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Abstract:

Purpose

Modern Methods of Construction (MMC) have been promoted as a solution to address housing shortages and meet sustainability goals in the UK. However, the practical functioning of MMC, particularly in relation to early-stage environmental analyses, remains underexplored. This study aims to fill this gap by providing empirical insights into how architects engage in environmental analysis in early-stage MMC housing designs.

Design/methodology/approach

This qualitative pilot study is based on a detailed case study of a UK architectural firm specializing in modular housing. Semi-structured interviews were conducted with eight architects with varying MMC experience. Thematic analysis of the qualitative data allowed for the exploration of key themes influencing early-stage environmental analysis, offering a narrative account of architects' experiences in MMC practices.

Findings

The study reveals that environmental analysis in MMC is shaped by social, organizational, and project-based factors. Three key themes emerged: uncertainty in environmental assumptions, dependencies on external consultants, and the dominance of Passivhaus principles in design decisions. These factors challenge the integration of environmental considerations during early design stages of MMC projects.

Research limitations/implications

As this is a single case study, the findings might not be generalizable. Future research should expand on multiple firms and project settings to validate and broaden these findings.

Originality/value

This study provides in-depth understanding of the challenges architects face when integrating environmental analysis into MMC. This reveals the relational and interdependent nature of environmental analysis in MMC projects, where decisions are shaped by multiple social, organizational, and project-specific factors. By emphasizing these interdependencies, this study provides original insights into how environmental considerations can be integrated more effectively into the early design stages of MMC projects.

Keywords: analysis, environmental; MMC; architects, early-stage design,

1. Introduction

The delivery of UK sustainable affordable housing at scale and speed has been promoted to largely rely on exploiting modern methods of construction (MMC) (Commons, 2019), specifically prefabricated high-spec modular units (Zhang et al., 2019). MMC generally refers to forms of off-site manufacturing for construction, including modular and panellised systems. In addition to cost and productivity benefits, and through the use of advanced digital technologies and manufacturing precision, MMC homes are thought to provide an overall reduction in energy consumption in comparison with traditionally built new homes (Government, 2018). However, despite its benefits, scholars have highlighted potential negative consequences associated with MMC (Green, 2019). Moreover, the adoption of such innovative construction methods and associated technologies is expected to have multiple and intersecting levels of impact on the project-, firm- and industry-levels (Dowsett et al., 2022),

In the UK, concerns and slow adoption still exist within the industry (Pan et al., 2007; Thurairajah et al., 2023), with research showing a low uptake of MMC across the construction sector in general and for housing specifically (Looby et al., 2022). Recent failures of organizations using MMC have been attributed to "innovation negativism," which is influenced by factors such as incomprehension, lack of evidence, and bad experiences (Saad et al., 2024). This negativism is not solely based on historical perceptions, but is also driven by current issues in communication and the establishment of a solid business case for MMC (Saad, Dulaimi, & Zulu, 2023). Contradictorily, while some studies emphasize the reluctance of the public sector to adopt MMC because of these negative perceptions and a lack of confidence in supply business models (Saad, Dulaimi, & Gorse, 2023), others point to the significant advances and suitability of offsite and pre-manufactured construction methods for mainstream adoption (Ofori-

Kuragu & Osei-Kyei, 2021). Furthermore, the literature suggests that the low uptake of MMC is not just a matter of perception, but also a reflection of the broader dynamics between supply and demand, decision-making processes, and the need for business model reforms (Saad, Dulaimi, & Gorse, 2023; Saad, Dulaimi, & Zulu, 2023).

Moreover, recent UK government inquiry into the future of MMC in housing highlights the ongoing struggles of the MMC sector despite government support for its adoption to address housing shortages (Parliament, 2023). The sector faces significant barriers, including financial instability, market fragmentation, a shortage of skilled labour, and a lack of confidence in MMC technologies. Furthermore, inconsistent regulations and standards complicate scalability, whereas public sector reluctance adds to slow uptake. The report calls for a more coordinated and holistic approach from the government, including clearer regulation, financial support, and efforts to bridge the skill gap (Parliament, 2023).

