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NET-ZERO & DIGITALISATION IN OFF-SITE CONSTRUCTION

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ABSTRACT

The UK Government set targets to achieve net-zero buildings by 2050. Consequently, there is a need for off-site construction companies to achieve net-zero over the coming years. However, small and medium-sized enterprises in off-site construction face challenges in implementing net-zero, as well as in implementing digitalisation, which can greatly support achieving net-zero targets. This paper reports on initial findings of a project focused on improving digitalisation and net-zero within an SME off-site construction company. Through process mapping and observations, implementation barriers to digitalisation and net-zero were identified, and a set of actions are suggested. The paper also discusses tools for optimising the lifecycle carbon impact of buildings. The recommendations include accurate carbon footprint measurement, creating a realistic reduction strategy, and adopting sustainable/low-carbon materials. Additionally, the paper recommends the use of smart technology to monitor as-built and compare it with the as-designed building.

KEYWORDS

Off-site construction; Net-zero; Lean construction; BIM.

INTRODUCTION

The construction industry is seen as a low-innovation industry, with a poor track record in schedule and budget compliance, and industrial accidents. Off-site construction has been posed as a means to help improve quality, productivity, reduce waste, and lower the carbon footprint of buildings (Generalova et al., 2016). Off-site is especially important now, given the current climate crisis, as the built environment has a crucial role to play in limiting global warming to 1.5°C and enabling the transition to net-zero by 2050 (UK Green Building Council, 2023).

To reduce overall emissions by 2050, it is recommended that the industry improve energy performance and reduce the carbon footprint of building materials through carbon emissions analysis and calculation models and by using sustainable materials (Sheikh, 2022; Chen et al, 2023). Furthermore, there is a need to multiply policy commitment alongside action and increase investment in energy efficiency (Sheikh, 2022). Figl, Ilg and Battisti (2019) explain that carbon neutrality must be considered at the early stages of building design and planning for the industry to meet the 2050 target.

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It is known that Building Information Modelling (BIM) and Lean provide diverse opportunities for improvements. However, most companies are not yet exploiting this to its full potential. The implementation of BIM, Lean, and net-zero carbon is evolving and is a significant area where academic research can create solutions applicable in practice.

This research aims to support net-zero and digital transformation within one off-site construction company, implementing new processes and technologies to enhance productivity. It seeks to achieve BIM adoption, carbon footprint measurement and reduction, and the adoption of sustainable/low-carbon materials within the off-site construction process. The focus of this paper is to discuss the existing application of BIM and Lean towards the design of net-zero buildings in the company, to enable it to move forward in achieving the UK Green Building Council (UKGBC) net-zero targets by 2050.

LITERATURE REVIEW

DIGITALISATION AND BIM

Construction is one of the least digitalised industries (Veselka et al, 2019), even though there has been an increasing adoption of digital technologies, such as BIM (Gan et al, 2023). BIM encourages collaboration between project stakeholders fostering an integrated project delivery (Rowlinson, 2016; Gan et al, 2023). Furthermore, BIM allows for evaluating alternative designs, and hence design optimisation (Gan et al, 2023).

However, according to Holzer (2011) and Rowlinson (2016), drawbacks for BIM implementation include a focus on software rather than improving the design process, and ambiguity concerning BIM features which causes confusion across the industry. Interoperability issues also exist, and where team members use software programs from different distributors, a neutral transfer format is required for the different data to work on a common building model (Figl, Ilg and Battisti, 2019). Additionally, the use of BIM is still very monodisciplinary and profession-based, which does not encourage an integrated process (Rowlinson, 2016). There is therefore a continued need for supporting the implementation process before BIM benefits can be fully realised.

In the UK, the construction sector has the highest number of small and medium-sized enterprises (SMEs), approximately 882,770 (Clark, 2023). Zhang et al. (2016) highlight that the use of BIM provides great opportunity to improve the performance of off-site construction, however, there is still a lack of adoption within smaller construction companies. Figl, Ilg and Battisti (2019) also highlight that SMEs may not be able to invest in expensive software or training for BIM. According to Makabate et al. (2020) the adoption of digitalisation through BIM is a necessity for most of SMEs in the coming years.

