# ASSESSMENT OF THE IMPORTANCE OF DESIGN FOR MANUFACTURE AND ASSEMBLY (DFMA) PROCESSES FOR SUSTAINABLE CONSTRUCTION

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## ABSTRACT

*The UK construction industry faces a growing demand for sustainable practices. This research explores how integrating Building Information Modelling (BIM), lean principles, and Design for Manufacture and Assembly (DfMA) can significantly contribute to achieving these goals. Research by Martinez et al. (2013) and Li et al., (2019) highlights the inefficiencies in industry and the resultant impact on productivity and sustainability, necessitating the need for modern measures to address these challenges. DfMA offers a promising path towards sustainable construction, and this study delves into the combined effects of BIM and Lean within DfMA workflows. BIM's collaborative design capabilities enable early identification and mitigation of sustainability concerns in construction. Lean principles, emphasising continuous improvement and waste reduction, complement DfMA's focus on resource efficiency. The research examines how BIM can optimise DfMA components for minimal environmental impact during design and construction; and how Lean practices, integrated within a BIM-DfMA framework, can further enhance resource efficiency. This is achieved by reducing rework through improved planning, optimising on-site logistics, and promoting just-in-time deliveries. Employing a qualitative approach, the study combines a literature review, semi-structured interviews and in-depth case studies of UK construction projects that have successfully integrated BIM, Lean, and DfMA. This methodology identifies best practices and barriers associated with this integrated approach. The findings aim to provide valuable insights for UK construction professionals and policymakers. By exploring the strategic integration of BIM, Lean, and DfMA, this research can inform industry best practices and guide policy development towards a more sustainable future for the UK construction sector.*

**Keywords*:* Importance, DFMA Processes, and Sustainable Construction**

## Introduction

Sustainable construction practices play a pivotal role in mitigating the environmental impact of the built environment. This literature review probes into the concepts, drivers, and barriers of sustainable construction, and explores three key methodologies that can significantly contribute to achieving sustainability goals in construction: DfMA, BIM, and Lean principles.

The construction industry, long characterized as "traditional," has witnessed minimal evolution until recent times, as noted by Martinez et al. (2013). In contrast to other sectors, its adoption of innovation has been slow, presenting challenges stemming from its highly fragmented nature, complex processes, dynamic business environment, and multi-stakeholder approach, as highlighted by Li et al. (2019). According to Barbosa et al., (2017), the construction sector has exhibited sluggish global productivity growth over the past two decades, averaging a mere 1% per year. This is notably lower compared to the broader global economy, which experienced an overall growth of 2.8%, and the more robust rate of 3.6% observed in the manufacturing industry. The report further underscores that fewer than 25% of construction companies have managed to align their productivity increases with the economies in which they operate.

The persistently low productivity in the construction industry is linked to the continued use of traditional methods involving manual operations and non-standard approaches. These practices lead to fragmentation, discontinuity, and inefficiencies, resulting in resource wastage and time overruns (Khoiry et al., 2018). In the UK, recent concerns highlighted in a KPMG report (2016) emphasise low productivity, project delivery uncertainties, skills shortages, and a lack of data transparency. These challenges highlight the urgent need for transformative measures in the construction industry to address its multifaceted issues and enhance overall performance towards a more productive and sustainable industry.

In addressing the need for more sustainable practices in Architectural, Engineering, and Construction (AEC) projects, Design for Manufacture and Assembly (DfMA) has emerged as a modern method of construction (MMC). This approach, encompassing modern prefabrication and Modular and Offsite Construction (MOC), plays a vital role in advancing sustainable development goals, particularly in reducing carbon footprints and achieving NetZero emissions in construction processes (Roxas et al., 2023; Li et al., 2023).

DfMA is gaining momentum as a transformative approach in construction. DfMA prioritizes off-site manufacturing, minimising on-site activities (RIBA, 2021). This shift tackles two key challenges: inefficiency and environmental impact.

Research asserts DfMA's potential to significantly improve productivity and reduce labour costs through prefabrication (Chen & Lu, 2018; Hallmark et al., 2012). Mesa et al. (2017) offers another perspective, characterising DfMA as a principle that enhances design for manufacturing, assembling, and cost while preserving the main product function.

## Objective of the Study

1. To review the importance of DfMA processes for sustainable construction.

## Drivers of Sustainable Construction

Sustainable construction in the UK is driven by a multi-dimensional approach that expands beyond traditional considerations of just economic viability, utility, and durability (Murtagh et al., 2020; UKGBC, 2023). It encompasses three key drivers: environmental, social, and economic, all working together to create a built environment that promotes human well-being, environmental stewardship, and a high quality of life (UKGBC, 2023).

