MODULAR AND OFFSITE CONSTRUCTION SUMMIT
JULY 27-29, 2022 EDMONTON, CANADA

Design-for-Manufacturing-and-Assembly (DfMA) for the Construction Industry: A Review

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ABSTRACT

Applying Design for manufacture and assembly (DfMA) principles in building has gained attention in recent years. Studies reported that the application of DfMA in building projects can significantly enhance overall productivity. However, the literature on DfMA in the construction industry is still limited. This paper aims to provide an updated and comprehensive review of DfMA approach and its applicability in the construction industry. Web of science, and Google Scholar databases were used to obtain relevant articles from the literature. The study is based on a systematic review of 52 selected articles through search keywords for DfMA. The bibliometric results mapped the research publications by year, journal, and country in which the DfMA study is conducted. The thematic analysis results revealed the research themes and trends. In conclusion, the DfMA literature has increasingly focused on integration and sharing of information during project life-cycle to optimize design, manufacturing, and assembly, and to address issues relating to the integration of off-site manufacturing with on-site assembly. Finally, the review is concluded by providing recommendations for researchers and practitioners, and by identifying future works and opportunities for the application of DfMA in the construction industry. The results of this paper can help future theoretical and empirical research and developments.

KEYWORDS

Design-for-Manufacturing-and-Assembly; DfMA; Industrialized building; Offsite Construction; Literature review

INTRODUCTION

DfMA is well-developed in the manufacturing industry, however in the construction industry, it is an emerging design and production strategy, which is focused on using the design to control and improve product performance while enhancing production efficiency (Lu et al., 2020). As an emerging topic, the literature on DfMA in the construction industry is still limited. A comprehensive review of the topic which captures the latest themes and trends is lacking from the literature, as the latest published review studies only covered up to 2020 (Gao et al., 2020; Lu et al., 2020; Wasim et al., 2020; Ofori-Kuragu and Osei-Kye, 2021). This current review provides a comprehensive literature review of DfMA in the construction industry up to 2022. This review's objectives are: (1) to synthesize the state-of-the-art of applying DfMA in the construction industry, and (2) to find main benefits and challenges of applying DfMA in construction projects. This goal

is achieved by classifying the literature and identifying authors' research themes. In conclusion section, a summary of the important points are presented.

METHODOLOGY

To conduct a comprehensive review and extract challenges, a systematic literature review (SLR) method was applied. An example of a mixed method, the study encompasses: the selection of databases and subsequently 52 articles on the topic of DfMA in the construction industry (Methodology), the review of the articles and identification of their quantitative characteristics (Bibliometric Analysis), our thematic study and the categorization of identified themes (Thematic Analysis), and our discussion about benefits, challenges, and future areas of studies (Discussion). Finally, the paper is concluded with recommendations being provided for researchers and practitioners (Conclusion).

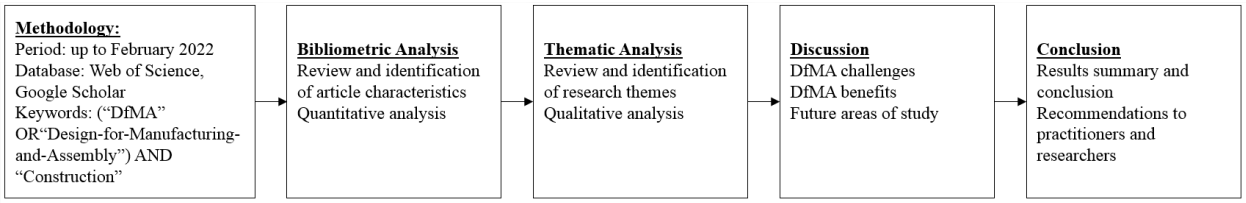

Figure 1. Methodology process of this study.

A SLR was conducted in two phases: (1) retrieve previous works from the academic database using pre-defined keywords; (2) filter the selected articles to include those that focused on DfMA in the construction domain. We selected Web of Science, and Google Scholar, for conducting a comprehensive study of journal papers. For keywords we considered a combination of terms, including "DfMA", "design for manufacture and assembly", "design for manufacture", "design for assembly", "architectural design", and "construction industry." To maintain a high quality, this study only contains peer-reviewed articles published in construction engineering related journals, and conferences proceedings are excluded.