CARBON NET-ZERO

Construction is one of the highest consumers of energy (Llatas et al, 2019). Globally, buildings and the construction industry account for 36% of final energy use and 39% of energy and process-related carbon emissions, of which 28% is operational carbon emissions and 11% is from the manufacture of building materials and products (International Energy Agency, IEA, 2019; World Green Building Council, 2019). Over the years, several strategies have been applied to tackle this, for instance, through the implementation of lean, adoption of renewable energy for operations, adaptive re-use of existing buildings, reuse and upcycle of waste by promoting a circular economy, use of digital technology, and use of environmental assessments and ratings. However, by 2035, a significant portion of the emissions from the built environment is predicted to be attributed to embodied carbon, due to the ongoing efforts to reduce operational carbon emissions from buildings (UK Green Building Council 2021a; 2023).

The World Green Building Council (2019) has therefore stipulated that by 2030, new buildings, infrastructure and renovations will have at least 40% less embodied carbon and net-zero operational carbon. By 2050, new buildings, infrastructure or renovations will have net-zero embodied carbon, and all buildings must be net-zero operational carbon. The industry needs to combine efforts and take decisive actions towards achieving these targets.

NET-ZERO DESIGN AND METHODS OF ASSESSMENT

According to the UK Green Building Council (2021b), net-zero carbon in building operations is achieved when the amount of carbon emissions associated with the building's operational energy on an annual basis is zero or negative. The World Green Building council, WGBC (2019) define a net-zero carbon building as one which is highly energy efficient and fully powered from on-site and/or off-site renewable energy sources, with any remaining carbon balance offset. Several assessments such as green building rating systems and sustainability certifications, have been developed over the years targeted at improving the environmental impacts of buildings (Llatas et al, 2019). Cole and Fedoruk (2014) explain that although green building performance and assessment methods have always aimed at achieving net-zero impact, net-zero energy buildings have now become a specific performance goal for attaining high recognition within the Leadership in Energy and Environmental Design (LEED) or Building Research Establishment Environmental Assessment Method (BREEAM) amongst others.

Furthermore, the focus has previously been on achieving net-zero in building operations. However, globally, embodied carbon related to materials manufacture accounts for a lower percentage of whole life carbon compared to operational carbon emissions (Gan et al, 2023). In the UK, buildings and infrastructure contribute to about 25% of greenhouse gas emissions and with the inclusion of transport emissions, this rises to 42% (UKGBC, 2023). 80% of this is associated with operational carbon from existing building stock and 20% from embodied carbon of new construction (London Energy Transformation Initiative, LETI, 2020). Although operational carbon is higher at present, embodied carbon emissions are expected to rise in the coming years. With increasing advances to improve the carbon emissions related to building operations, embodied carbon emissions will represent a larger portion of the carbon production of buildings and this figure could increase to 40-70% of new buildings in the UK (LETI, 2020).

According to the UK Green Building Council (2021b), a building can only achieve net-zero carbon "when the amount of carbon emissions associated with a building's product and construction stages up to practical completion is zero or negative, through the use of offsets." There is a potential to improve the performance of buildings at the design phase, by calculating the environmental, economic, and social impacts produced by the buildings during its life cycle. Therefore, obtaining an understanding of the lifecycle performance and incorporating quantitative assessments will improve building design and operation and foster a low-carbon built environment (Gan et al, 2023). It can also provide insights into possible economic gains and will also advance measures targeted towards achieving net-zero emissions in buildings.

The British Standard BS EN 15978:2011 sets out the overall principles of embodied and whole life carbon measurement in the built environment. The embodied carbon of a building refers to the emissions emitted producing building materials, their transport and installation to site as well as their disposal at the end of their life (LETI, 2020; BS EN 15978, 2011). Operational carbon, on the other hand, refers to emissions associated with the in-use operation of a building throughout its life (LETI, 2020). This includes emissions associated with heating, hot water, cooling, ventilation, lighting systems, cooking, equipment, and lifts. A visual representation of this is provided below in Figure 1.