Wu et al., (2016), recognises the significant environmental impact of conventional construction practices as a major driver for sustainability, noting that the industry consumes vast amounts of natural resources and contributes to environmental degradation. Sustainable construction aims to address this by minimising air emissions, waste generation, water use, and land use (Ogunmakinde & Egbelakin, 2022; Kibert, 2016). This includes reducing greenhouse gas emissions through energy-efficient design, low-carbon materials, and a focus on embodied carbon throughout a building's life cycle.

Sustainable construction practices offer significant long-term economic benefits. Energy-efficient buildings with durable, low-maintenance materials reduce operational costs and command higher market value (Al-Saffar & Salman, 2014). Furthermore, government policies like stricter energy regulations, carbon reduction targets, and tax breaks for green buildings aligning with the Construction 2025 strategy, provide further economic incentives (HM Government, 2013).

These interconnected drivers are pushing the UK construction industry towards a more sustainable future. As environmental concerns continue to rise, and economic advantages become more apparent, sustainable construction is poised to become the standard rather than the exception.

**Sustainable Construction Challenges**

The construction industry remains a significant environmental concern, contributing heavily to resource consumption, waste generation, and greenhouse gas emissions. Sustainable construction faces obstacles, with building construction alone responsible for 40% of waste and resource consumption and 25% of global carbon emissions (Oluleye et al., 2022). High waste generation rates pose sustainability challenges (Sivashanmugam et al., 2022), worsened by high energy consumption during material production (Iacovidou & Punell, 2016). Traditionally operating within a linear economy model, the construction industry's practices contribute to environmental pollution (Hossain et al., 2020; Arsenos & Giannadakis, 2023). Inefficiencies from disjointed processes and outdated methods result in delays, cost overruns, and increased environmental impact (Sebastian, 2011; Vokes & Brennan, 2013). Reluctance to adopt modern technology hinders progress in sustainable construction (Häkkinen & Belloni, 2011). To address these challenges, the industry must adopt innovative techniques like prefabrication to enhance productivity and reduce costs (Chen & Lu, 2018; Hallmark et al., 2012), along with integrating BIM and lean methodology for additional benefits (Machado et al., 2016; Sack et al., 2009).

**Design for Manufacture and Assembly (DfMA)**

The concept of DfMA has historical roots dating back to ancient times, particularly evident in the sophisticated prefabrication methods used during the Roman era for military fortifications and enduring structures like hospitals and aqueducts (Gibbs, 1999). Its significance transcends industries, with notable application in automotive and aerospace sectors, championed by pioneers like Henry Ford in the early 1900s and during World War II, DfMA gained momentum and saw substantial growth and development in the 1960s–1970s (Boothroyd, 2005; Thompson et al., 2018), leading to the formulation of processes and guidelines aimed at improving design quality, productivity, and profitability.

While widely utilised in automotive, aerospace, and mechanical manufacturing, DfMA has recently found application in the AEC industries (Vaz-Serra et al., 2021). DfMA principles in construction enhance product buildability from the initial stages of design, aiming to streamline processes and improve efficiency (Abd Razak et al., 2022; Gao et al., 2020). Despite historical advocacy for industrialization in construction, the widespread adoption of DfMA in construction is recent (RIBA., 2021). Unlike standardised products, construction projects are bespoke and contextualized within specific site conditions, posing unique challenges for implementation (Yuan et al., 2018).

Traditional construction processes are often inefficient and unsustainable, prompting the need for more automated and sustainable alternatives (Lloret et al., 2015; Prakash et al., 2018). Urban

construction practices can lead to negative impacts on the economy and daily life due to noise, pollution, service disruptions, and safety concerns (Vokes & Brennan, 2013).
Transitioning to sustainable construction practices has been limited and ad-hoc, indicating the necessity for a systematic approach.

DfMA emerges as a transformational solution for improving modern methods of construction (MMC) (See Appendix A) by streamlining construction processes and enhancing efficiency, viability, and sustainability (Vokes & Brennan, 2013). Its adoption aligns with the need to break away from the inefficiencies of traditional construction methods. Recognizing its significance, RIBA (2013) defined DfMA as intentionally designing elements to facilitate manufacturing in a controlled factory environment, emphasising efficiency and precision. The UK government also expressed commitment to DfMA, particularly the Platform Method, in public projects outlined in the National Infrastructure and Construction Pipeline (O'Rourke, 2013). The Platform DfMA integrates modular design concepts to enhance productivity (Chatzimichailidou, 2022). At its core, DfMA aims to optimise product design for economical production and assembling, involving the manufacturing of discrete sections in a factory and final assembling at the construction site (Tuvayanond & Prasittisopin, 2023). Simplifying design processes to facilitate manufacturing and assembling, DfMA reduces costs without compromising quality, making it a promising methodology for the future of construction (Antony & Arunkumar, 2020).