While most of the research in MMC is focused on the building manufacturing and assembly phases (Nguyen et al., 2022), the design and development phase–when design optimisations that are relevant to minimising environmental impacts take place–has received less attention. The challenges associated with the environmental performance of MMC house buildings are focused on: the complex interfacing between the different building systems (Pan, Gibb and Dainty 2006), lead times, and the lack of flexibility for design changes (Alonso-Zandari & Hashemi, 2017), and the lack of design and decision support frameworks, models, or tools for strategic guidance on sustainability (Dave et al., 2017).

The aim of this study is to investigate the process of environmental analysis of MMC developments through the exploration of architects' perceptions and approaches to environmental analysis in early stage MMC housing design. This study draws on an

in-depth case study (Stake, 2008) of a leading architecture firm specialising in modular housing design in the UK. The analysis suggests that social and organisational factors, as well as the project-based nature of design activities, influence how and if environmental analysis is undertaken in the early stages of MMC housing design. Furthermore, while contributing to the environmental sustainability of MMC theory and practice, the findings open the need for future exploration into the wider contextual, social, and organisation issues that underpin environmental analysis practices in architectural design projects, including MMC.

This paper is organised as follows: The following literature review section provides an overview of how the design process for MMC differs significantly from other prefabrication techniques, and then delve into relevant literature on why early-stage design decisions matter for environmental performance and the architect approaches for early-stage environmental analysis. The research methodology section outlines the approach and data collection and analysis methods, followed by the findings section, which is organised around the three themes that emerged from the pilot case study analysis: uncertainty factors, dependency factors, and Passivhaus First. Finally, the discussion and conclusion section outline the relevance of our findings to the extant literature and the focus for future research.

2. Literature review

The design process for Modern Methods of Construction (MMC) differs from other prefabrication techniques in several ways. It emphasizes integration across design, production, and assembly stages, facilitated by BIM to manage information flow and

reduce errors (Peng et al., 2021). Moreover, MMC relies heavily on offsite construction, where components are manufactured in controlled environments before being assembled on-site. This approach contrasts with traditional prefabrication, which may not always involve such extensive offsite work (Doan et al., 2024). MMC also incorporates Design for Manufacture and Assembly (DfMA) principles, ensuring that designs are optimized for both manufacturing and assembly to minimize errors (Gharehbaghi et al., 2021). The design process in MMC also focuses on economic feasibility and productivity, with strategies aimed at reducing costs and labour in mechanical, electrical, and plumbing (MEP) systems (Baek et al., 2023). Overall successful MMC projects rely on interdisciplinary collaboration between architects, engineers, and construction managers to align all aspects of the process.

The distinctive design methodology of MMC, with its emphasis on integration across design, production, and assembly phases, is essential for optimizing both environmental and economic outcomes. International initiatives such as Germany's Aktivhaus provide additional insights into how MMC can incorporate advanced technologies into environmental performance while maintaining flexibility and efficiency (Sobek, 2024). The Aktivhaus project's utilization of photovoltaic systems, heat pumps, and adaptable modular designs demonstrates how early-stage design decisions significantly influence the long-term sustainability of modular construction. These examples highlight the importance of the early integration of environmental considerations into MMC, supporting the assertion that assumptions embedded within the early stages of design can have significant consequences for design outcomes (De Wilde, 2018; Singh et al., 2022)).

This research examines the significance of early-stage design activities within the context of MMC UK housing in relation to environmental performance.

Accordingly, the subsequent sections will delve into the reasons underlying the importance of early-stage design decisions for environmental performance and the architectural methods for conducting early-stage environmental analyses.

2.1. Architectural design process and how architects work:

Traditional architectural design processes are mainly focused on space, form, aesthetics, and function; they rely on input from a range of domain experts (Østergård et al., 2016). Architects must often deal with incomplete requirements, contradictions, and changing conditions, and solving one issue may lead to other problems (Lin and Gerber 2014). These challenges are amplified in Modern Methods of Construction (MMC), which contrasts with traditional material-led approaches that constrain design flexibility. In traditional methods, material selection dictates design and delivery, which often limits innovation. However, MMC enables a building design-led approach, in which the design is optimized for manufacturing and assembly from the start (Mapston & Westbrook, 2010). Technologies such as BIM and DfMA facilitate this shift, enhance quality control, reduce waste, and improve cost efficiency. Consequently, MMC emphasizes the early integration of technical knowledge and promotes collaboration between architects, engineers, and manufacturers, leading to more adaptable, efficient, and sustainable construction practices (Gunawardena & Mendis, 2022).