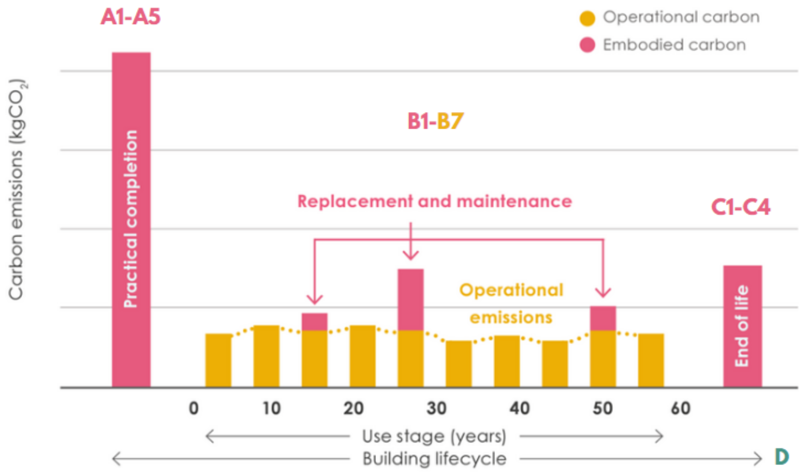

Figure 1: Carbon emissions breakdown over building's life cycle (Adapted from LETI Embodied Carbon primer 2020 and BS EN 15978:2011)

The potential to reduce carbon emissions reduces throughout the stages of a building project. According to Tsikos (2023), the lack of detailed data in early design makes it difficult to assess the impact of design decisions. Being able to quantify the embodied and operational carbon emission impact for a building project, that is the whole life carbon impact, would have a positive effect on construction and go a long way to achieving the net-zero carbon emissions. Furthermore, Collinge et al (2015) and Llatas et al (2019) explain that compared to other assessment methods developed over the years targeted at environmental aspects such as green building rating systems and sustainability certifications, the lifecycle assessment (LCA) is considered the most appropriate as it quantifies the buildings performance for sustainability through all life cycle stages. However, although LCA can be integrated in building design stages, one of its limitations is its time-consuming nature and vast amount of data required.

Gan et al (2023) explain that the use of BIM facilitates the calculation and mitigation of both embodied carbon and operational carbon emissions of buildings. BIM can be used to define construction material options and facilitate automatic derivation of material quantities for accurately determining embodied carbon (Hollberg, 2020; Roggeri et al, 2021). Furthermore, BIM has the capability to incorporate and manage a large amount of building information thus simplifying the Life Cycle Assessment (LCA) analysis by providing a visual representation of its impact (Llatas et al, 2019). Roggeri et al (2021) combined BIM with building energy modelling (BEM) to design a timber modular prototype and extract information to determine the energy impact in the building's lifecycle. To ensure net-zero design, the embodied energy/carbon, the environmental impact and the energy consumption were calculated. Similarly, Gan et al (2023) developed a BIM model to calculate upfront embodied carbon and aid energy simulation in determining operational carbon over the building's lifecycle whilst considering net-zero. They propose opportunities such as selection of low-carbon materials, operational efficiencies, modular integrated construction, and so on.

Nevertheless, although guidelines have been developed over the years by organisations such as the London Energy Transformation Initiative (LETI), UK Green Building Council (UKGBC), and the World Green Building Council (WGBC) since the announcement of the carbon net-zero targets by the WGBC and UKGBC, there is still a knowledge gap within construction industry regarding the implementation of net-zero.

