AJEMA GLOBAL RESEARCH NETWORK

AMERICAN Journal of Engineering, Mechanics and Architecture
Volume 2, Issue 10, 2024 ISSN (E): 2993-2637

Justification of the use Cases of BIM and Lean in DFMA with Identification of Associated Themes

Anuri Chinatu NJOKU
School of Science, Engineering, The University of Salford, United Kingdom

Abstract: Considering the fact that the UK construction industry faces a growing demand for sustainable practices, this research is conducted to explore the justification of the use cases of BIM and Lean in DfMA with identification of associated themes. 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 justification, among others was that the integration of BIM and Lean methodologies within the framework of DfMA for sustainable construction is a research area of profound importance. The construction industry, identified as a cornerstone of economic growth, not only directly contributes to a nation's economic prosperity but also exerts indirect influences on the growth trajectories of other industries. Besides the exploration of the integration of BIM and Lean within the DfMA context is paramount for achieving a holistic understanding of their collective contributions to sustainable construction practices in the industry. Interestingly, the research examined 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. 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. One of the recommendations was that there is need to develop standardised guidelines and best practices for BIM, Lean, and DfMA integration to benefit all stakeholders.

Keywords: Justification of the use cases of BIM and Lean in DfMA with identification of associated themes.

Introduction

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.

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. The growing adoption of DfMA can be attributed to its recognized advantages. Studies consistently report benefits such as increased accuracy, faster construction times, and reduced environmental impact (Chen and Lu., 2018; Abd Razak et al., 2022; Gao et al., 2018). Qi & Costin (2023) further highlight DfMA's ability to address inefficiencies in traditional construction by facilitating efficient off-site processes. This translates to highly optimised designs, improved sustainability, and increased productivity in construction projects. These reports indicate that by overcoming the limitations of conventional methods through off-site manufacturing, DfMA paves the way for a more sustainable and productive future for the construction industry.

While DfMA offers advantages, implementing it effectively requires overcoming hurdles. Communication, collaboration, information sharing, and conflict resolution pose significant challenges (Qi & Costin, 2023). Roxas et al., (2023) observed a critical gap in understanding DfMA's full potential and the challenges it presents across the entire construction process, despite growing interest and noted existing research often focuses on specific aspects rather than providing a holistic view. Another obstacle lies in streamlining the logistics of off-site manufacturing and assembling. DfMA relies on digitalization, automation, and early collaboration between various disciplines. However, construction professionals often lack the necessary skills in manufacturing and logistics (RIBA, 2021). Even if these skills exist within a project team, they are typically spread across distinct roles (architects, engineers, etc.), hindering a unified understanding. To address these issues, a proposed framework advocates for integrating Building Information Modelling (BIM) tools with Lean construction principles. This framework also emphasises fostering interdisciplinary design and collaboration. Researchers believe that combining BIM and Lean concepts can effectively tackle the current shortcomings hindering successful DfMA implementation (Nguyen et al., 2021).

Justification

The integration of BIM and Lean methodologies within the framework of DfMA for sustainable construction is a research area of profound importance. The construction industry, identified as a cornerstone of economic growth, not only directly contributes to a nation's economic prosperity but also exerts indirect influences on the growth trajectories of other industries (Abd Razak et al., 2022). The exploration of the integration of BIM and Lean within the DfMA context is paramount for achieving a holistic understanding of their collective contributions to sustainable construction practices in the industry.

Despite the increasing recognition of DfMA in the construction industry, the literature on construction oriented DfMA remains limited, and its practical application in real-life projects has been constrained by numerous factors (Rankohi et al., 2023). While studies have demonstrated that the implementation of DfMA in construction projects can significantly improve overall productivity (Roxas et al., 2023), there are notable research gaps that need addressing. These include the development of standard construction oriented DfMA guidelines and the integration of these design approaches with emerging technologies (Jung & Yu, 2022; Sun et al., 2020). Current research on DfMA implementation has limitations. It often fails to consider the entire project life cycle, from design through to delivery. This overlooks crucial challenges like collaboration issues, logistical hurdles, and production problems (Abrishami & Martín-Durán, 2021). Additionally, the novelty of DfMA can pose difficulties for practitioners, leading to lower adoption rates and hindering the full potential of this approach (Qi & Costin, 2023; Yuan et al., 2018; RIBA., 2021). To address these limitations, further research is needed to develop clear guidelines for effective DfMA implementation, including the digitalization of processes. BIM and Lean methodologies are seen as promising solutions for overcoming these existing constraints (Abrishami & Martín-Durán, 2021; Yuan et al., 2018)