**DfMA and Sustainability**

DfMA's growing popularity in construction stems not only from its efficiency gains but also from its potential to improve sustainability. Studies displaying the application of DfMA principles within industrialized building systems and volumetric modular construction have demonstrated substantial reductions in construction waste and dematerialisation (Abd Razak et al., 2022; Sloditskie & Sadough, 2022). Banks et al., (2018), noted that the core benefit of DfMA is its life-cycle focus. By considering a building's entire lifespan upfront, DfMA encourages design choices that minimise environmental impact, aligning well with sustainable construction principles. The growing popularity of DfMA in construction stems from its potential to improve sustainability:

- **Reduced Waste:** Factory production with better control minimises material waste and optimises resource use. Faster assembly on site reduces energy and water consumption (Edwards, 2002; Banks et al., 2018).
- **Streamlined Logistics:** Fewer vehicle trips are needed due to prefabricated components, resulting in lower emissions compared to traditional construction with ongoing deliveries (Ng & Hall, 2019).
- **Early Error Detection:** DfMA prefabrication allows for early identification and correction of design flaws, minimising rework and material waste later in construction (Ng & Hall, 2019).
- **Circular Economy Potential:** DfMA can facilitate the reuse of components and sub-assemblies, promoting a more sustainable construction cycle (RIBA., 2021).
- **Standardisation:** A key advantage of DfMA lies in its ability to achieve economies of scale. This is made possible by repeatedly manufacturing the same or similar components using standardised processes. RIBA (2021) noted that while standardisation ensures quality and

avoids the need to "reinvent the wheel," it can limit design flexibility. However, this trade-off can potentially speed up design and assembling phases of projects.

DfMA presents a compelling strategy for sustainable construction, championing reduced waste, optimised logistics, early detection of design issues, and fostering collaboration for sustainable material selection. While additional research is required to thoroughly examine DfMA's sustainability potential in construction, its benefits for efficiency and environmental responsibility are evident. Utilising a diverse range of tools and technologies, DfMA aims to facilitate collaboration across the entire value chain, engaging design teams, clients, contractors, and offsite manufacturers (RIBA, 2013).

**BIM and Sustainable Construction**

As the importance of BIM has gained recognition, there has been a notable increase in activity within the building industry, particularly in relation to BIM and sustainable design strategies and their inclusion in the DfMA process. The study will explore the application of BIM to sustainable building design, focusing on two perspectives:

- Design Optimisation: BIM streamlines collaboration, reduces design time, and assesses energy efficiency for sustainable development (Eastman, 2011). DfMA tools within BIM reduce waste and involve clients in decisionmaking (Bakhshi et al., 2022; Yazdi et al., 2021). BIM-based design is common in architecture, facilitating efficient model generation and modification (Welle et al., 2011). Studies focus on using BIM as a central model for building energy performance analysis (Maile et al., 2007).
- Collaborative Project Delivery: BIM acts as a central hub for construction data, promoting seamless collaboration and interoperability between design software tools (Ahn et al., 2014; Fischer, 2006). This comprehensive model allows for evaluation of various performance aspects, including architectural design, structural integrity, energy efficiency, acoustics, and lighting. The UK government's mandate for BIM Level 2 in public projects (Bew & Richards, 2008) emphasises the importance of BIM in DfMA. Akob et al., (2019) noted that this collaborative approach, characterized by federated models within a Common Data Environment (CDE), fosters significant efficiency gains and reduces waste throughout the construction process. The resulting cost and resource savings contribute to both economic and environmental sustainability in DfMA projects.

**Methodology**

To achieve the objectives outlined in the study, an extensive literature review and qualitative semi-structured interviews were carried out. Semi-structured interviews were chosen as the primary method for gathering in-depth information from participants. To ensure the participants had valuable insights, researchers used a targeted approach (purposive sampling) to recruit individuals with construction expertise, particularly in DfMA and digital technologies. For the qualitative data gathered through interviews and case studies, thematic analysis software (NVIVO 2.0) was used. Research ethics for this study adhered to the University of Salford Academic Ethics Panel and aligned with the Academic Ethics Policy. To ensure the research's quality and trustworthiness, triangulation was employed by combining data from multiple sources, including literature review, interviews, and case studies.

**Case Study**

**Case Study 1: The Forge, Southwark, London.**

**Project Details**

Location: Southwark, London, United Kingdom.

| | |
|---|---|
| Client: | LandSec |
| Architect: | Bryden Wood |
| Contractor: | Sir Robert McAlpine, Mace |
| Manufacturer(s): | TataSteel, Easi Space, DAM, NG Bailey, Hall & Kay, Armstrong, Hotchkiss |
| Completion Date: | July 2021 |

*Figure 1: The Forge, Southwark, London. Source -(Bryden Wood, 2024).*

**Project Overview**

The Forge project in Southwark, London stands as a pioneering venture, displaying the synchronous application of BIM and Lean methodologies within DFMA for sustainable construction. Spearheaded by NG Bailey, in collaboration with Landsec, Bryden Wood, and Easi-Space, The Forge is hailed as the UK's first net-zero carbon commercial development, excelling in both construction and operational sustainability (NG Bailey, 2023). This innovative building achieves net-zero carbon status in both construction and operation, aligning with the UK Green Building Council's definition (UKGBC). The project's groundbreaking aspect lies in its use of platform Design for Manufacture and Assembly (P-DfMA) - a first for a major commercial building (Tata Steel, 2024). This innovative approach, along with the project's design and construction techniques, has earned funding from Innovate UK, recognizing its potential to revolutionize the construction sector (Tata Steel, 2024). The project highlights the benefits that can be delivered using P-DfMA techniques, Modern Methods of Construction (MMC) and digital technologies on a large-scale new build commercial office development (Bryden Wood, 2024).