BARRIERS TO THE IMPLEMENTATION OF NET-ZERO WITHIN CONSTRUCTION

According to Terblanche (2019), barriers to the implementation of net-zero buildings include high costs, limited resources and technology, client's perception of value, and lack of incentives from local authorities to promote net-zero buildings at the planning phase. There is also a lack of knowledge regarding net-zero buildings by construction professionals across the whole building design, operation and maintenance stages, leading to low implementation. Similarly, Aelenei et al (2023) mention the cost required to effectively integrate necessary technologies. Furthermore, there is not enough demand for low-carbon materials and technology and most companies just focus on low-cost products instead. Additionally, beneficiaries are not being fully aware of net-zero and its benefits for their projects (Aelenei et al, 2023). They do not have information on the materials, construction technologies and available funding opportunities. With more knowledge and understanding of the standards and guidelines by the beneficiaries and construction professionals, there will be an increase in the market demand thus encouraging construction professionals to develop themselves. This will also produce more reliable data on which policy makers can use to evaluate the success of these policies and measures.

Although several studies considered design towards net-zero and methods of assessment (Llatas et al 2019; Terblanche, 2019; Roggeri et al, 2021; Gan et al 2023), these studies have focused on quantitative data within their studies. However, the feasibility of using digitalisation and methods towards carbon net-zero design lies in its simplicity of use and effectiveness in verifying and quantifying its impacts (Llatas et al, 2019). With the transition from traditional construction to modularised and off-site construction, it is important that net-zero design and practice can be achieved within modular and off-site construction, especially as they consist of SMEs. This paper, therefore, seeks to add to the efforts of existing studies by providing qualitative data regarding the adoption of digitalisation and net-zero design in off-site.

METHOD

This study employs a qualitative methodology utilising Action Research (AR) which seeks to resolve practical problems. AR integrates research and action and involves collaborative participation from the case study participants to enhance the credibility and authenticity of the results (Argyris & Schön, 1991; Erro-Garcés & Alfaro-Tanco, 2020). For this paper, a literature review was first conducted to understand the efforts made so far regarding net-zero design and identify barriers limiting its practical adoption within off-site companies. The research also involved an in-depth understanding of a specific off-site construction company's operations, and the identification of barriers towards digitalisation and Net-zero in design, and the proposition of strategies for improvement. Data collection tools employed include process mapping, interviews with the operations manager, and observations of the company’s processes. Through the analysis of the design, off-site manufacture and on-site installation processes within the company, patterns were identified. Table 1 demonstrates the literature search applied in this study. It also highlights a lack of studies considering net-zero within off-site construction.

The selected case study – Company A - is an SME off-site volumetric construction company located in the North of the UK. The company specialises in the production of modular units, particularly in the healthcare sector, such as wards, theatres, endoscopy facilities, training facilities, etc. They also provide temporary buildings for site accommodations. These typically have a service life of less than two years and are either returned to the factory upon project completion or rented out to the next client. The company has a good client base as off-site construction is advantageous in the healthcare sector, because it causes the least disruption to the existing hospital environment and the construction is partially completed off-site, thereby reducing the total on-site construction time. The company was selected as there is an ongoing Knowledge Transfer Partnership project being developed between the company and the research team, funded by Innovate UK. The first stage of the project involved getting acquainted with the company and understanding their strategic objectives, key processes, products, and clients. It also involved getting an understanding of the volumetric modules’ workflow from design through to off-site production and on-site installation, including transport. This also involved understanding the typical design and construction of modular units off-site in the factory.

Table 1: Literature Search strategy (Data from UOH online library repository)

					No. of results	Scholarly and Peer reviewed	Engineering/ Architecture
Modular construction	AND	BIM			854	322	229
Off-site construction	AND	BIM			593	145	115
Modular construction	AND	Net-zero			161	58	42
Off-site construction	AND	Net-zero			66	29	21
Construction	AND	BIM	AND	Net-zero	123	56	41
Modular construction	AND	BIM	AND	Net-zero	2	2	2
Off-site construction	AND	BIM	AND	Net-zero	1	1	1

RESULTS

PROCESS MAPPING

This section summarises the processes from planning and design to handover of the project to the clients (see Figure 2). The company's projects are typically obtained via two routes. In the first route, they receive design briefs directly from clients for the full design of off-site structures. Here, they are the main contractors and provide all the drawings and details required for the project. In the second route, they receive the drawings from bigger construction firms and here they are sub-contractors to deliver modular buildings. RIBA Stage 3 or 4 architectural drawings are provided to Company A, and they create detailed modular designs to fit closely with the architectural drawings. They also have sub-contractors for structural, mechanical, electrical, and other required designs. Once all is agreed by the client, detailed drawings are prepared for the factory production of the modules off-site and the final installation on-site.