In general, design decisions depend on the architect's experience (Jabi, 2016; Lawson, 2006), in addition to other factors such as site, legislation, and user requirements. Moreover, as Styhre and Gluch (2009, p. 224) point out, architects' work is "fundamentally collaborative and includes tight communication with various stakeholders, including clients, contractors, and end-users". Architectural design is therefore situated in a complex organisational form, known as constellation, which often limits the extent to which architects and other professional groups engaging in design

work are able to "maintain and develop their creative skills in the present economic regime." (Ibid, p. 225). Oliveira et al. (2020) discussed the need to explore the social and organisational context of environmental analysis as a way of understanding the constraints and opportunities that drive the design process, which is often encountered differently across different scales of both project and organizational practice. The effects of these encounters in MMC settings are still poorly understood.

Styhre and Gluch (2009), with reference to Cohen et al. (2005) study of British architects' experience of their role in design practice, found that architects identified themselves as artists, businesspeople, and public servants (the last being about providing a quality "built environment for the general public" (p. 226). As they progress in their careers and gain more experience, the realities of continuous struggle between money and aesthetics make architects rebalance their original ambition and educational objective of providing new and creative solutions to housing and built environment problems with a more realistic, although paradoxical, view of what it is possible to accomplish. The sustainability of their professional practice becomes contingent on their resourcefulness and capability to "balance aesthetic, technical, and economic concerns in the specific project." (p. 228). A key skill of the architect then becomes the ability to stay "attuned to and interpret and translate the different values brought to bear by the many actors involved in the design process. This requires the exercise of lateral thinking, including flexible and creative responses to clients, sensitivity to users' needs, and working with, rather than against, building codes and regulations." (p. 241).

2.2. Environmental analysis process and tools:

In the early design stages, ideas about the actual building materialise, setting the context for later developments, including future building performance, and decisions made early in the design process can have significant consequences for the design

outcome (Méndez Echenagucia et al., 2015; Østergård et al., 2016; Zhou, Tam, et al., 2023) . The key to optimising the dwellings' environmental performance is addressing daylighting and overheating implications through the selection of combinations of units (e.g., walls with different window placement and size), appropriate to individual spatial and temporal conditions (Fazeli et al., 2022; Shibeika et al., 2021). In the case of rapid MMC delivery, this process can be a complex and intensified design optimisation problem. The intensification of the design process is mostly due to short lead times and can be inadequately informed owing to unknown architects' assumptions about environmental performance (Sonja Oliveira et al., 2017). Consequently, insufficient environmental analysis is often conducted (De Wilde, 2018), resulting in many cases of poorly performing and unhealthy housing.

Inherently, the early design stage is mostly characterised by high levels of uncertainty about different aspects of the design, leading to difficulties in developing a clear idea of performance early in the design process (Krish, 2011; Zhou, Ma, et al., 2023). As a result, a growing body of research is focused on developing and testing methods and tools to reduce uncertainty in the early building design stages (de Wilde, 2023). For example, machine learning approaches have been adopted to reduce environmental uncertainty and help designers evaluate and compare the expected environmental performance of buildings (Feng, Lu et al. 2019). Rohde et al. (2021) focused on indoor quality and developed an assessment tool that can aid architects and designers by providing feedback and design comparisons to enhance early design decision making. Rezaei et al. (2019) integrated Building Information Modelling (BIM) and Life Cycle Analysis (LCA) to help designers select sustainable materials for building design. While useful in providing insights into the possibilities for reducing

uncertainty, the fine mechanics of how to design a building that delivers good environmental performance remains evasive.