**Sustainable Benefits of DfMA with BIM and Lean Integration:**

Forge exemplifies how DfMA, when integrated with BIM and Lean practices, can revolutionize construction towards achieving significant sustainability goals. Here is a breakdown of the key benefits:

- **Lower Carbon Footprint:** The project aimed for a 24% reduction in embodied carbon per square metre compared to traditional methods (Bryden Wood, 2024; LandSec, 2024), with substantial reductions in carbon emissions across the substructure and superstructure (Bryden Wood, 2024; LandSec, 2024). Steel usage is projected to decrease by 40% (Bryden Wood, 2024). Using these techniques has contributed to a circa. 25% reduction to date in embodied carbon from the initial design stage and 178 tonnes in steel by using the platform approach - that is the equivalent of just under 13.5 London Double Decker buses in weight was saved (LandSec 2024).
- **Lower Project Cost:** A predicted 9.5% reduction in capital expenditure signifies significant cost savings (Bryden Wood, 2024; LandSec, 2024), with project duration expected to decrease by 13% (Bryden Wood, 2024).
- **Less Onsite Operatives:** The project anticipated a 50% reduction in the number of site operatives required for superstructure and facade construction (Bryden Wood, 2024).
- **Improved Efficiency:** BIM enabled collaborative design and precise prefabrication, leading to a predicted 13.5% increase in productivity and improved safety standards on-site (Tata Steel, 2022). The platform approach demonstrates effectiveness with a 3.5m slab-to-slab height, potentially allowing an additional floor for every 7 – 12 storeys within a given planning height envelope compared to traditional designs (Construction Innovation Hub, 2022).
- **Reduced Waste**: Offsite manufacturing using Platform-DfMA significantly minimises on-site material wastage, leading to environmental benefits and potentially diverting over 20,000 operative hours from the on-site workforce (Bryden Wood, 2024).

**Challenges and Limitations:**

While The Forge presents a significant leap forward, it is important to acknowledge potential challenges and limitations encountered as noted by Construction Innovation Hub, (2022):

- **Upfront Planning Complexity:** Implementing Platform-DfMA may require a more complex upfront planning phase compared to traditional construction methods.
- **Industry Mindsets:** Shifting traditional industry mindsets towards embracing innovative approaches like PlatformDfMA can be a challenge.
- **Logistics and Quality Control:** Ensuring efficient logistics and robust quality control measures for offsite manufactured components is crucial.

**Lessons learned for the future:**

The Forge provided valuable insights into the platform approach to construction, showcasing its transformative potential in building design, procurement, manufacturing, and construction processes. Construction Innovation Hub, (2022) noted the key takeaways from this pioneering use of a DfMA solution include:

- Adaptability to Varied Construction Methods: While the platform approach offers efficiency, buildings will always have unique elements requiring interface with traditional build methods, emphasising the need for flexibility in design to accommodate these variations.

- Enhanced Quality Control: Improvements in on and offsite quality control processes are essential to meet tighter tolerances in construction, ensuring consistent standards across all components.
- Evolution of Construction Logistics: Managing construction logistics must evolve to fully leverage the benefits of P-DfMA, necessitating flexible 'Just in Time' supply and logistics solutions linked to real-time monitoring systems for sustained productivity gains.
- Risk Management: An innovative approach to managing construction risk is crucial, necessitating effective risk reduction, management, and sharing strategies to ensure optimal risk allocation.
- Interdisciplinary Collaboration: Improved definition and understanding of interrelationships between construction packages and sophisticated collaborative working models are vital to optimise construction processes and incentivize positive behaviours among stakeholders.
- Exploration of New Commercial Models: Collaborative and incentivized commercial models should be explored to balance risk and reward and enable early involvement of the supply chain in design and logistics planning.
- Client Confidence and Adoption: Defining clear commercial models is essential to increase client confidence and promote the adoption of the platform approach to construction.

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## Findings and Discussions

### Theme 1: DfMA: Improving Construction Efficiency

### Sub-theme 1: DfMA's Impact on Waste Reduction and Efficiency

The first theme explores the positive impact of DfMA on construction efficiency and its contribution to sustainable practices. Participants consistently pinpointed DfMA's role in reducing waste and improving construction efficiency (P1, P3, P4 and P5). Proactive planning facilitated by controlled factory environments and precise methodologies leads to a substantial reduction in construction waste, as noted by P1: "*The controlled environment allows for minimal waste generation compared to traditional on-site construction*." P1 went on to state "*you're going to know to the T how much material you're going to need*".