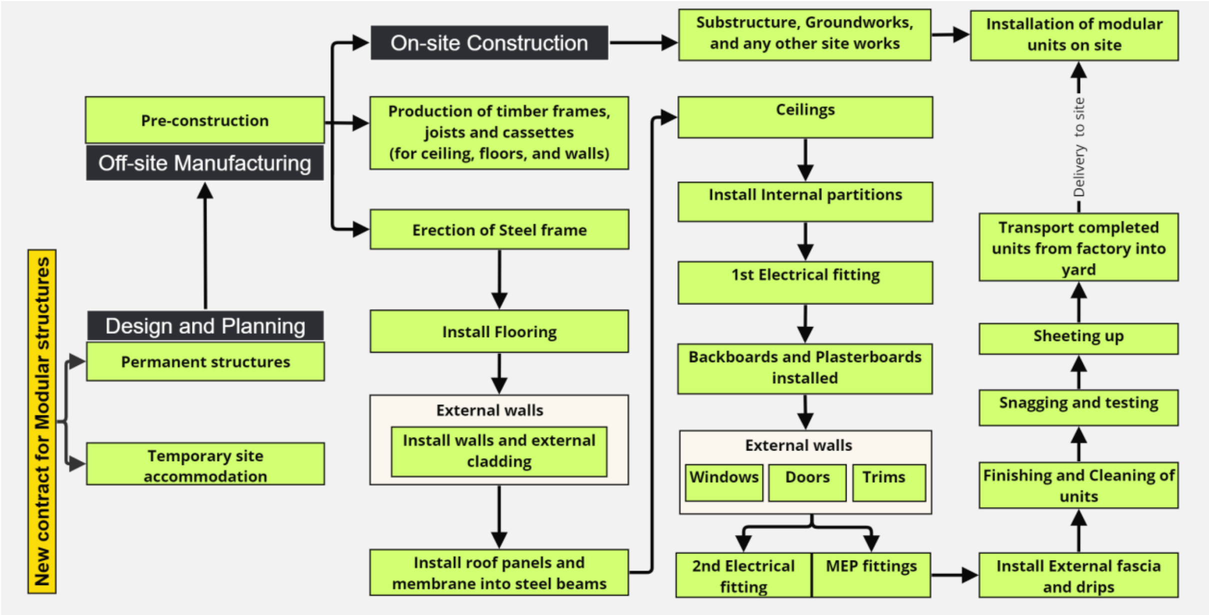

Figure 2: Summary of Production workflow at Company A

Through the production of the process map using flowcharts, the authors were able to identify areas for further improvement within the company.

KEY ISSUES IN DIGITALISATION AND NET-ZERO AT THE COMPANY

Current application of BIM

The use of BIM at Company A is currently limited to the big projects where it is mandated by clients or large construction companies. Although the company has architects sub-contracted to assist with BIM, they usually rely on 2D drawings and only started creating 3D models in-house using Autodesk Revit recently. It is worth noting that the company has not adopted all features of BIM such as 4D or 5D BIM. Autodesk Revit was initially introduced to enable them to view 3D models from the architects or incorporate modular design layout before sending off to steel fabricators for structural analysis.

Additionally, the team's design capabilities regarding BIM are still being developed, with only one design staff having the skillset to generate 3D models. Moreover, most of the factory and installation team still work off 2D paper drawings, which sometimes create issues with changes to drawings not being reflected, thus affecting the production process. In addition, the company produces material quantities and schedules for projects manually, especially for timber. Similarly, where clash detection is needed, this is currently done using 2D drawings. This has caused problems on-site, where the company needs to reconfigure designs to address clashes that were only identified during installation.

