (405 $kgCO_2/m^2$), another with brick veneer cladding (535 $kgCO_2/m^2$), with that of a conventional masonry cavity wall (612 $kgCO_2/m^2$). The study is well detailed, and all assumptions and quantities are clearly documented. The findings appear robust and are generally in line with findings in the literature that compare timber construction with masonry. The study is more of a specific comparison between timber frame and that of conventional masonry, rather than an overarching comparison of MMC with conventional.

Some of the studies cited in this work were particularly strong in their conclusions. Hernández *et al.* (2023), for example, concluded that their 'research has significant implications for promoting the adoption of MMC globally, leading to more sustainable and efficient construction practices'. The study compared a particular type of MMC, referred to as VAP in Chile – which stands for *viga* (beam), *aislación* (insulation) and *pilar* (column). The authors found that this VAP system (176 $kgCO_2/m^2$) compared favourably to a more conventional building (304 $kgCO_2/m^2$) – reporting a difference of 128 $kgCO_2/m^2$. While the results appear to be well researched, it is likely a stretch to conclude that this research justifies the adoption of MMC globally on the grounds of a single case study.

Gao *et al.* (2024) reported a similar difference between a prefabricated (269 kgCO_2/m²) and traditional (394 kgCO_2/m²) building of 124 kgCO_2/m². The case studies in this analysis were both high-rise residential, but it is not clear what was being compared. It appears that a cast-in-place concrete case study with a total floor area of ~14,000 m² was compared with a section of a separate large project with 152,000 m² of floor area in total. The part of this project being compared with the traditional case was a group of six residential buildings that had a floor area of 91,000 m².

Although there were some studies highlighting significant differences between traditional and MMC case studies, there were often specific rationales provided for the comparisons that, in all cases, were not broad enough to generalise the conclusion beyond the case studies themselves.

4.4 FILTERING THE INFLUENCE OF MATERIAL

Figure 7 presents the spread of embodied carbon results between traditional and MMC case studies while removing data that compare buildings with different materials or significantly different floor areas. The result of this filtering is a comparison overview tending towards negligible difference. The average embodied carbon of the traditional construction case studies here is 306 kgCO_2/m², while the MMC average is 286 kgCO_2/m². The median value of the MMC sample set is 3 kgCO_2/m² higher than the traditional equivalent. Some more in-depth analysis of these materially comparable case studies is presented in the following subsections.