This aligns with previous research by Edwards (2002) and Banks et al. (2018), emphasising controlled factory production's role in minimising material waste. This sentiment was echoed by P5, who identified waste reduction as the primary benefit of DfMA, and succinctly captured this sentiment, stating, "*The first thing that came to mind was about waste. It's getting rid of the amount of waste we have from construction…*" The Forge case study, meticulously documented by Tata Steel (2022), displayed a substantial reduction in on-site material wastage, leading to environmental benefits and potential cost savings. Research on DfMA by Abd Razak et al. (2022), specifically its application in industrialized building systems and volumetric modular construction, also indicates significant reductions in construction waste and a decrease in the number of materials used.

By efficiently managing the offsite environment and minimising construction waste, DfMA ensures precise material estimation and reduces on-site errors and waste, displaying its positive environmental impact. Additionally, by streamlining material delivery and site operations, DfMA improves site management, further reducing waste. Overall, DfMA significantly enhances efficiency and waste reduction in construction projects, making it more sustainable.

### DfMA: A Tool for Cost Reduction in Construction

Industry professionals overwhelmingly identify cost reduction as a key driver for adopting Design for Manufacture and Assembly (DfMA). Interviews throughout this research consistently highlighted the financial advantages of DfMA.

P1succinctly summarized the sentiment: "*Benefit number one is always you save money. You save money for the client; you save money for your own company.*" However, simply implementing DfMA is not a magic bullet. Careful project analysis is crucial to maximise these cost savings. P1, in the same quote, emphasises the importance of upfront planning, mentioning their role includes "*doing the analysis on how much volume of material would be there*" for incoming projects. This meticulous analysis ensures DfMA is applied strategically for maximum cost optimisation.

While some might be hesitant due to the initial investment required for planning and optimisation, the findings suggest a strong return on investment. P3 offered a compelling perspective: "*One* *dollar you invest in DfMA, you save about a thousand pounds during construction*." This upfront investment leads to significant cost savings later. This aligns with the findings of RIBA (2021), further solidifying the financial benefits of DfMA.

The financial benefits extend beyond anecdotal evidence. The Forge project, a case study by Bryden Wood (2024) and LandSec (2024), predicted a significant 9.5% reduction in capital expenditure with DfMA implementation. Additionally, the project anticipates a decrease in project duration by up to 13% (Bryden Wood, 2024).

Interview findings further solidify the cost-saving potential. P3 highlighted how DfMA "*leads to less waste and fewer mistakes, which can really cut down on costs*." By minimising waste and errors through controlled factory environments, DfMA offers substantial cost savings during construction. Finally, P4 summarized a core benefit: DfMA's ability to directly reduce construction costs, stating, "*Obviously there is the reduced cost of construction*."

These findings reinforce the overarching theme: cost benefits are a major advantage of DfMA, making it a compelling choice for modern construction practices. This aligns with research by Antony & Arunkumar (2020), who noted that DfMA simplifies design processes to facilitate manufacturing and assembling, reducing costs without compromising quality. This makes DfMA a promising methodology for the future of construction.

Looking beyond immediate savings, DfMA offers long-term benefits through enhanced efficiency and reduced maintenance requirements. Prefabricated components, manufactured under controlled conditions, tend to be of higher quality, resulting in fewer defects and lower maintenance costs over the building's lifespan. Despite the initial investment, DfMA provides excellent value for money due to its time and cost-saving benefits throughout a project's lifecycle. DfMA offers a compelling solution for cost reduction in modern construction practices. By streamlining processes, minimising waste, and improving efficiency, DfMA can significantly reduce construction costs while delivering long-term value.

## Conclusion

DfMA has emerged as a powerful strategy for achieving sustainable construction. This research confirms DfMA's significant environmental and economic benefits. By emphasising prefabrication and optimised assembly processes conducted in controlled factory settings, DfMA minimises on-site material waste and rework, leading to substantial reductions in overall project waste. Additionally, DfMA promotes efficient use of resources and energy consumption throughout the construction lifecycle. Faster project timelines achieved through DfMA translate to a reduced environmental footprint associated with extended construction activities. Furthermore, the controlled factory environments inherent in DfMA often lead to higher-quality construction, potentially lowering long-term maintenance needs and associated environmental impact.

## Recommendations

1. Education and Training: Provide comprehensive programs to equip construction professionals with the necessary skills to implement BIM, Lean, and DfMA effectively.
2. Introduce government-backed financial incentives to offset initial investment costs associated with BIM software, DfMA training, and infrastructure

3. Develop standardised guidelines and best practices for BIM, Lean, and DfMA integration to benefit all stakeholders.
4. AI-driven BIM: Integrate Artificial Intelligence (AI) and machine learning into BIM to further optimise design, reduce waste, and enhance DfMA integration.
5. Moving forward, the construction industry should adopt a comprehensive approach to sustainable construction that considers the entire building lifecycle.