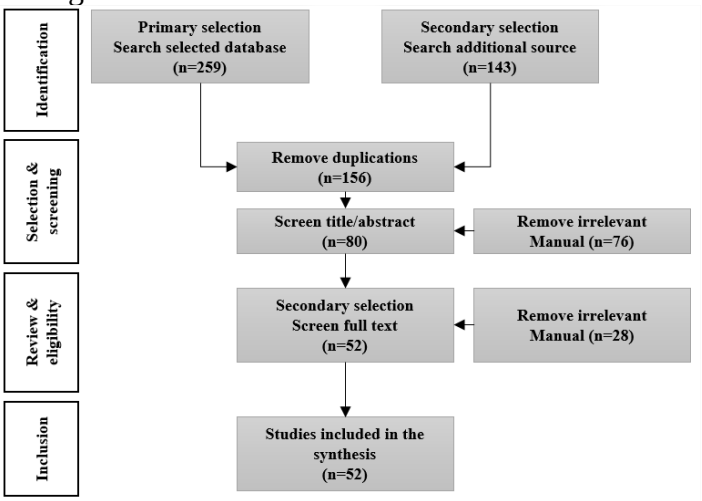

Figure 2. The PRISMA diagram for the process of selecting journal articles.

To capture all DfMA research in the construction domain, the period of publication was not limited to certain years, and the study covers all previous years up to the present, February 2022. In the screening process, a multi-stage filtering method is conducted to extract relevant articles from the initial general searching results. In each stage, each article's keywords and abstracts were reviewed to check whether they were in the scope of this study. Finally, only the articles whose main

research focus was on DfMA in the construction industry were included. A total of 259 articles were found in the searched databases. After multiple screening of the articles by authors and excluding articles such as Subject Index and Editors Notes, the total number of selected articles was 52. The article selection process is depicted in the PRISMA diagram (Moher et al., 2009) in Figure 2.

BIBLIOMETRIC ANALYSIS

The distribution of articles by journal and year are shown in Figure 3. Among the journals, *Automation in Construction* has the highest number of articles (13%) while *Architectural Engineering and Design Management* and *Sustainability/Building Engineering* have 10% and 8% respectively. The maximum percentage of papers in a single year were published in 2021 (42%).

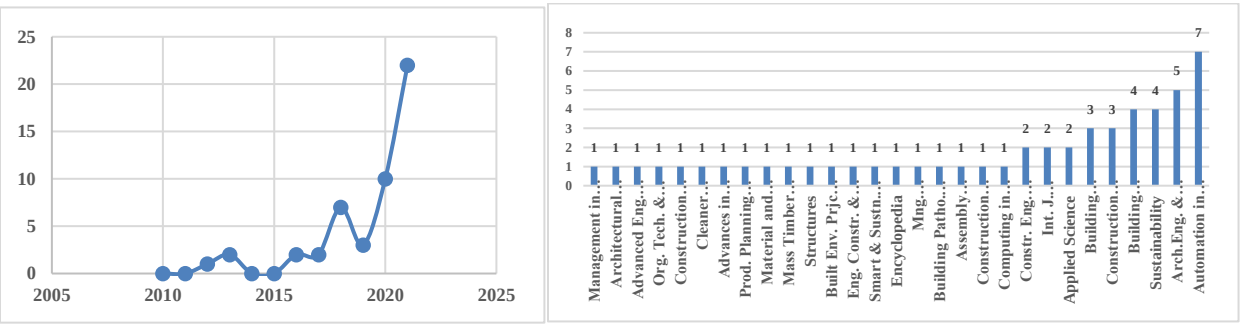

Figure 3. Left: total number of articles by year; right: total number of articles by journal.

The other characteristic identified in this section is the number of articles based on the country of the institution to which the first author is affiliated. With 15 articles, first authors residing in the UK have the majority of the articles about DfMA in the construction industry. The remaining counts are: 10 first authors residing in Australia; 7 in Hong Kong; 6 in US; 5 in Canada; 4 in China; 3 in each of Sweden, Singapore, Italy; and 2 in each of Spain, Finland, Switzerland, Denmark, Germany, and Iran.

THEMATIC ANALYSIS

The qualitative content analysis is conducted to elucidate content and data through a classification process of coding and theme identification, followed by a thematic analysis which helped generate new interpretive constructs and descriptions based on the articles' underlying themes (Ekanayakeet al. 2020). As shown in Figure 4, four DfMA research themes are identified- technology, application, project life-cycle, and prefabrication- and discussed in this section.

DfMA Technologies

The first theme is *technology*. A majority of studies discussed technological requirements for applying DfMA in construction projects (Marinelli, 2022; Favi et al., 2021; Wasim et al., 2020). This theme can be divided in three sub-themes: technical issues, proposed system technological requirements, and technology application demonstration. We group the technology applications as follows: visualization or simulation, real-time information sharing, communication or collaboration, and training or safety (Bakhshi et al., 2022).

DfMA Application Areas

The second theme is *application* areas. Many studies discussed the application areas of DfMA method in construction projects, and provided case study evidence to support their findings. The most cited application areas are: design optimization (Gao et al., 2020), quality assurance (Wuni

et al., 2020), automation (Yazdi et al., 2022), supply chain integration (Li et al., 2021), assembly techniques improvement (Soh et al., 2021), cost-scheduling optimization (Bakhshi et al., 2022).