Moreover, environmental analysis and performance prediction in early design often rely on estimation or assumptions based on historical data from similar projects (de Wilde, 2023; Zapata-Poveda & Tweed, 2014), leading to environmental analysis being carried out too late in the design process (Attia et al., 2012). The design process for MMC is more intensive and shorter than that of traditional construction methods, leading to more complex environmental analysis and multi-criterion decision-making (Augenbroe, 2012) which requires higher degrees of process, information, and organisational integration across the MMC project stakeholder.

Environmental analysis relies on multidisciplinary design teams with efficient visualisation of technical information to aid architects in the decision-making process (Landgren et al., 2019), despite the recognised value and benefits of building simulation tools and techniques to improve communication and aid environmental analysis in building design (S. Oliveira et al., 2017), these tools have limitations in providing adequate feedback for design decision-making (Lin & Gerber, 2014), and it has been seen by architects as only an evaluation tool (Jabi, 2016), and cannot provide the architect with the relevant methodology to develop the design solution. For example: "*Daylight protractors, heat loss or solar gain calculations do not tell the architect how to design the window"* (Lawson, 2006).

When considering environmental performance during the building design process, architects are found to focus on holistic design issues, such as the shape and orientation of the building, passive strategies for heating and lighting, and natural ventilation (Attia et al., 2012; Zhou, Ma, et al., 2023), and engineers are found to be more concerned about the quality and control of the building systems (Attia et al.,

2012). Zapata-Poveda and Tweed (2014) highlighted the reliance of architects on informal tools and experience-based advice from building service engineers rather than performance simulation tools during the early stages of design up to RIBA developed design stage three. Such studies provide help with understanding the potential value of MMC building design, but they are still focused on the outcomes rather than on the synthesis of the design process itself. Therefore, the aim of this project is to investigate the process of environmental analysis for MMC developments through the exploration of architects' perceptions and approaches to environmental analysis in early stage MMC housing design.

3. Research methodology

In addition to the literature gap identified above, the research presented in this paper is also driven by the practical need from architectural practice for further understanding of how environmental analysis and related design decisions are embedded in early design stages. While there is an abundance of case studies on energy-efficient smart buildings, most of the research on environmental analysis is focused on building performance analysis and checking whether targets have been met (De Wilde, 2018), and less is found about the process leading to the final product and how decisions about environmental analysis were reached.

This study was based on an exploratory pilot study conducted between March and June 2021, following an in-depth case study approach (Stake, 2008). The case study approach is particularly valuable in architecture, where it can provide a comprehensive understanding of complex issues and contribute to the development of solutions (Ratnasari & Sudradjat, 2023). Moreover, case studies have been instrumental in identifying trends and design methodologies in specific architectural contexts, such as regionalism in Pakistani architecture (Asghar et al., 2020), and have been recognized as

a valuable approach in landscape architecture for education, innovation, and knowledge dissemination (Francis, 2001).

3.1. Empirical setting

The following case study focuses on an esteemed and resilient architecture firm that has completed and designed various MMC housing projects for more than a decade. The selected firm was chosen as it specializes in housing and has extensive experience in MMC delivery. Additionally, the firm was in the process of developing guidelines for environmental MMC design and had received numerous prestigious awards for successful MMC projects. The selection of this case study was based on the firm's well-known expertise, shared experience, and esteemed reputation in the field. The firm is substantial, employing over 250 individuals, and has been operational since the early 1970s, with MMC being a consistent aspect of its operations over the past 15 years.

The whole practice was invited to participate via an internal call shared by email, in total 8 architects participated in the study, all of whom had varied ranges of MMC expertise and overall architectural practice experience. Although self-selection sampling (Saunders, 2012) may introduce potential bias, it also ensured that participants had relevant experience and expertise in the area under investigation, thus contributing valuable insights into the research. Furthermore, while the sample size was small, research suggests that six to seven interviews typically capture the majority of themes within homogenous groups (Guest et al., 2006; Guest et al., 2020), making the eight interviews conducted sufficient for the scope of this exploratory pilot study. We also ensured diverse roles within the firm were represented to minimize bias towards specific project types or design approaches.