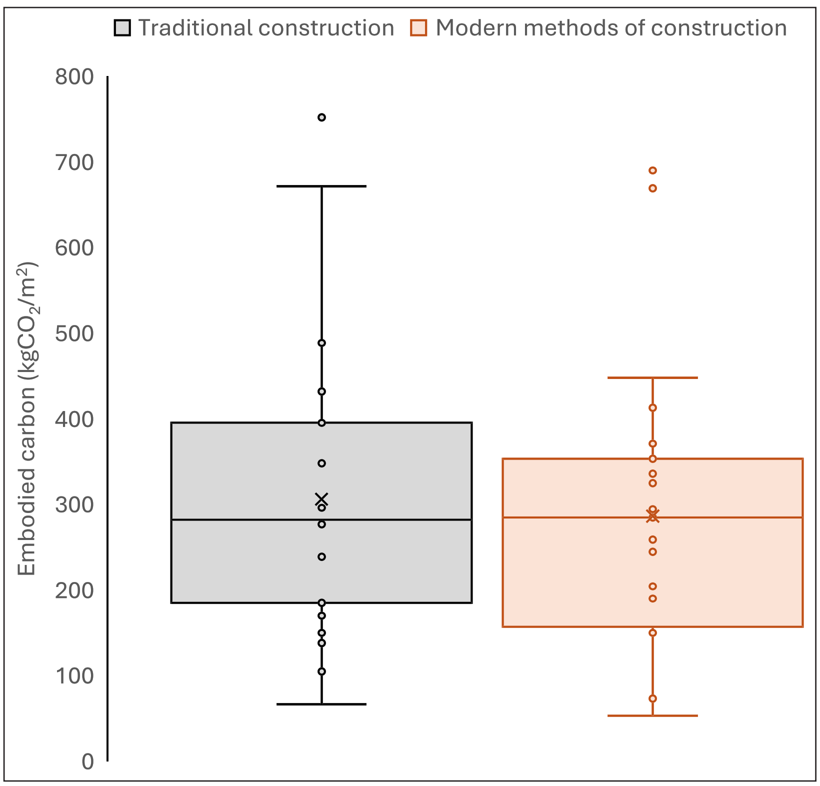


Figure 7: A comparison of embodied carbon in traditional construction and MMC.

Note: Studies were excluded that compared different materials or compared buildings with a floor area difference >50%.

4.4.1 Timber

Quale *et al.* (2012) compared the average embodied carbon of three modular timber residential buildings to five conventional timber buildings, concluding that the modular buildings resulted in lower emissions. However, upon further examination the conclusion is highly sensitive to specific assumptions. The study included the transport of workers to site, for example, which is generally outside the scope of an LCA assessment; if this were removed, the results would be approximately equal. In terms of the material consumption of the case studies, the authors cited how, in the case of modular construction, there was a requirement for a doubling of the walls ('marriage walls') for transporting and joining, which resulted in a 25% increase in material by mass. This was made up for by assuming no timber waste occurred in the modular case while more timber waste occurred in the conventional case than the additional timber needed for the marriage walls. Assuming a more efficient on-site waste management strategy would have resulted in the conventional case scoring lower on embodied carbon. This is an example of the high sensitivity of results in LCA studies to the assumptions made.

In another study that compared a traditional stick-built timber construction with a 2D panelised and 3D modular system, Smith *et al.* (2018) found that the 2D panelised version used 7% more timber material, while the modular 3D version consumed 69% more than the traditional counterpart. The study was well explained and clearly illustrated the additional timber used in the modular case due to the double walls. However, the authors concluded that the additional consumption of timber was a positive environmental outcome, noting how all the timber buildings were negative emissions and how the modular constructed homes, therefore, stored the most carbon. This is a questionable conclusion to draw given that the end-of-life release of this 'stored' carbon was not considered in the analysis. Accounting only for the carbon uptake of the growing trees prior to cut-down, without assuming a balancing of the carbon emissions at the end of life, is opposed to most of the pertinent research in this particular field of LCA of timber buildings (Andersen *et al.* 2021; Arehart *et al.* 2021; Hoxha *et al.* 2020).

4.4.2 Concrete

A number of case studies compared precast concrete construction with *in situ* concrete. The study by Morton and White (2024), previously discussed, highlighted negligible difference between the precast and *in situ* concrete structures. Of the case study comparisons that compared two concrete buildings, there were only six with a difference greater than 45 $kgCO_2/m^2$. Aside from the results from Gao *et al.* (2024) discussed in Section 4.3.1, Balasbaneh and Sher (2021) presented the biggest difference in an assessment between a prefabricated, prefinished volumetric residential building (395 $kgCO_2/m^2$) and an on-site constructed alternative (325 $kgCO_2/m^2$). The study also included a panelised version of the same building (353 $kgCO_2/m^2$). It is not clear from this study if the material quantity data were from actual or hypothetical buildings and assumptions made for carbon intensity factors were not detailed.

4.4.3 Steel

Few studies compared 'traditional' steel constructed buildings with MMC steel case studies. Perhaps this was because an implied assumption throughout the literature is that the use of steel is synonymous with MMC – since elements are always manufactured off site. In a UK-focused study, Kechidi and Banks (2023) presented results of two modular steel homes, a 'standard' one (290 $kgCO_2/m^2$) and a 'refresh' of it (254 $kgCO_2/m^2$). They showed how design optimisation could yield embodied carbon savings for the modular homes and also cited how the 'standard' version was still 5% lower than traditionally built (brick and block) homes (305 $kgCO_2/m^2$).