Synergies between BIM, Lean, and DfMA

Achieving sustainable construction practices in the UK requires innovative approaches. Studies indicate that DfMA, BIM, and Lean Construction each offer individual benefits for sustainability, but their true power lies in their constructive collaboration. DfMA prioritizes off-site prefabrication, leading to less on-site waste and improved resource utilization (Edwards, 2002). It also allows for optimised logistics, reducing transportation emissions (Edwards, 2002). Prefabrication enables early detection and correction of design flaws, minimising wasted materials and rework costs later (Ng & Hall, 2019). BIM acts as a powerful tool for sustainable design. It facilitates early client involvement, allowing them to participate in decisions about sustainable materials and systems from the outset (O'Rourke, 2013). BIM also enables collaborative design, fostering the selection of more sustainable building elements (Yazdi et al., 2021). Additionally, BIM offers design optimisation tools to minimise material use (Liu et al., 2023).

Lean Construction principles align perfectly with DfMA's focus on efficiency and reduced waste. Lean practices like optimised designs and efficient production processes minimise waste in both fabrication and assembling (Ng and Hall, 2019). Furthermore, Lean emphasises continuous improvement, fostering ongoing optimisation of DfMA workflows for a more sustainable construction process (Naiju, 2021). By minimising waste and optimising processes, Lean Construction promotes resource efficiency in DfMA projects, contributing to a more circular economy (Gbadamosi et al., 2019). Standardisation, a key element of Lean manufacturing, reduces complexity, errors, and production waste (Medynski et al., 2023). Lean also advocates for "Just-in-Time" logistics, ensuring components arrive on-site precisely when needed, minimising storage space requirements, and optimising workflow efficiency (Dubisz & Rokicki, (2022).

Research 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 Analysis

Case Study Selection Criteria

This study emphasises foundational elements for sustainable construction, including technical aspects and intangible elements, extending beyond adoption to driving efficiency and innovation in Design DfMA projects. It highlights technical considerations like standardisation and information management for consistency. Emphasis is on fostering a collaborative culture among project teams for successful outcomes. Additionally, project management and logistics review are deemed critical for seamless DfMA project execution. The study showcases how integrating Lean and Building Information Modelling (BIM) principles enhances sustainability objectives, fostering continuous improvement and innovation in the construction industry.

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).

Figure2: 3D Model of the Forge (NG Bailey, 2022).

Technologies and Methodologies Implemented:

- **Standardisation:** The adoption of P-DfMA facilitated standardisation across various construction elements, including structural steelwork, temporary works, cladding, and MEP components. This standardisation, based on a prototype developed by Landsec and Bryden Wood, not only increased design flexibility but also reduced waste, enhanced workforce skills, and improved health and safety standards. The DFMA approach was pivotal in the project's success, with the offsite team developing the entire MEP distribution as a Knock-Out Panel (KOP). Manufactured offsite and installed using a P-DfMA approach, the KOP achieved a remarkable 95% of high-level installation, highlighting significant advancements in construction methodology. P-DfMA utilises standardised components assembled through a 'kit of parts' methodology, resulting in faster completion times compared to traditional construction techniques (TataSteel, 2024).
- **Early Collaboration:** Mark Griffin, Offsite Integration Manager at NG Bailey, noted the significance of integrating DfMA at the project's outset, enabling the optimisation of manufacturing and installation sequences (Construction Innovation Hub, 2022). This approach not only provided valuable data for offsite manufacture and onsite installation but also reduced on-site labour hours and transportation needs. Additionally, the collaborative efforts of stakeholders, including Landsec, architects, engineers, designers, contractors, and supply chain partners, were instrumental in maximising the benefits of the P-DfMA solution (NG Bailey, 2023). Collaboration began at the project's onset, with stakeholders setting ambitious targets for the prototype to outperform traditional steel and concrete structural solutions (NG Bailey, 2022).
- **Delivery Embedded in Design:** The project transcended focusing solely on building components, but also embraced efficient construction processes through Lean principles. This involved higher levels of design completion at an early stage with input from supply chain partners and construction managers. This focus on "design for manufacture and assembly" ensured efficient manufacturing and on-site assembly of key components (Construction Innovation Hub, 2022).
- **Continuous Improvement:** The project team actively engaged with researchers from the University of Cambridge Department of Engineering to scrutinize site data, aiming to comprehend the productivity enhancements achievable through DfMA processes, automated construction methods, and data-informed decision-making. This collaborative effort exemplifies the project's commitment to Lean principles, which focus on continuous improvement and the elimination of waste throughout the construction process (Construction Innovation Hub, 2022).

- **Design Optimisation:** The Forge project optimised collaboration through a digital component library, developed by Bryden Wood (Construction Innovation Hub, 2022). This comprehensive library contained crucial data on components, such as material specifications and costs, enabling access for all project participants. Additionally, Bryden Wood utilised standard design software and platform-specific routines to automatically generate precise data on structural component positioning and orientation (Construction Innovation Hub, 2022). This streamlined the creation of a complete bill of materials and the Building Information Model, facilitating coordination across various project elements. Moreover, BIM played a pivotal role in facilitating collaborative design efforts and streamlining construction processes (Sir Robert McAlpine, 2022; Construction Innovation Hub, 2022).
- **Streamlined Logistics:** Moreover, the project successfully slashed over 500 tonnes of embodied and operational carbon emissions, with streamlined logistics and reduced transportation needs from offsite manufacturing playing key roles (Tata Steel, 2022).

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).

Case Study 2: The Boiler House, Hayes, London.

Project Details:

Location:	Hayes, London, United Kingdom.
Client:	HUB Realstar Group
Architect:	Stride Treglown
Concept Architect:	Studio Egret West
Materials:	Cross-Laminated Timber (CLT)

Timber Engineer: Eurban Limited

Main Contractor: Henry Construction Projects Ltd

Completion: 2018

Project Overview:

This case study explores how these combined approaches contributed to a sustainable, efficient, and high-quality construction project. The Boiler House stands out as one of the UK's largest private housing projects employing a CLT (Cross-Laminated Timber) structure, effectively reducing its carbon footprint. Comprising 54 bright and spacious studios, one, and two-bedroom apartments, it fosters community engagement and wellness with amenities such as rooftop gardens and an on-site bike store. The distinctive exterior, embellished with shimmering stainless-steel shingles, pays tribute to the area's industrial heritage. Additionally, the central orange staircase, reminiscent of the former boiler house chimney, adds a unique charm to the building. With a BREEAM rating of 'Very Good', the Boiler House seamlessly integrates into the broader Old Vinyl Factory development plan in Hayes (Stride Treglown, 2024). It showcases the successful application of BIM and lean principles in DfMA for sustainable construction

Figure 3: Facade photograph of the Boiler (Eurban ltd: https://www.eurban.co.uk/project/boiler-house/)

Key Approaches:

The architect of the project, Stride Treglown, attributed the success of the venture to several key approaches that were followed:

- **Sustainable Construction:** The use of CLT minimised the building's embodied carbon footprint due to its renewability and efficient manufacturing process. According to Architect Stride Treglown (2024) the project achieved a BREEAM rating of "Very Good," signifying its commitment to environmental sustainability.
- **Application of DfMA:** DfMA principles were implemented throughout the design and construction phases. Working closely with the CLT system designer, Eurban Limited, the project team meticulously planned the building's intricate details, including MEP integration, roof landscaping, and balcony support. This collaborative approach ensured efficient on-site assembly and minimised waste.
- **Lean Approach:** Lean practices, combined with the inherent advantages of CLT (precision and rapid assembling), resulted in the CLT superstructure being erected in just seven weeks, significantly outpacing traditional construction methods for similar projects.
- **BIM for Collaboration:** Building Information Modelling (BIM) played a crucial role in the project. The comprehensive 3D model facilitated close collaboration between various stakeholders, leading to a wellcoordinated design. Moreover, the BIM-enabled visualizations are credited with contributing to over 80% of the residential units being sold before construction even began.

Figure 4: 3D Model showing the component parts of the Boiler House (Eurban Limited-https://www.eurban.co.uk/project/boiler-house/)

Key Achievements

The following achievements were noted by Stride Treglown and Eurban Limited

Reduced Environmental Impact: The implementation of Cross-Laminated Timber (CLT) construction and efficient DfMA processes at The Boiler House project significantly reduced its environmental impact. The case study revealed that CLT, being a sustainable and renewable material, contributed to lowering the project's embodied carbon footprint compared to traditional construction methods. Additionally, DfMA principles were employed to minimise waste generation by prefabricating components off-site with precision, thus reducing material wastage during assembling. This combination of CLT and DfMA not only enhanced the project's environmental sustainability but also aligned with broader industry goals of reducing carbon emissions and promoting eco-friendly construction practices.

Improved Efficiency and Speed: The integration of DfMA and Lean practices at The Boiler House project resulted in notable improvements in construction efficiency and speed. Through the application of Lean methodologies such as value stream mapping and continuous improvement, construction processes were streamlined to eliminate inefficiencies and enhance productivity. DfMA principles further contributed to efficiency gains by enabling the off-site fabrication of building components, allowing for parallel construction activities, and reducing on-site assembling time. As a result, the project achieved faster completion times and reduced costs, demonstrating the potential of integrated DfMA and Lean approaches to drive efficiency in construction projects.

Enhanced Collaboration and Communication: BIM played a pivotal role in facilitating collaboration and communication among project stakeholders at The Boiler House. The use of BIM technology enabled architects, engineers, and contractors to work collaboratively on a shared digital platform, fostering effective communication and coordination throughout the construction process. By providing a centralised repository of project information, BIM facilitated real-time decision-making and problem-solving, resulting in a well-coordinated and streamlined construction workflow. This enhanced collaboration among stakeholders contributed to the project's success and demonstrated the value of BIM in promoting effective communication in construction projects.

High-Quality Construction: The meticulous planning and execution of DfMA processes, combined with the use of CLT, ensured the delivery of a high-quality building envelope at The Boiler House. DfMA principles guided the design and fabrication of building components to exact specifications, minimising errors, and defects during assembling. Additionally, the structural integrity and performance of CLT provided a durable and resilient building solution, further enhancing the overall quality of construction. As a result, the project achieved exceptional standards of construction quality, meeting or exceeding regulatory requirements and industry standards. This emphasis on quality assurance and precision engineering underscores the importance of integrating DfMA and advanced construction materials like CLT to deliver superior building outcomes.

Discussion of the findings

This section unpacks the significant themes that emerged from the data analysis, providing a deeper understanding of BIM, Lean, and DfMA integration for a more sustainable construction industry in the UK. These themes link to the dissertation's overarching aim and objectives. By critically examining the collected data, this chapter seeks to answer the research questions and offer valuable insights. It explores how the synchronous application of BIM and Lean principles within DfMA can be effectively utilized to promote sustainability within the UK construction sector.

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.