Moreover, the single-case study approach is not without limitations. The firm under study was carefully selected due to its substantial experience in MMC delivery

over a long period, making it a relevant and rich source of data. This approach allowed for an in-depth examination of firm-specific practices, which is essential for understanding the complexities of MMC in real-world applications. The aim was to explore meaning and interpretation rather than generate generalizable findings, and the focus on one firm facilitated a more nuanced investigation into environmental analysis practices in MMC, which would be more difficult to achieve with a broader but less detailed industry-wide study. In future research, expanding the sample to include multiple firms and using additional data collection methods, such as surveys or site observations, would help further validate and extend the findings of this initial exploratory research.

The pilot study was approved by the UWE ethics committee. Within that application consent forms were designed to seek participants' agreement before any interviews took place. Furthermore, all names and personal data were anonymised and stored in a secure place through the whole research period and was only accessed by the researchers. Through the analysis and writing up of the case, only job titles were used.

3.2. Data collection methods

The main source of data for this pilot study was semi-structured interviews with key experts within the firm (eight in total). All participants had over five years of experience in MMC housing design and held different roles within the firm, from project architects to associate directors (see also table 1). In this firm architects normally take main design responsibility in one project at a time, while associates and directors oversee the work of project architects in multiple projects. The interviews aimed to capture wider views from a range of roles to minimise potential bias towards specific types of projects or approaches. Each interview lasted between 2 hours 45 minutes and 4 hours.

Role	Experience of modular housing
Associate	Limited to two projects
Senior architect	Range of projects
Architect	Range of projects
Architect	Limited to one project
Architect	Range of projects
Architect	Limited to one project
Architect	Limited to one project
Associate director	Range of projects

Table 1: Interviewees details

Due to Covid19 restrictions including lockdown, social distancing, and uncertainty regarding project delivery, the construction and MMC industry was faced with, and the interviews were held online rather than in person. The interviews were designed around key thematic areas to address the research aim, which was to investigate the process of environmental analysis for MMC developments through the exploration of architects' perceptions and approaches to environmental analysis in early stage MMC housing design, as outlined below. An indicative sample of the interview questions is provided for each theme.

- Theme 1 - Understanding the nature of the design practice and early-stage environmental analysis design processes, which do not occur in a vacuum, and there are many variables (cost, time, project parties/stakeholders) that play a central role in driving the design process. As mentioned above, the intention was to understand the lived experience of architects in this specific 'MMC housing' context, including their projects' priorities, challenges, and drivers.

- *Could you tell us a little on how you consider environmental analysis (particularly daylighting and overheating) in early stage MMC modular housing design stages?*

- *Are there particular environmental analysis criteria related to daylighting and overheating that are seen as important to you? Why?*

- Theme 2: Understand designers' assumptions and perceptions of environmental analysis given the iterative nature of the design process in its early stage and other project criteria, and this was focused on the Architectural design process and how architects work literature which was discussed in section 2.1

  - *At those early stages, at which point do you consider implications of environmental analysis decision making on the housing design?*

  - *From your experience what are the challenges involved in considering these implications?*

- Theme 3 - Understand designers' relationships with technology, professional identity implications, and career implications/threats, guided by the literature review in section 2.2 above around environmental analysis process and tools.

  - *What are the skills and knowledge that, in your view, enable you to consider and take into account the environmental criteria for daylighting and overheating? Who else is involved in the decision process?*

  - *In your view, is there a need for any urgent improvements of the processes or practices in this context?*

3.3. Data Analysis method

After completing and transcribing all the interviews, data analysis began with an initial rereading of the interview transcripts to identify key issues and patterns. The data set included more than 20 hours of recordings and approximately 80 pages of transcripts, which were organized into a comprehensive “data bank” (Rynes & Gephart Jr, 2004). The analysis followed a thematic approach, as outlined by Braun and Clarke (2006), with multiple stages to ensure thorough exploration of the data.

The first stage involved descriptive coding, in which individual text segments were coded to capture specific issues related to early-stage environmental considerations in the MMC housing design. Descriptive codes, such as "tools," "regulations," and "design process," are valuable in summarizing key data points and provide a foundation for further analysis (Richards, 2005).