4.4.4 Modular vs. 2D MMC

Figure 8 presents the embodied carbon difference between traditional construction and modular and other MMC types (primarily 2D systems), separately. In Figure 8, the full sample set (left) and a filtered sample set (right), which excludes comparisons that are not materially comparable, are both presented. Comparing the two datasets, a reduced spread is observed in the case of the filtered data. These filtered data suggest a marginally increased embodied carbon when adopting modular MMC and a marginally reduced embodied carbon when adopting other MMC options relative to traditional construction. Again, the results are marginal in the context of building LCA and hence not significantly for, or against, the adoption of MMC as a lower embodied carbon solution. The box plot from the unfiltered datasets illustrates a greater spread in results, particularly when comparing modular-type MMC with traditional construction.

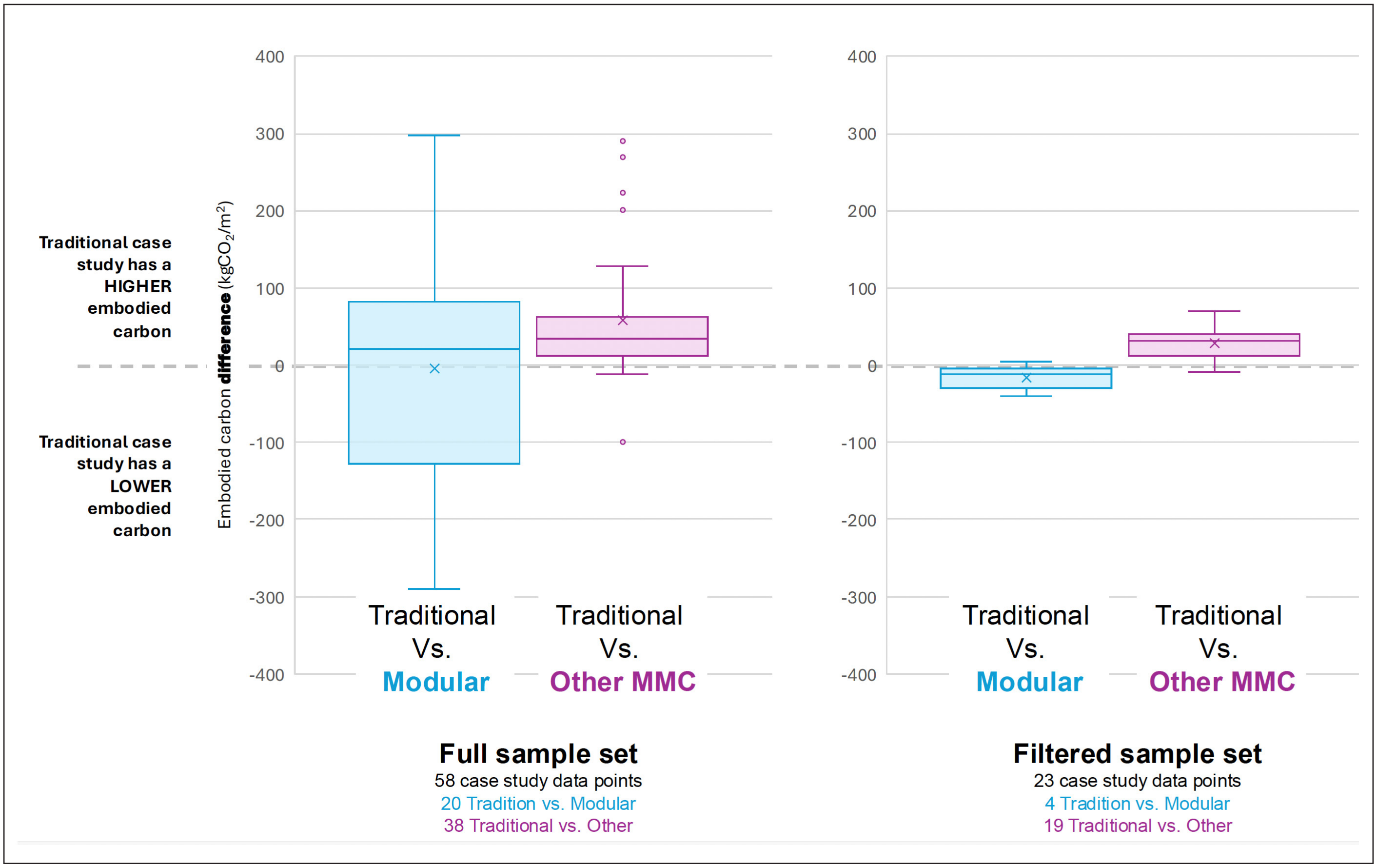


Figure 8: Comparison of the embodied carbon difference between traditional construction and MMC, grouped by modular and other MMC types for the full dataset (left) and the filtered data set (right).

CONCLUSION

The perception that buildings constructed using MMC will result in a reduction in embodied carbon is not founded on robust evidence. While MMC case studies, on average, have marginally lower embodied carbon, the underlying data are inconsistent, the difference is negligible, and the data are sensitive to assumptions made in individual case studies. This study has interrogated all cited studies and highlighted several key assumptions that can swing a result in favour of, or against, a particular typology. These include assumptions relating to material embodied carbon intensity factors, waste on site compared to in a factory, design optimisation of one case and not the other, assumptions in transportation, and assumptions about the end-of-life carbon emissions.

There is good argument presented in several studies that noted that prefabricated components are less material-efficient given they are designed primarily for speed. This key driver for MMC naturally encourages repetition in building elements at a factory level and hence a limited number of options at a building level. Inherent overdesign during the building's life is a consequence of this. These components must also resist additional design loads during transportation, lifting and installation, particularly for modular construction. Conversely, there is an alternative argument made for the efficiency gains