Current state of Net-Zero

In terms of the company's operations, one challenge is the lack of readily available data to quantify corporate carbon emissions, such as waste quantities. The waste generated from off-site manufacturing processes is not clearly quantified, except for paper waste. Additionally, data on the end-use of waste is not easily accessible from local waste management contractors. Moreover, manual material take-offs for materials like timber lead to high waste production, and sawdust is not quantified and often mixed with other dust waste from materials like plasterboard and plastic.

Despite these issues, the company has made significant strides in reducing their carbon footprint. For instance, they have included a biomass wood burner in their factory to aid with heating, and timber off-cuts are used as biomass fuel for the wood burner while the rest are sold.

They have also obtained electric vehicles for company use and converted most of their factory lights to dimmable LED lights.

Regarding net-zero building design, there is a lack of information regarding the embodied carbon of building materials used for the module envelope design. Life cycle assessments are not yet conducted for projects, and embodied carbon of materials is not considered during procurement. However, the company ensures that the timber they purchase is certified by either the Forest Stewardship Council UK (FSC) or Programme for the Endorsement of Forest Certification (PEFC) to ensure environmental sustainability. The main considerations for material selection are fire performance, thermal transmittance co-efficient (u-values), and cost.

To improve operational energy and carbon emissions, the company conducts BREEAM assessments and/or obtains Energy Performance Certificates (EPCs) for their big projects. Building energy modelling and analysis are currently outsourced and typically conducted after the technical design has been completed. Although Simplified Building Energy Modelling (SBEM) is conducted for many projects, dynamic thermal modelling to carry out full building performance analysis is done when requested by clients or when complex HVAC systems are used. To achieve carbon net-zero in all future projects, it is recommended that the whole life carbon analysis is conducted from the design stage through to final construction.

BARRIERS TO BIM AND NET-ZERO AT THE COMPANY

Regarding digitalisation, one of the barriers identified is that the construction process is very fast-paced, which stops the company using BIM more widely, due to the initial lack of productivity, which is common during the initial stages of BIM implementation. Similarly, many of the company's smaller jobs are still done in 2D as the clients do not require 3D models.

Another limitation is that many of their sub-contractors work in 2D, so it is not possible to do, for instance, automated clash detections. There are also interoperability issues with diverse file types used by different sub-contractors or the client and lack of coordination using BIM (except for big projects where BIM is mandated). Another limitation is the cost of training and software required, such as licenses for Autodesk AEC collection. The cost of training and software required to use advanced tools like energy modelling or whole-life carbon analysis is another current limitation.

PROPOSED BIM AND LEAN STRATEGIES TOWARDS NET-ZERO

Off-site construction aims to reduce project costs through standardisation, unification, and typification (Generalova et al, 2016). However, considering the net-zero targets, it is imperative to consider the whole life carbon impact of materials used. The implementation of Lean and digital strategies will facilitate better value generation and profitability through improved productivity, reduced waste, and the development of carbon efficient products. Lean principles are aligned with sustainability goals as they offer positive economic, environmental, and social impacts to a project. For instance, waste elimination and process streamlining enable efficient project completion and cost reductions, improve schedule adherence, improve predictability, and minimise uncertainties and delays. Additionally, projects can benefit from energy efficiency, use of sustainable materials, and safety on site for all workers. The identified areas for improvement were developed with the company's team and are summarised as follows:

Building Information Modelling (BIM)

The use of BIM will improve integration between planning, design and construction. This can lead to shorter design processes and better outputs, which meet industry targets. Additionally, increasing in-house design capabilities will help in reducing reliance on third parties. The design process will be better aligned with off-site processes, enabling more standardised physical production at the factory. According to Zhang et al (2016), data from the BIM model could provide relevant information to enable an integrated design, manufacture, and construction and in-use/maintenance process. It could also support the manufacturing process from procurement of materials to the end transport and installation on construction site. Errors can be identified during design rather than production through the implementation of BIM.