In the second stage, descriptive codes were examined to develop analytical codes (Miles et al., 2020). Analytical codes represented deeper interpretations of the data, moving beyond surface-level observations to highlight underlying patterns and relationships. For instance, the code “making assumptions about performance” was identified as a key concept during this stage, reflecting how architects approach environmental analysis with MMC in uncertain conditions.

Finally, codes were organized into broader themes that captured both implicit and explicit ideas within the data (Miles et al., 2020). This step involved constant comparisons across interviews to ensure that the themes accurately represented recurring ideas across the participants. The process of theme development was iterative, and the research team reviewed and refined the themes through discussion and comparison with the research objectives. Thematic saturation (Miles et al., 2020) was

achieved when no new themes or codes emerged from the additional rereading of the transcripts.

As a result of the thematic coding process, three themes emerged from the data, which are presented and discussed in the following section.

4. Research findings

The problem that the pilot study addresses is the process for environmental analysis for MMC developments, which is achieved through the exploration of architects' perceptions and approaches to environmental analysis in early stage MMC housing design. Several examples of MMC projects were identified through the interview process. One project for a London council incorporated pre-panelised facades and bathroom pods, although it was not primarily modular in nature. A housing association similarly utilized MMC for bathroom pods and facades during their development. Another instance involved a series of 12 small infill sites in London, where offsite construction was considered to address the challenges associated with compact urban spaces. Additionally, a modular housing tower project employed volumetric MMC, with capacity studies focusing on urban design and environmental performance. Lastly, a local authority project incorporated modular units atop existing 1960s housing blocks, with the aim of minimizing disruption to residents during the construction process. These projects demonstrate the diverse applications of MMC in both new developments and the retrofitting of existing structures. Each project is associated with environmental analysis, leveraging MMC's potential to enhance energy efficiency, reduce construction waste, and optimize building performance, particularly through improved control over material utilization and building standards during offsite manufacturing.

Overall, three key themes emerged from the analysis of the collected data on the lived experiences of architects and how these insights may help better understand environmental analytical needs in the context of MMC, which will be discussed in more detail in the following subsections.

- Uncertainty factors (making assumptions/understanding ourselves/not ready and no tools).
- Dependency factors (reliance on experts; dependence on clients, contracts, costs, sites, and regulations).
- PassivHaus first, a specific interpretation of this concept, which takes primacy over specifically considering daylighting and overheating as environmental design requirements across a range of contexts in MMC housing.

4.1. Uncertainty factors:

When asked to describe and explain initial approaches to environmental design analysis in project overall and in MMC housing in particular, most participants hesitated to explain what approaches they undertook; instead, they discussing approaches undertaken by others, asking for reassurance during interview if topic covered was 'right' and referring to learning and education, tools and processes needed to integrate environmental analysis early in projects.

Participants often discussed the need to make assumptions on environmental analysis in the early stages of the project. Participant eight noted how '*input*' from other experts '*didn't come to fruition*'; which had the effect on the team needing to '*make certain assumptions that would have been integrated later once the modular layout had been firmed up*.' Others have discussed the lack of knowledge on these issues and the need for wider education and tools.

> *'...we're still at very, very early stages to educating or to understand ourselves. We just about understand ourselves in-house so we're in the motion of probably prepared to do the next future project.*' Participant 6

Participant three noted how a lack of tools in the early stages of the project prevented the design team from conveying and convincing the implications of poor environmental design.

> *'...But yeah so I guess we have an idea of what's going to work and what's not anyway but when you're conveying that to the client, if we had those tools very early on where you can have a look, knowing (the room) is always going to be dark. It's pretty clear that's not going to be a great room to be in and do we want to build there; maybe we should push it somewhere else. That would probably make a much stronger argument early on and you could yeah make those arguments move convincingly.'*

A few participants conveyed their reliance on personal experience as an important way to 'gauge' how a building might perform in the environment. Participant five discussed how the lack of knowledge on the environmental performance of foundation and insulation types in MMC housing construction, drawing on knowledge from personal experience.