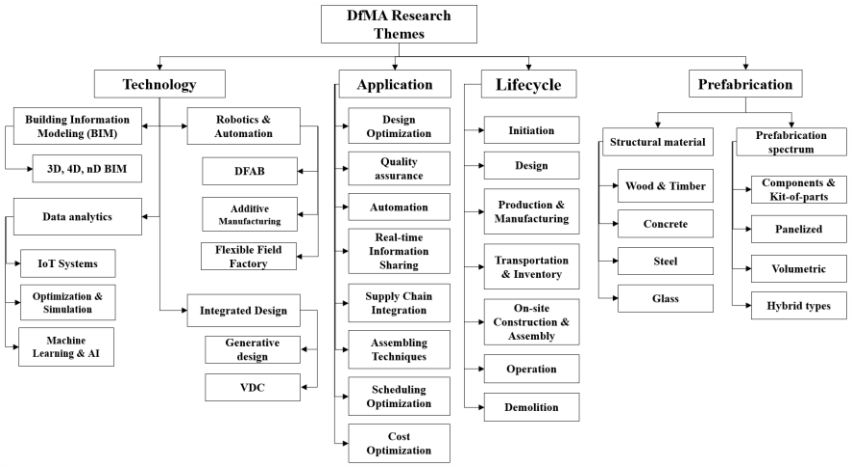

Figure 4. Identified themes in DfMA literature.

DfMA and Project life-cycle

The third theme is project *life-cycle*. A construction project's life cycle consists of a sequence of stages to be completed in order to reach project goals. These stages are defined by RIBA (2020) as: definition, preparation and briefing, concept design, spatial coordination, detailed design, manufacturing/construction, handover, and use/operation. In this study, we considered the end of service life / demolition / deconstruction phase as well, to ensure the comprehensiveness of results related to the impact of DfMA on circular economy and sustainability. Literature shows that the majority of studies discussed the impact of DfMA method in various project phases, from which, design, manufacturing, and site assembly stages garnered the most attention (Lu et al., 2021; Gao et al., 2020; Wuni et al., 2020; Alfieri et al., 20220).

DfMA and Prefabrication

The fourth theme is *prefabrication*. DfMA principles have been applied to variety of prefabricated projects for various materials. Literature shows that many studies discussed the application of DfMA in prefabricated and offsite construction projects (Bao et. al. 2021; Vaz-Serra et al., 2021; Tan et al., 2021). The majority of studies discussed DfMA techniques for improving steel and timber panelized prefabricated projects, while other studies focused on component based, kit-of-parts, and volumetric modular strategies.

RESULTS AND DISCUSSION

Based on the results of this study five major benefits and nine major challenge groups are identified, which might be encountered during the implementation of DfMA in various phases of construction projects.

Benefits

Several benefits are identified in the DfMA literature as: *improved quality; reduced fabrication and construction cost; reduced construction time; reduced construction labor and improved health and safety; enhanced Sustainability and circular economy*. Literature shows DfMA can improve the quality of construction projects throughout the design to manufacturing and construction phases (Bao et al., 2021; Favi et al., 2017). DfMA optimization reduces the cost of construction projects. Many studies have identified the impacts of DfMA research on cost reduction in the

construction industry (Lu et al., 2020; Tan et al., 2020; Wasim et al., 2020). Several studies about applying DfMA in production, supply chain, and assembly, reported reduced construction period (Yin et al., 2019; Yuan et al., 2018; Qi et al., 2021). The majority of these studies applied a combination of advanced technologies (IoT, RFID, BIM, Cloud), optimization techniques and simulation algorithms. Literature states that the application of DfMA increases labor productivity by reducing or eliminating labor-intensive tasks on-site (Bakhshi et al., 2022; Machado et al., 2016). This results in improvements in health and safety during onsite assembly. Finally, few studies focused on sustainability and the environmental impact of applying DfMA in construction projects (Favi et al., 2017; Gao et al., 2018). In particular, studies with focus on DfD indicate increased sustainability as an impact of DfMA on reducing construction waste and carbon emissions, and improving circularity.

Challenges

Literature reports that the application of DfMA is still marginal (Bao et al., 2021; Wasim et al., 2021). Existing literature provided little information about DfMA adoption in the construction sector. However, a few barriers have been identified so far: community resistive mindset (Montali et al., 2018); unsupportive embedded industry practices (Lu et al., 2020); lack of regulations and incentives by governmental bodies (Chen et al., 2018); lack of proper planning and building codes (Bao et al., 2021); knowledge limitations and organizational readiness (Gerth et al., 2013); inefficient supply chain management (Tan et al., 2020); lack of suitable delivery method and contracting strategy (Vas Serra et al., 2019); and lack of suitable technical requirements (Bakhshi et al., 2022).