According to Gan et al (2023), building energy modelling allows the advanced calculation and analysis of building performance considering the location and geometry of the building, its construction and materiality, thermal zones, occupancy schedule, equipment, HVAC systems etc. Developing a digital model and simulating virtual construction environment will allow for building performance modelling and whole life carbon assessment during the design stage to final construction, aiding the evaluation of project carbon emissions. Furthermore, BIM adoption will make it possible to optimise the planning of works in the construction phase.

Carbon Footprint

In addition to the project carbon emissions, the authors further recommend strategies to improve the corporate carbon footprint in terms of business operations. This involves developing a carbon reduction plan and striving to achieve the carbon reduction targets, building on existing design and construction experience and utilising state-of-the-art and knowledge to refine construction methods. The corporate carbon emissions resulting from the company's operations and assets will also be calculated and avenues for further improvement will be highlighted. This involves calculating the annual scopes 1, 2 and 3 carbon emissions using tools and guidance set out by the UK government (2021) and the Greenhouse Gas Protocol (2022). Scope 1 emissions are incurred directly by the company, Scope 2 emissions are indirectly incurred by the business and Scope 3 emissions are indirectly incurred emissions from upstream and downstream activities within their value chain.

Material and Resources

There is also a need for the company to evaluate its resources and improve procurement processes for materials. This will involve an assessment of procured materials and wasted materials to look at cost savings and opportunities for reuse where possible. Also, considering new materials and incorporation of low carbon materials that have better capabilities for reuse, recycle or upcycle at the end of their life while still meeting regulations for fire performance, thermal performance, and considering cost. One common use of BIM is to obtain bill of material quantities (Soust-Verdaguer et al, 2017) which will be useful to Company A and save them from deriving this through manual calculations.

Building product information can assist in accurate measurements of embodied and whole life carbon emissions and can improve accuracy around carbon reporting. There is a need to consider third-party certification for construction products to show the reliability of the data; these could include responsible sourcing certification, Environmental Product Declaration (EPDs) and so on. EPDs are internationally recognised and communicate the environmental impact of a product. For construction products, life cycle assessment (LCA) is carried out to estimate the environmental impact at different stages of the lifecycle using EPDs, and there is an increasing demand for construction products to have EPDs.

Smart Building Technology

The use of smart building technologies, such as building management systems, can improve efficiency and monitor building performance, enabling also existing performance data to feed forward the improvement of new projects. The evaluation of energy performance is based on the estimated or measured amount of energy consumed annually for providing heating and cooling for comfort, as well as for meeting the domestic hot water requirements (Cole and Fedoruk 2014). According to Aelenei et al (2023), a gap exists between the energy performance of buildings as-designed and as-built which can be ascribed to various factors. Therefore, better monitoring of buildings using smart technologies can help fill this gap and improve the quality of simulations (Sturgis, 2017).

According to Zhang et al (2016), there is a need to further improve the performance of the industry, to better incorporate sustainability into building design and construction practises. Although this study has provided insights using one off-site construction company as case study, the outcome of this study could be adopted within similar off-site SMEs construction companies. The incorporation of these strategies throughout the project phases will enable them to evaluate the effect of their designs and building materials on a building's lifecycle carbon performance and follow opportunities for further optimisation.

CONCLUSIONS

This paper presents the initial steps towards achieving net-zero within an off-site construction company and the possibilities of adopting BIM and Lean principles to improve digitalisation, calculate whole-life carbon emissions and improve overall building performance. Future work will involve the implementation of these strategies and quantify their effectiveness. This will involve whole life carbon assessment of sample projects within the company. Additionally, the authors will implement a BIM execution plan within projects; and continuous and up-to-date carbon footprint calculation to develop a carbon reduction plan with achievable targets. A materials database for typical materials will be developed by the team considering not just fire performance and thermal performance but also embodied carbon and end of life of materials.

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