Sub-theme 2: Efficient and Fast Construction

Faster installation times achieved through DfMA offer significant environmental benefits. Participants highlighted these advantages, with P2 mentioning reduced installation time as a key benefit that contributes to waste reduction, stating that in the proposed DfMA approach to their construction they "*saw that time on site is reduced by a couple of weeks*." Similarly, P3 and P4 noted that faster installation minimises on-site handling and potential damage, thus reducing waste, P3 clearly stated "*First off, it can really speed things up. When you design something with DfMA principles in mind, it is usually quicker and easier to build onsite. That means less time waiting around and more time getting stuff done*". The Forge case study by Tata Steel (2022) further emphasised that DfMA implementation reduced on-site labour hours and transportation needs. These findings resonate with Jung & Yu's (2022) research, which reported positive effects of DfMA on reducing product development periods, enhancing productivity, and improving product quality. Other studies by Chen and Lu, (2018); Abd Razak et al., (2022); and Gao et al., (2018) also agree that through benefits such as increased accuracy, and faster construction times gained from DfMA, construction would have a reduced negative environmental impact.

DfMA not only reduces waste but also enhances efficiency, quality, and safety on construction sites. The ability of DfMA to streamline processes and accelerate project timelines while minimising environmental footprint is commendable. Overall, the study findings reaffirm my belief in the potential of innovative approaches like DfMA to drive positive change and sustainability in construction practices, particularly through its fast and efficient delivery of construction projects.

Sub-theme 3: Improved Quality, Safety and Standardisation

DfMA not only reduces waste but also enhances quality, safety, and standardisation on construction sites. P3 explained how DfMA ensures standardised production and precise assembling, minimising rework and waste from errors or ill-fitting components, P3 noted, "*By designing for manufacture and assembly, everything fits together just right, improving quality*."

This notion aligns with beneficial principles of design and assembly simplification and the standardisation of parts outlined by Boothroyd (2005) and Kim et al. (2016). The Forge case study provided a valuable illustration of these benefits confirming that standardisation based on a prototype developed by Landsec and Bryden Wood, not only increased design flexibility but also reduced waste, enhanced workforce skills, and improved health and safety standards. Improved safety on construction sites aligns with waste reduction efforts, as P4 pointed out. Fewer injuries mean less material wastage from damaged components or rework. Tata Steel (2022) projected that BIM-enabled collaborative design and precise prefabrication would increase productivity by 13.5% and enhance on-site safety standards. These findings corroborate DfMA's potential for a positive ripple effect, contributing to sustainability through improved quality, safety, and reduced waste.

Theme 2: BIM and Lean: Collaborative Tools for Sustainable DfMA

Sub-theme 1: BIM: Streamlining Design and Collaboration for DfMA

BIM emerged as a critical factor in optimising DfMA processes. Interview participants consistently emphasised its importance (P1, P2, P3). BIM facilitates clash detection and design coordination, minimising errors and rework that contribute to waste, P4 elaborated this stating "*We extensively utilized BIM alongside DfMA practices to enhance project outcomes. For example, during the design phase of a recent project, we employed BIM to develop a detailed digital model of the building, incorporating all prefabricated components and their specifications. This allowed us to conduct thorough clash detection analysis, identifying and resolving potential issues before construction commenced*." The Boiler House project exemplifies how BIM aided in optimising component design and minimising material usage (Eurban Ltd, 2024). These findings align with research by Succar et al. (2012) who highlight BIM's ability to improve collaboration and eliminate design errors.

Sub-theme 2: Lean Principles: Optimising DfMA for Efficiency and Sustainability

Lean principles, when integrated with DfMA, foster continuous improvement and waste minimisation throughout construction. Some participants highlighted the value of lean processes and concepts in optimising DfMA processes (P2, P4, P3). P3 emphasised how waste minimisation aligns with core Lean principles for efficient production within controlled factory environments "*One significant aspect is the emphasis on waste reduction and continuous improvement […] construction processes become more efficient, minimising waste generation and resource consumption*.". The Forge case study by Tata Steel (2022) demonstrated how Lean practices like Value Stream Mapping helped streamline DfMA workflows. These findings resonate with Ballard (2008) who highlights the waste reduction focus of Lean principles aligning with sustainable construction goals. Participants acknowledged the potential synergy between DfMA and Lean (P3, P5). P3 explains how Lean practices align with DfMA's goals "*Lean principles such as […] just-in-time delivery and pull planning streamline manufacturing and […] promote waste reduction, resource optimisation, and innovation, fostering a culture of sustainability in construction projects*". P5 highlights the potential benefits of Lean in large-scale DfMA .