> *'....got to be honest I don't have any appreciation of perhaps a different foundation type or um insulation type that we would need for volumetric but I suppose we would maybe from my personal experience, naively think that a lot of the environmental issues - shall we say can be overcome a lot more with the panellised offsite construction methodology anyway.'*

Participant five also discussed their reliance on intuition as a guide for decision making:

'You know there is the whole kind of thought process about don't put too much glazing on an elevation and, make sure there's at least a dual aspect for both ventilation and to create a good environment internally. But I can't say that it's driving a scheme you know I don't think I've ever stopped and said wait a second, I need to change that beyond an intuition.'

4.2. Dependency factors:

The most prominent theme highlighted the ways architects approached environmental analysis in the early stage of MMC housing design as being dependent on others, including other experts, clients' interests, types of sites, project costs, regulations, policy, and government. Other experts in terms of assessment of daylight and sunlight, as well as overheating implications, were seen as necessary in the early stages of design.

Most participants conveyed reliance on either the internal 'Sustainability' expert team or external Mechanical and Electrical (M&E) or other consultants. The engagement of other experts, whether inhouse or outside of the firm involved 'an exercise of going backwards and forwards' before a compromise was reached. Participant 8 described a process involving engagement of an M&E consultant who '*would give clear (window) opening sizes*'; meaning that the architects needed to '*work out which parts of the window could open and to what extent*' before a compromise was reached – in most instances, the meeting of ventilation rates, daylight, and sunlight meant compromise on other issues–often found too late in the process. Participant seven, similarly conveyed a reliance on others for environmental analysis.

'...that would normally be a separate consultant, normally the energy consultant would get involved with the overheating so you're right that is a, then a separate consideration and that might then have a another layer of constraints that you

need to add to the windows…the window positions and sizes…so you kind of end up having to balance between the two.'

The types of clients and their interests as well as budgets set aside for projects were also discussed to influence the extent to which environmental analysis might take place. Participant five discusses how interests in wider sustainability goals and climate change by clients often influenced decision making and gave steers how environmental analysis might be approached.

'…I think the client might kind of override them (environment analysis). If it's a local authority or a housing association then having conversations about how and certainly on an estate regeneration project where you're trying to offer a benefit to those that already live in the estate. Improving the energy is certainly a big win and the external environment of course.'

Participant six noted how clients' approaches to taking on a broader set of expertise at early stages can influence how and if environmental analysis takes place. This was viewed to be outside the architects' control- despite often making recommendations on the need to engage other consultants that might benefit the scheme, the decision in most instances is within the client's remit.

'…the project I'm working on with the 12 in-fill sites… the client was very active and very happy about all of various people, but sooner or later they employ an agent which is fundamentally the one in charge of the project on behalf of the client. This watered down and brings it (sustainability) last on the agenda; for example we would consider and ask for consultants to have a sustainability plus an M&E background now. So we don't only include traditional services, so we expect a bit more from M &E services that understand sustainability as a sort of

consultant appointment…a year and a half down the line we're still recruiting or asking for this appointment.'

4.3. PassivHaus first:

A further theme involved many of the participants referring to PassivHaus as a first-principles approach applied to all projects, regardless of project environmental remit or scope.

'if a client comes to us with a project then we assume that they're wanting a passive housing project unless they choose not to have a Passivhaus project is that, that's kind of the base line that we're trying to achieve.'

There seems to be a dominant, widely accepted interpretation of this PassivHaus concept that equates environmental analysis against specific criteria (such as daylight and overheating) with a more holistic and demanding design approach, this is highlighted by interviewee 4;

',,,, the new kind of like part L regs and that kind of thing, if we use a Passivhaus as a base line then we know we've covered those elements and we'll definitely achieve those, those um standards. So yeah I think it's a good idea to be starting that as your base line and then if you ask to work backwards.'

The consequence of this assumption/habit is a loss of sensitivity for practical considerations in specific cases, such as MMC housing, which was our focus.

The findings and insights indicate that the interpretation and translation of the natural environment into building design is dependent on contextual organisational factors such as professional practice identity and how the organisation has legitimated environmental aspects. In architectural practice, massing, elevating, building

orientation, ventilation, heat loss, and daylight/shadowing have always been integral parts of the design process. This might explain why, in the interviews, we did not detect any sense of urgency to automate (or change) the current approach to environmental criteria and analysis or any particular problems perceived by the participating architects. On the client side, everything was mainly referred to as compliance- and cost-driven. Additionally, although not the key focus of the study, it was found that end users were rarely referred to in the discussions, despite daylighting and overheating being socially experienced differently by different users. Apart from one participant, very little discussion mentioned the values or needs users may place on daylighting or overheating mitigation. We discussed some aspects of the relationships with environmental consultants earlier.