## REFERENCES


Abd Razak, M. I., Khoiry, M. A., Wan Badaruzzaman, W. H., & Hussain, A. H. (2022). DfMA for a better industrialised building system. *Buildings*, 12(6), 794.

Ahn, K. U., Kim, Y. J., Park, C. S., Kim, I., & Lee, K. (2014). BIM interface for full vs. semi-automated building energy simulation. Energy and Buildings, 68, 671-678. https://doi.org/10.1016/j.enbuild.2013.08.063

Al-Saffar, A. E., & Salman, Z. H. (2014). A Proposed Management System for Construction Practices during Sustainable Buildings Life Cycle. Journal of Engineering, 20(07), 15-35.

Antony, K. M., & Arunkumar, S. (2020, February). Dfma and sustainability analysis in product design. *Journal of Physics*: Conference Series (Vol. 1455, No. 1, p. 012028). IOP Publishing. http://doi.org/10.1088/17426596/1455/1/012028

Arsenos, P., & Giannadakis, G. (2023). Construction Projects' Waste Prevention and Expected Minimisation of Cost and Environmental Impacts through Adopting a Comprehensive System for Document Management. Environmental Research, Engineering and Management, 79(2), 77-87. https://doi.org/10.5755/j01.erem.79.2.33532

Bakhshi, S., Chenaghlou, M. R., Rahimian, F. P., Edwards, D. J., & Dawood, N. (2022). Integrated BIM and DfMA parametric and algorithmic design based collaboration for supporting client engagement within offsite construction. Automation in Construction, 133, 104015. https://doi.org/10.1016/j.autcon.2021.104015

Banks, C., Kotecha, R., Curtis, J., Dee, C., Pitt, N., & Papworth, R. (2018). Enhancing high-rise residential construction through design for manufacture and assembly–a UK case study. Proceedings of the institution of civil engineersmanagement, procurement and law, 171(4), 164-175. https://doi.org/10.1680/jmapl.17.00027

Barbosa, F., Woetzel, L., Mischke, J., Maria João Ribeirinho, Sridhar, M., Parsons, M., Bertram, N., & Brown, S. (2017). Reinventing construction through a productivity revolution. McKinsey & Company. Available from: https://www.mckinsey.com/capabilities/operations/our-insights/reinventing-construction-through-a-productivityrevolution (accessed March 9, 2024).

Bew, M., & Richards, M. (2008). *BIM Maturity Model. Paper presented at the Construct IT Autumn 2008 Members' Meeting*. Brighton, UK.

Boothroyd, G. (2005). Assembly automation and product design. crc press.

Bryden Wood (2024). The Forge. Available online: https://www.brydenwood.com/projects/the-forge/s93059/

Landsec (2024). Another milestone, Uks-first net-zero-carbon-commercial. Available online: https://landsec.com/insights/future-trends/development/another-milestone-uks-first-net-zero-carbon-commercial*Bryden Wood, 2024).*

Bryden Wood (2024). The Forge. Available online: https://www.brydenwood.com/projects/the-forge/s93059/ Chatzimichailidou, 2022).

Chen, K., & Lu, W. (2018). Design for Manufacture and Assembly Oriented Design Approach to a Curtain Wall System: A Case Study of a Commercial Building in Wuhan, China. *Sustainability*, 10(7), 2211. https://doi.org/10.3390/su10072211

Construction Innovation Hub (2018). The Forge – Shaping the future. Constructioninnovationhub.org.uk. Available online: https://constructioninnovationhub.org.uk/media/4rhpz3q5/platforms-in-action-full-pdf-story.pdf

Abd Razak, M. I., Khoiry, M. A., Wan Badaruzzaman, W. H., & Hussain, A. H. (2022). DfMA for a better industrialised building system. *Buildings*, 12(6), 794.

Akob, Z., Zaidee, M., Hipni, A., & Koka, R. (2019, April). Coordination and collaboration of information for pan borneo highway (Sarawak) via Common Data Environment (CDE). In IOP Conference Series: Materials Science and Engineering (Vol. 512, No. 1, p. 012001). IOP Publishing. https://doi.org/ 10.1088/1757-899X/512/1/012001

Eastman, C., Teichholtz, P., Sacks, R., & Liston, K. (2011). BIM Handbook: A Guide to Building Information Modeling for Owners, Managers, Designers, Engineers and Contractors. John Wiley & Sons.

Edwards, K. L. (2002). Towards more strategic product design for manufacture and assembly: priorities for concurrent engineering. Materials & design, 23(7), 651-656.