P4 mentioned the benefits of lean in sorting out logistics and transportation challenges in DfMA, noting that "*You've got to plan the logistics, navigate through traffic snarls, and stick to tight delivery schedules to avoid throwing off the construction time line, I believe lean can help in this manner as well…*" This agrees with findings by Sternberg et al. (2013) who declared that lean principles have been demonstrably effective in identifying and eliminating waste within logistics operations, thereby improving business performance.

Theme 3: Barriers and Challenges to Implementing DfMA with BIM and Lean

Sub-theme 1: Upfront Investment Costs

Several participants pinpointed the initial investment costs associated with BIM software and DfMA infrastructure as a potential barrier (P2, P4). Compared to traditional methods, BIM and DfMA require upfront investments in technology and training, which some smaller companies might find challenging, as noted by P3. These findings align with research by Gupta et al. (2018) who identified upfront investment costs as a significant barrier to BIM adoption in the construction industry. Sufficient investment in digital technology is required to further enhance DfMA.

Sub-theme 2: Collaboration and Integration Challenges

The findings showcase the challenges of collaboration and information exchange across teams in the construction industry, particularly when integrating BIM, Lean, and DfMA methodologies. Participants highlighted the necessity for effective communication and collaboration among diverse stakeholders such as architects, engineers, and fabricators (P1, P5, P4). The Forge case study by TataSteel (2022) further emphasised the importance of establishing clear communication protocols during the DfMA process.

The construction industry's traditionally siloed and fragmented nature exacerbates these collaboration challenges (Khoiry et al., 2018). Unlike other sectors, the construction industry has been slow to adopt innovation, facing hurdles due to its highly fragmented nature, complex processes, dynamic business environment, and multi-stakeholder approach, as noted by Li et al. (2019). Despite the advantages offered by DfMA, effective implementation requires overcoming obstacles such as communication barriers, collaboration issues, information-sharing difficulties, and conflict resolution challenges (Qi & Costin, 2023).

Sub-theme 3: Resistance to Change

Resistance from traditional contractors and a lack of awareness regarding DfMA benefits were noted as potential barriers (P3). Established construction companies may be hesitant to adopt new methodologies due to a comfort zone with traditional practices, as explained by P2. These findings align with research by Wong et al. (2016) who identified resistance to change as a common hurdle in construction innovation.

Conclusion

In conclusion, DfMA, coupled with BIM and Lean principles, presents a transformative approach to sustainable construction. By promoting resource efficiency, minimising waste across all project stages, and optimising construction processes, this methodology paves the way for a more sustainable future for the building industry.

Recommendation

1. Develop standardised guidelines and best practices for BIM, Lean, and DfMA integration to benefit all stakeholders
2. Highlight successful case studies displaying the benefits of DfMA with BIM and Lean to encourage industry buy-in.
3. Integrate Artificial Intelligence (AI) and machine learning into BIM to further optimise design, reduce waste, and enhance DfMA integration.