5. Discussion and conclusions

This study set out to investigate the process of environmental analysis of MMC developments through the exploration of architects' perceptions and approaches to environmental analysis in early stage MMC housing design.

One of the key findings of this study is that architects face uncertainty when integrating environmental analysis at the early design stages in MMC projects. This aligns with the existing literature, such as Østergård et al. (2016) and Lin and Gerber (2014), which also highlights the challenge of incomplete information and unpredictable project variables during the early design phases. The current study extends this understanding by demonstrating that in the context of MMC, uncertainty is not only linked to traditional design concerns, such as site-specific conditions and client requirements, but also to the modular nature of the construction itself, where design decisions must account for offsite manufacturing constraints. This adds complexity to

environmental analysis, as architects must balance factors, such as energy performance and material efficiency, under conditions of limited foresight.

The study also found that architects working in MMC projects rely heavily on external consultants for specialized environmental analysis, a dependency that influences design decisions. This finding supports previous research on the interdisciplinary nature of MMC, such as Pan et al. (2007) and Ofori-Kuragu and Osei-Kyei (2021), which emphasized the collaborative requirements of modular construction. However, this study provides a more nuanced perspective by revealing that such dependency can create bottlenecks in the design process, particularly when consultants are brought in late or unfamiliar with the specific environmental requirements of MMC. This study highlights the need for earlier and more integrated involvement of environmental consultants in MMC projects to ensure that environmental goals are embedded in the design process from the outset, rather than being treated as a separate or secondary consideration.

A surprising finding was the dominance of Passivhaus-first principles in guiding environmental analysis for MMC projects, even though this approach might not be the most suitable for modular design. While Passivhaus standards are widely recognized for their focus on energy efficiency, this study shows that applying these principles across all projects can limit design flexibility and overlook other environmental considerations. This finding challenges prior research (Johnston et al., 2020) that generally promotes Passivhaus as a leading standard for sustainable design. By revealing the limitations of a one-size-fits-all application of Passivhaus principles, this study contributes to the debate on whether MMC requires more context-specific environmental frameworks tailored to the modular construction process, particularly when balancing energy efficiency with manufacturing constraints.

The insights from this study, as well as prior research, suggest that social and organizational factors, along with the project-based nature of design activities, strongly influence how and when environmental analysis is conducted in early stage MMC housing designs. Earlier studies have called for a holistic approach to the design process, emphasizing the need to consider interrelated variables, such as client demands, cost, and time constraints (Oliveira et al., 2020; Shibeika et al., 2021), in addition to the more intangible aspects of "aesthetic" and "tacit knowledge" within professional teams (Styhre & Gluch, 2009; Tsoukas, 2005). This study builds on these insights by revealing how uncertainty and dependency on external consultants can delay key environmental decisions, thus reinforcing the relational and interdependent nature of environmental analysis in MMC projects.

These findings advance the theoretical understanding by illustrating that environmental analysis in MMC is not an isolated process but is shaped by broader social and organizational dynamics. Moreover, while this study focuses on the UK context, the challenges identified, such as dependency on external expertise and the timing of environmental considerations, are likely applicable to MMC practices globally. These issues reflect broader patterns in modular construction, suggesting that other countries facing similar MMC adoption issues may encounter comparable challenges. This study emphasizes the need for MMC firms, both in the UK and internationally, to invest in internal environmental expertise and ensure that environmental considerations are integrated from the outset. Future research should explore how these challenges manifest in different international contexts, to further refine the global applicability of these findings.

Future research should continue to explore these dynamics across different firm contexts, focusing on how organizational structures and collaborative workflows either

facilitate or hinder the timely and effective integration of environmental analysis into MMC design. By addressing these issues, firms can balance energy efficiency, design flexibility, and project constraints, thereby improving the environmental and practical outcomes of MMC projects.

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