Banks, C., Kotecha, R., Curtis, J., Dee, C., Pitt, N., & Papworth, R. (2018). Enhancing high-rise residential construction through design for manufacture and assembly–a UK case study. Proceedings of the institution of civil engineersmanagement, procurement and law, 171(4), 164-175. https://doi.org/10.1680/jmapl.17.00027

Gao, S., Jin, R., & Lu, W. (2020). Design for manufacture and assembly in construction: a review. Building research & information, 48(5), 538-550. https://doi.org/10.1080/09613218.2019.1660608

Gibb, A G F. (1999). Of-site Fabrication Prefabrication Pre-assembly and Modularisation, John Wiley & Sons.

Häkkinen, T., & Belloni, K. (2011). Barriers and drivers for sustainable building. Building Research & Information, 39(3), 239-255. https://doi.org/10.1080/09613218.2011.561948

Hällmark, R., White, H., & Collin, P. (2012). Prefabricated bridge construction across Europe and America. *Practice periodical on structural design and construction*, 17(3), 82-92.

HM Government. (2013). *Construction 2025 Industrial Strategy: Government and Industry in Partnership* [online]. HM Government. Available from: https://assets.publishing.service.gov.uk/media/5a7b7ea140f0b62826a03f2c/bis-13-955construction-2025-industrial-strategy.pdf.

Hossain, M. U., Ng, S. T., Antwi-Afari, P., & Amor, B. (2020). Circular economy and the construction industry: Existing trends, challenges and prospective framework for sustainable construction. Renewable and Sustainable Energy Reviews, 130, 109948. https://doi.org/10.1016/j.rser.2020.109948

Iacovidou, E., & Purnell, P. (2016). Mining the physical infrastructure: Opportunities, barriers and interventions in promoting structural components reuse. Science of the Total Environment, 557, 791-807. https://doi.org/10.1016/j.scitotenv.2016.03.098

Khoiry, M. A., Kalaisilven, S., & Abdullah, A. (2018). A Review of Minimising Delay in Construction Industries. *E3S Web of Conferences*, 65, 03004. https://doi.org/10.1051/e3sconf/20186503004

Kibert, C. J. (2016). Sustainable construction: green building design and delivery. John Wiley & Sons.

KPMG (2016). How Offsite Manufacturing Can Transform Our Industry; Smart Construction Report, 2016. Available:https://assets.kpmg/content/dam/kpmg/pdf/2016/04/smart-construction-report-2016.pdf (accessed March 15, 2024).

Li, X., Shen, G. Q., Wu, P., & Yue, T. (2019). Integrating Building Information Modeling and Prefabrication Housing Production. *Automation in Construction*, *100*, 46–60. https://doi.org/10.1016/j.autcon.2018.12.024

Lloret, E., Shahab, A. R., Linus, M., Flatt, R. J., Gramazio, F., Kohler, M., & Langenberg, S. (2015). Complex concrete structures: Merging existing casting techniques with digital fabrication. Computer-Aided Design, 60, 40-49. https://doi.org/10.1016/j.cad.2014.02.011

Machado J. Digital Standardisation of Lean Manufacturing Tools According to Industry 4.0 Concept. Applied Sciences. 2023; 13(10):6259. https://doi.org/10.3390/app13106259

Maile, T., Fischer, M., & Bazjanac, V. (2007). Building energy performance simulation tools-a life-cycle and interoperable perspective. Center for Integrated Facility Engineering (CIFE) Working Paper, 107, 1-49.

Martínez,S.,Jardón,A., GonzalezVíctores,J.&Balaguer,C. (2013). "Flexible field factory for construction industry", *AssemblyAutomation,* Vol. 33 No. 2, pp. 175-183. https://doi-org.salford.idm.oclc.org/10.1108/01445151311306708

Mesa, J., Maury, H., Arrieta, R., Corredor, L., & Bris, J. (2017). A novel approach to include sustainability concepts in classical DFMA methodology for sheet metal enclosure devices. Research in Engineering Design, 29(2), 227–244. https://doi.org/10.1007/s00163-017-0265-4

Murtagh, N., Scott, L., & Fan, J. (2020). Sustainable and resilient construction: Current status and future challenges. *Journal of Cleaner Production*, *268*, 122264. https://doi.org/10.1016/j.jclepro.2020.122264

NG Bailey (2023). The Forge - NG Bailey - Offsite Hub. Available online: https://www.offsitehub.co.uk/project/theforge-ng-bailey/

Ng, M. S., & Hall, D. M. (2019, July). Toward lean management for digital fabrication: A review of the shared practices of lean, DfMA and dfab. In Proceedings of the 27th Annual Conference of the International Group for Lean Construction (IGLC), Dublin, Ireland (pp. 3-5). https://doi.org/10.24928/2019/0204.

