EVALUATION OF THE EFFECTIVENESS OF COLLABORATIVE APPLICATION OF BIM AND LEAN IN PROMOTING SUSTAINABLE CONSTRUCTION PRACTICES THROUGHOUT THE DFMA PROCESS.

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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: Collaborative Application, Bim, Lean, Sustainable Construction Practices, And Dfma Process.

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 review will investigate how DfMA promotes resource efficiency and waste reduction through prefabrication. It will then enumerate BIM's role in fostering collaboration, optimising design, and minimising rework. Finally, the integration of Lean principles with construction processes will be examined, focusing on waste minimisation and workflow streamlining.

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. 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.

OBJECTIVE

- To evaluate the effectiveness of a collaborative application of BIM and Lean in promoting sustainable construction practices throughout the DfMA process.

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.

BUILDING INFORMATION MODELLING (BIM)

BIM, as defined by NBS (Hamil, 2021), is a process managing construction project information throughout its lifecycle, utilising digital representations and suitable technologies (Eastman et al., 2011). This involves detailed 3D models and structured data covering products, execution, and handover. BIM enhances design and construction capabilities, fostering integrated processes and resulting in higher-quality buildings, cost reduction, and shorter project durations (Eastman et al., 2011). Research highlights BIM's potential for project coordination, error minimisation, stakeholder communication, and informed decision-making (Azhar et al., 2011; Succar et al., 2009; Eastman et al., 2011), leading to cost savings, schedule optimisation, and improved building performance (Azhar et al., 2011).

BIM facilitates integrated project delivery (IPD) and design optimisation, critical components for efficiently producing green building designs (Wong & Fan, 2013). Additionally, BIM is a technology that enables the embedding of expert knowledge into systems and models, utilizing engineering databases, parametric modelling, and interoperability technologies to manage knowledge effectively in the construction industry (Lee, 2022). It contributes to sustainable decision-making in building procurement and management by facilitating the storage, sharing, and integration of essential building information throughout the entire life cycle (Oloke, 2021).

In the UK, BIM implementation in residential projects offers benefits such as quality assurance, collaboration improvement, and visual representation, despite facing challenges related to financial barriers, lack of strategic leadership, and fragmentation in the construction industry (Georgiadou, 2019). Furthermore, BIM's capabilities include the use of precise and updated information for construction solutions, particularly in energetic simulations, supporting decision-making during project development.

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.

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.

LEAN CONSTRUCTION

Lean Construction, as defined by the Lean Construction Institute (2024), is a management philosophy focused on eliminating waste and optimising value-adding processes to improve project delivery and meet customer needs. This approach, centred on the "Transformation-Flow-Value" (TFV) production system, aims to streamline resource flow and enhance value creation (Koskela et al., 2022). By identifying and eliminating wasteful tasks, Lean Construction enhances manageability, safety, completion times, costs, and quality in construction projects. This focus on waste minimisation and maximised productivity through efficient production systems leads to improved manageability, safety, faster completion times, lower costs, and higher quality in Lean Construction projects (Abdelhamid et al., 2008). Lean construction categorizes waste into seven distinct categories: excessive inventories, unnecessary transportation, delay defects, excess production, unhelpful movement of people, and excess processing (Al-Aomar, 2012).

While traditionally focused on financial metrics, Lean principles are increasingly recognized for their contribution to environmental sustainability in construction (Rosarius & García de Soto, 2021). This alignment stems from lean's core tenet: waste reduction. Integration of lean construction and sustainable construction principles in the construction industry leads to diverse benefits, including sustainable competitive advantage, enhanced process flow, and increased productivity and common lean tools and techniques, such as just-in-time, visualisation tools, value analysis and value stream mapping, facilitate sustainability (Ogunbiyi et al., 2014). This integration also establishes links between lean and sustainability in waste reduction, environmental management, value maximisation, and health and safety improvement. Lean practices promote resource efficiency through optimised designs, improved production procedures, and local material sourcing, and eliminating wastes in logistics (Sternberg et al., 2013). This reduces reliance on external resources, minimises transportation distances, and lowers embodied carbon emissions in DfMA projects. The construction industry noted to struggles with resource inefficiency Lean construction addresses these challenges through:

- **Reduced resource allocation:** Lean principles prevent wasteful allocation of equipment, materials, and labor on DfMA construction sites.
- **Minimised material loss:** Improved site management and material handling practices minimise material waste and deterioration.
- **Eliminated waiting times:** Lean workflows aim to eliminate delays and waiting times, leading to smoother project flow and reduced resource waste.
- **Sustainable logistics:** Lean principles are effective in identifying and eliminating waste within logistics operations, improving business performance, and minimising the environmental impact of DfMA projects.