accrued on site when using MMC, resulting from a reduction in material wastage and the better optimisation of waste management in factories. These savings are a site management issue, while the additional loads experienced during transportation, or the inherent sub-optimal number of options of MMC elements, are more of a practical limitation of prefabrication. In any case, overall, this review has shown that there is insufficient evidence to suggest embodied savings due to the adoption of MMC.

A more pertinent question emerging from this research is whether the research question itself is ill-defined. MMC, or indeed prefabrication and off-site construction, are too broad in their definition to be scientifically evaluated by individual case studies or even small sample sets. The review highlights the issues with pursuing a precise answer to a question where precision does not exist and instead recommends that future studies, as is the case with several of the cited literature, focus more specifically on specific insights relating to the individual case studies and refrain from concluding broader conclusions.

To arrive at such a broad conclusion, a single study with a large and diverse sample set of both MMC and traditionally constructed buildings would be required to evidence any robust difference between these construction typologies. Future case studies should also assess and compare the influence of different MMC techniques on embodied carbon. In the absence of such studies, we conclude that the evidence to date suggests there is no significant difference between the type of construction method used but that real embodied carbon savings are instead gained through project decisions, geometric design optimisation and appropriate selection of materials on a case-by-case basis.

This study compliments the more comprehensive review of all MMC credentials conducted by Sánchez-Garrido *et al*. (2023) by adding detail and insight into embodied carbon specifically.

NOTE

1 For the sake of this section, we define a significant difference to be greater than 100 $kgCO_2/m^2$.

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COMPETING INTERESTS

The authors have no competing interests to declare.

DATA ACCESSIBILITY

The datasets generated and/or analysed in this study are available from the corresponding author upon reasonable request.

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SUPPLEMENTAL DATA

Supplemental data for this article can be accessed at: https://doi.org/10.5334/bc.515.s1

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