Limitation of this study

This review is limited to the English literature only and journal articles identified through searching the Web of Science, and Google Scholar databases. However, adding conferences papers and industry reports can increase the value of the results. There is a lack of empirical studies on implementation of DfMA in the construction literature, as there is not enough projects in which this strategy has been applied. A review and synthesise of more empirical studies could help scholars and industry practitioners to address current challenges to the implementation of this method.

Future areas of study

DfMA cannot work efficiently in isolation. More studies on the combination of DfMA with newly developed technologies (IoT, 3D printing, nD BIM, digital cloud-based platforms, etc.), delivery methods (integrated project delivery, progressive design-build, etc.), and business models (spin-off company, virtually integrated, etc.) are required. Based on the results, this study proposes the following directions for future research:

Collaborative information sharing systems: there is an increasing collaborative and integrative trend in construction management studies, and this applies to DfMA literature as well (Bakhshi et al., 2022; Qi et al., 2021). To improve adoption of DfMA method in construction projects, more studies on collaborative information sharing systems on multiple levels (project, organization, and industry) are required.

Technological adaptation: literature shows very little empirical research exists on DfMA technological adaptation in construction sector. Initial research efforts on this topic are focused on the combination of BIM, and cloud-based technologies with DfMA (Tan et al., 2020; Gbadamosi et al., 2019). More in-depth research and multiple case studies for the application of AI, big data

analytics, block-chain, and IoT technologies are required for improving DfMA's adaptation and applicability in the industry.

Flexible supply chain: As the construction industry encounters uncertainties (i.e., Covid-19 crisis), supply-chain flexibilities become vital (Hall et al., 2018). More studies on developing dynamic, agile and practice-oriented DfMA models are required to improve supply-chain visibility, integration, flexibility, agility, and circularity.

Generative design: Few studies (Qi et al., 2021; Wei et al. 2021; Li et al., 2021) stated that the integration of DfMA with BIM-based generative design can enhance automation and optimize the design for prefabricated and offsite construction projects. In fact, the combination of DfMA with BIM-based generative design provides a promising path to automation and AI-based BIM application for the modular construction.

Design for robotics and 3D printing: due to increasing labour costs and the population aging crisis existing around the world, robotics and 3D printing are essential tools for the future of the construction industry (Estakhrianhaghighi et al., 2020). However, the current industry situation is not prepared for the full scale application of these techniques. The integration of DfMA and BIM with robotics and 3D printing, can increase the level of automation and productivity even with current labour issues. More studies required in this regard.

CONCLUSION

This paper presented a comprehensive review of the DfMA concepts and applications in the construction industry. A structured methodology was used to identify the most recent applications, benefits, and challenges of applying DfMA in offsite construction. The literature has focused on optimization applications during the design and manufacturing phases of projects. The application of DfMA method from a principal role in the design and manufacturing phases to other phases will be expanded, particularly to the procurement phase. The continued growth in the use of BIM and cloud-based platforms for visualization and sharing of information is expected. We also speculate that the up-front cost of adoption of DfMA in construction projects, will become less of an obstacle to its widespread use. The following results are concluded:

Bibliometric analysis results:

- Databeses: Automation-In-Construction has the highest overall number of articles among the journals, while the *Architectural Engineering and Design Management* and *Sustainability/Building Engineering* got the second and third places. The biggest number of DfMA articles published in a single year, occurred in 2021.
- Countries: UK was the dominant country in which DfMA studies are conducted.

Thematic analysis results:

- Technology: The majority of articles focus on DfMA adoption technical requirements, and technology application in construction projects, with less articles focusing on systems technological development.
- Application areas: Over half of the articles had a principal focus on design optimization, supply chain integration or information access/sharing.
- Project life-cycle: The main focus is on the design and manufacturing phases.
- Prefabrication: DfMA literature emphasized on the application of DfMA for prefabricated construction from components/kit-of-parts, to panelized and volumetric modules. In terms of material, steel and wood have got the most attention, while several authors studied the application of DfMA for pre-cast concrete beams, and glass curtain walls.

In summary, this study synthesized the state-of-the-art of applying DfMA in the construction industry and identified main benefits and challenges of applying DfMA in construction projects.

ACKNOWLEDGEMENTS

This research is funded by scholarships from the Fonds de Recherche du Québec, Nature et Technologies (FRQNT), Pomerleau Industrial Research Chair in Innovation and Construction Governance at Polytechnique Montréal, and The Québec Wood export bureau through Industrial research grants provided by CNRC, whose supports are gratefully acknowledged.

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