By promoting waste reduction, resource efficiency, and sustainable logistics, Lean construction offers a powerful tool for achieving environmental sustainability in DfMA projects. Further research can explore how specific Lean practices integrate with DfMA workflows to maximise these environmental benefits.

EMBEDDING LEAN IN DFMA

Lean principles can be embedded within DfMA's philosophy. For instance, Banks et al. (2018) considered lean supply chain management in high-rise building design, and Ramaji et al. (2017) optimised assembly parts and geometry for a dormitory project using DfMA and Lean principles. Ogunbiyi et al. (2014) further highlightminimi the shared benefits of DfMA and Lean in the AEC industry, including reduced construction costs and efforts, and increased productivity.

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

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).

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).

FINDINGS AND DISCUSSION

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. Participants further elaborated on the value of BIM in DfMA projects. P1 highlighted its role in streamlining production. BIM-based DfMA tools have demonstrated effectiveness in waste reduction and sustainability promotion by involving clients directly in the initial decision-making process (Bakhshi et al., 2022; Yazdi et al., 2021). P5 emphasises BIM's role in promoting collaboration and standardisation within construction projects. They describe BIM as a framework for project delivery "If you take building information modelling as a process on how you deliver a building, a lot of it is about setting out this is how we are going to work from the outset. And that gives you a framework to then create the building itself".

The UK government's mandate for BIM Level 2 in public projects (Bew & Richards, 2008) emphasises its importance in DfMA. Akob et al. (2019) noted that this collaborative approach fosters significant efficiency gains and reduces waste throughout construction. The resulting cost and resource savings contribute to both economic and environmental sustainability in DfMA projects.

Participants also highlighted BIM's role in promoting sustainable construction practices. P2 emphasised BIM's contribution to waste reduction. P1 mentioned BIM's potential for life cycle assessment. Moreover, BIM models can quantitatively measure the energy efficiency of proposed infrastructure (Eastman, 2011).

BIM serves as a cornerstone for streamlined and DfMA workflows and sustainable construction practices. By facilitating collaboration, minimising errors, and enabling early design optimisation, BIM empowers project teams to achieve cost and resource efficiency throughout the building life cycle.

Sub-theme 2: BIM and Lean Integration

The integration of BIM and Lean principles emerged as a powerful driver for optimising DfMA processes. Participants acknowledged the combined benefits of these methodologies (P1, P5). BIM facilitates data-driven decision-making, while Lean fosters continuous improvement, creating a perfect synergy for optimising DfMA workflows (P4). The Boiler House project exemplified this successful integration, demonstrating how BIM and Lean can work together to reduce waste and optimise DfMA processes (Eurban Ltd, 2024). These findings align with research by Alarcon et al. (2010) who highlight the synergistic relationship between BIM and Lean in achieving sustainable construction goals.

BIM and Lean offer a complementary approach to DfMA. By leveraging BIM's data-driven capabilities and Lean's focus on continuous improvement, construction projects can achieve significant efficiency gains, minimise waste, and contribute to a more sustainable building industry.

CONCLUSION

The integration of BIM and Lean principles further strengthens DfMA's sustainability potential. BIM facilitates accurate design and analysis, enabling project teams to optimise material usage and minimise environmental impact from the outset. BIM's clash detection capabilities also contribute to sustainability by minimising errors and rework during construction, reducing wasted materials and associated environmental burdens. Lean principles, with their focus on continuous improvement and waste reduction, perfectly complement DfMA. By streamlining production processes and optimising resource allocation, Lean practices minimise waste throughout the construction cycle. Moreover, Lean's emphasis on continuous improvement encourages ongoing efforts to identify and implement even more sustainable practices throughout the building life cycle. While DfMA offers a compelling approach, challenges such as integrating complex supply chains and overcoming skills shortages require attention. Addressing these challenges through targeted education, training programs, and industry-wide collaboration is crucial for the widespread adoption of DfMA and its associated sustainability benefits.

RECOMMENDATIONS

- Foster collaboration and communication among project stakeholders to ensure buy-in and commitment to sustainable construction. This may include changing procurement methods to agreements such as IPD and IPI
- Public Funding for Research and Development: Allocate public funding for research and development in BIM, Lean, and DfMA technologies to accelerate innovation and cost reduction.
- Develop advanced BIM capabilities for real-time data analytics and lifecycle management to promote sustainable construction practices.
- Utilizing environmentally friendly materials with low embodied carbon footprints.
- Integrate Artificial Intelligence (AI) and machine learning into BIM to further optimize design, reduce waste, and enhance DfMA integration.

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