Ogunmakinde, O. E., Egbelakin, T., & Sher, W. (2022). Contributions of the circular economy to the UN sustainable development goals through sustainable construction. Resources, Conservation and Recycling, 178, 106023. https://doi.org/10.1016/j.resconrec.2021.106023

Oluleye, B. I., Chan, D. W., Saka, A. B., & Olawumi, T. O. (2022). Circular economy research on building construction and demolition waste: A review of current trends and future research directions. Journal of Cleaner Production, 357, 131927. https://doi.org/10.1016/j.jclepro.2022.131927

O'Rourke, L. (2013). The future of DfMA is the future of construction. Engineering Excellence 674 Journal (2013), 77.

Prakash, K. S., Nancharaih, T., & Rao, V. S. (2018). Additive manufacturing techniques in manufacturing-an overview. Materials Today: Proceedings, 5(2), 3873-3882. https://doi.org/10.1016/j.matpr.2017.11.642

RIBA (2013). RIBA Plan for Work 2013. Designing for Manufacture and Assembly. Royal Institute of British Architects. London. Available online: http://consig.org/wp-content/uploads/2018/10/RIBAPlanofWorkDfMAOverlaypdf.pdf (accessed 5th March 2024).

RIBA. (2021). DfMA Overlay to the RIBA Plan of Work. 2nd ed. Royal Institute of British Architects, London, UK

Roxas, C. L. C., Bautista, C. R., Dela Cruz, O. G., Dela Cruz, R. L. C., De Pedro, J. P. Q., Dungca, J. R., Lejano, B. A., & Ongpeng, J. M. C. (2023). Design for Manufacturing and Assembly (DfMA) and Design for Deconstruction (DfD) in the Construction Industry: Challenges, Trends and Developments. *Buildings*, *13*(5), 1164. https://doi.org/10.3390/buildings13051164

Sacks, R., Dave, B. A., Koskela, L., & Owen, R. (2009). *Analysis framework for the interaction between lean construction and building information modelling*. 221–234.

Sebastian, R. (2011). Low disturbance urban projects through smart manufacturing and building information modelling. Proceedings of SIM 2011 Sustainable Intelligent Manufacturing, June 29-July 1, 2011, Leiria, Portugal, 37-45.

Sivashanmugam, S., Rodriguez, S., Rahimian, F., & Dawood, N. (2022, November). Maximising the construction waste reduction potential–barriers and catalysts. In Proceedings of the Institution of Civil Engineers-Civil Engineering (Vol. 176, No. 6, pp. 6-14). Emerald Publishing Limited. https://doi.org/10.1680/jcien.22.00163

Sloditskie, G., & Sadoughi, A. (2022). Dematerialization in Housing Industry: Modular Light Wood Frame versus Conventional Wood Frame Structure for Multi-Family Housing. In Construction Research Congress 2022 (pp. 766-772).

TataSteel (2024). The Forge, Southwark, London. Tata Steel in Europe. https://www.tatasteeleurope.com/construction/case-study/the-forge-southwark-london

Thompson, M. K., Jespersen, I. K. J., & Kjærgaard, T. (2018). Design for manufacturing and assembly key performance indicators to support high-speed product development. Procedia CIRP, 70, 114-119. https://doi.o()rg/10.1016/j.procir.2018.02.005

Tuvayanond, W. & Prasittisopin, L. (2023). Design for Manufacture and Assembly of Digital Fabrication and Additive Manufacturing in Construction: A Review. Buildings 2023, 13, 429. https://doi.org/10.3390/buildings13020429

UKGBC (2023) System Enablers for a Circular Economy. Technical report: UK Green Building Council Available online: https://ukgbc.org/wp-content/uploads/2023/01/Circular-Economy-System-Enablers-Report.pdf

Vaz-Serra, P., Wasim, M., & Egglestone, S. (2021). Design for manufacture and assembly: A case study for a prefabricated bathroom wet wall panel. Journal of Building Engineering, 44, 102849. https://doi.org/10.1016/j.jobe.2021.102849

Vokes, C & Brennan, J. (2013). Technology and Skills in the Construction Industry, Evidence Report 74, UK Commission for Employment and Skills, September 2013.

Welle, B., Haymaker, J., & Rogers, Z. (2011, December). ThermalOpt: A methodology for automated BIM-based
multidisciplinary thermal simulation for use in optimisation environments. In Building simulation (Vol. 4, pp. 293-313).

Wu, P., Wang, J., & Wang, X. (2016). A critical review of the use of 3-D printing in the construction industry. Automation in Construction, 68, 21-31. https://doi.org/10.1016/j.autcon.2016.04.005

Yazdi, A. J., Fini, A. A. F., & Forsythe, P. (2021). Mass-customisation of cross-laminated timber wall systems at early design stages. Automation in Construction, 132, 103938. https://doi.org/10.1016/j.autcon.2021.103938

Yuan, Z., Sun, C., & Wang, Y. (2018). Design for Manufacture and Assembly-oriented parametric design of prefabricated buildings. *Automation in Construction*, 88, 13-22.