REFERENCES

1. 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.
2. Abrishami, S., & Martín-Durán, R. (2021). BIM and DfMA: A paradigm of new opportunities. *Sustainability*, 13(17), 9591.
3. 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
4. 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:
5. https://www.mckinsey.com/capabilities/operations/our-insights/reinventing-construction-through-a-productivityrevolution (accessed March 9, 2024).
6. Boothroyd, G. (2005). Assembly automation and product design. crc press.
7. Bryden Wood (2024). The Forge. Available online: https://www.brydenwood.com/projects/the-forge/s93059/
8. 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
9. 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
10. Dubisz, D., & Rokicki, R. (2022). Standardisation of logistic units in terms of increasing the efficiency of the reverse supply chain of returnable packaging. European Research Studies Journal, 25(2B), 428-438.
11. Edwards, K. L. (2002). Towards more strategic product design for manufacture and assembly: priorities for concurrent engineering. Materials & design, 23(7), 651-656.
12. Gao, S., Low, S. P., & Nair, K. (2018). Design for manufacturing and assembly (DfMA): a preliminary study of factors influencing its adoption in Singapore. *Architectural Engineering and Design Management*, 14(6), 440–456. https://doi.org/10.1080/17452007.2018.1502653
13. Gbadamosi, A. Q., Mahamadu, A. M., Oyedele, L. O., Akinade, O. O., Manu, P., Mahdjoubi, L., & Aigbavboa, C. (2019). Offsite construction: Developing a BIM-Based optimiser for assembly. Journal of cleaner production, 215, 1180-1190. https://doi.org/10.1016/j.jclepro.2019.01.113
14. 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.
15. Jung, S., & Yu, J. (2022). Design for Manufacturing and Assembly (DfMA) Checklists for Off-Site Construction (OSC) Projects. *Sustainability*, 14(19), 11988.
16. Kim, M. K., McGovern, S., Belsky, M., Middleton, C., & Brilakis, I. (2016). A suitability analysis of precast components for standardised bridge construction in the United Kingdom. Procedia engineering, 164, 188-195. https://doi.org/10.1016/j.proeng.2016.11.609

17. 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

18. Liu, Z. Q., Zhang, F., & Zhang, J. (2016). The building information modeling and its use for data transformation in the structural design stage. Journal of Applied Science and Engineering, 19(3), 273-284. https://doi.org/10.6180/jase.2016.19.3.05

19. 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

20. Medyński D, Bonarski P, Motyka P, Wysoczański A, Gnitecka R, Kolbusz K, Dąbrowska M, Burduk A, Pawelec Z, 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

21. 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

22. 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.

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

24. Nguyen, B. N., London, K., & Zhang, P. (2021). Stakeholder relationships in off-site construction: a systematic literature review. *Smart and Sustainable Built Environment*, *ahead-of-print*(ahead-of-print). https://doi.org/10.1108/sasbe-11-20200169

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

26. Qi, B., & Costin, A. (2023). BIM and Ontology-Based DfMA Framework for Prefabricated Component. *Buildings*, *13*(2), 394. https://doi.org/10.3390/buildings13020394

27. Qi, B., & Costin, A. (2023). BIM and Ontology-Based DfMA Framework for Prefabricated Component. *Buildings*, *13*(2), 394. https://doi.org/10.3390/buildings13020394

28. Rankohi, S., Bourgault, M., Iordanova, I., & Carbone, C. (2023). Developing a construction-oriented DfMA deployment framework. *Buildings*, 13(4), 1050.

29. 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

30. Sir Robert McAlpine (2022). The Forge, Landsec's first net zero office, opens in London. Available online: https://www.srm.com/news-and-comment/the-forge-opens-in-london/

31. Sternberg, H., Stefansson, G., Westernberg, E., af Gennäs, R. B., Allenström, E., & Nauska, M. L. (2013). Applying a lean approach to identify waste in motor carrier operations. International Journal of Productivity and Performance Management, 62(1), 47-65.

32. Succar, B., Sher, W., & Williams, A. (2012). Measuring BIM performance: Five metrics. Architectural Engineering and Design Management, 8(2), 120-142. https://doi.org/10.1080/17452007.2012.659506

33. Sun, Y., Wang, J., Wu, J., Shi, W., Ji, D., Wang, X., & Zhao, X. (2020). Constraints hindering the development of high-rise modular buildings. *Applied Sciences*, 10(20), 7159.

34. TataSteel (2024). The Forge, Southwark, London. Tata Steel in Europe.

35. https://www.tatasteeleurope.com/construction/case-study/the-forge-southwark-london

36. Wong,K.&Fan,Q.(2013), "Building information modelling (BIM) for sustainable building design", *Facilities*, Vol. 31 No. 3/4, pp. 138-157. https://doi.org/10.1108/02632771311299412

37. 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

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