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A Comparative Analysis of Design for Manufacturing And Assembly (DFMA) Implementation Challenges In On-Site Construction (ONSC) and Off-Site Construction (OSC)

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Abstract: Design for Manufacturing and Assembly (DfMA) offers a transformative approach to enhance productivity in the construction industry. Although the benefits of DfMA are widely recognized, challenges remain in the integration of its principles throughout the different stages of construction projects, which include both off-site construction (OSC) and on-site construction (OnSC). This paper presents a focused analysis of the challenges encountered in integrating DfMA into construction projects, with a particular emphasis on OnSC projects. Through a qualitative comparative analysis (QCA) approach and by using the literature review and expert interviews, this study conducts a comparative analysis between the identified challenges in OnSC and those common in OSC. By identifying the complexities of DfMA implementation in OnSC projects and conducting a comparative assessment with DfMA challenges in OSC, this study illuminates the evolving nature of DfMA practices. It sheds light on how these practices are adapting in response to the unique demands and characteristics of both OSC and OnSC. The results of this study have the potential to provide organizations with guidance for the successful implementation of DfMA strategies across all project phases, resulting in increased productivity. In doing so, the research contributes insights to the fields of construction management and innovation.

Keywords: Design for manufacturing and assembly (DfMA), Off-site construction (OSC), On-site construction (OnSC), Productivity, Challenges

1 INTRODUCTION

The construction industry has consistently underperformed in productivity compared to the global economic and manufacturing sectors (McKinsey Global Institute 2017). Design for Manufacturing and Assembly (DfMA) has gained significant attention in the construction industry due to its potential to improve efficiency, productivity, and quality (Goulding et al. 2015). In recent years, there has been a growing focus on DfMA-oriented design in research related to modular and prefabricated construction projects, where a significant portion of building components are produced off-site and subsequently transported to construction sites for assembly (Chen and Lu 2018).

However, the implementation of DfMA in construction projects faces various challenges (Rankohi et al. 2023), which may differ depending on whether the construction is carried out on-site (OnSC) or off-site (OSC). This paper compares the challenges identified in DfMA implementation for OnSC with those identified in previous studies for OSC. In this study, "on-site construction (OnSC)" is defined as the work carried out on the actual project site, both as a part of OSC projects and those involving unique OnSC methodologies.

By examining the challenges for implementing DfMA in OnSC, the study seeks to gain a comprehensive understanding of the similarities and differences in DfMA adoption for OSC, considering all phases of a construction project, including on-site components.

This paper is structured in such a way as to facilitate a comprehensive understanding of the topic. In the first section, a ‘Literature Review’ provides an overview of DfMA in construction. Afterward, the 'Methodology' section reveals the research strategy and the techniques utilized when collecting and analyzing data. Next, in the 'Research Findings and Discussion' section, the data analysis is explained, highlighting key results and their implications. As a final section, the 'Conclusion' section summarizes the study's main conclusions and contributions, while emphasizing significant results.

2 LITERATURE REVIEW

It was in the late 1960s and early 1970s that formal approaches to Design for Manufacturing (DfM) and Design for Assembly (DfA) emerged (Bogue 2012). The DfMA approach has been widely applied for many years in the automobile, aerospace, general mechanical, and various other manufacturing industries to develop products (Vaz-Serra, Wasim, and Egglestone 2021). Recently, the Architecture, Engineering, and Construction (AEC) industry has started to investigate the DfMA process. As a methodology, DfMA emphasizes simplicity and minimizes materials, labor, and manufacturing-related activities (Wasim, Vaz Serra, and Ngo 2022). According to Boothroyd (1994), DfMA addresses the issue of fragmentation within the construction industry.

Various scholars (Boothroyd 1994; Bogue 2012; Vaz-Serra, Wasim, and Egglestone 2021) have noted that the methodology of DfMA relies on specific guidelines, standards, and rules, with various policies implemented to facilitate its effective implementation. Typically, the key principles of DfMA include minimizing, standardizing, and modularizing components (Song, Kuo, and Chen 2022).

Numerous studies highlight the advantages of DfMA, including cost and time reduction (Tan et al. 2020; Lu et al. 2021), improved quality (FAVI, GERMANI, and MANDOLINI 2017; Bao et al. 2022), reduced construction labor (Machado, Underwood, and Fleming 2016; Bakhshi et al. 2022), and better waste management (Roxas et al. 2023). Despite these benefits, the adoption of DfMA in the construction industry faces several challenges. Resistance to change and a preference for traditional construction methods (Montali et al. 2018; Langston and Zhang 2021), a lack of government support and incentives (Chen and Lu 2018), higher initial costs, strict government regulations, and risk aversion (Langston and Zhang 2021), as well as inadequate technical standards (Bakhshi et al. 2022), are notable obstacles.

Although current research offers insights into DfMA's application in OSC, there is still a considerable lack of understanding regarding its challenges and opportunities in OnSC settings. This deficiency is particularly significant considering the persistent low productivity levels in the construction industry compared to other industries. Furthermore, while the benefits of DfMA in improving productivity, efficiency, and quality in OSC are recognized, its wider implementation in OnSC—where processes and integration often necessitate hands-on management at project sites—remains underexamined. This paper seeks to address this gap by comparing the obstacles to implementing DfMA in OSC and OnSC environments.

3 METHODOLOGY

To conduct this study, a qualitative comparative analysis (QCA) approach was used. QCA is a methodological approach and a collection of research tools that blend in-depth analysis of individual cases with systematic comparisons across cases (Legewie 2013). A Systematic Literature Review (SLR) and Semi-structured interviews with industry experts were conducted to identify the challenges faced in DfMA implementation for both OnSC and OSC in the prior study done by the quthors. The identified challenges were then categorized and analyzed to identify commonalities and differences between the two construction approaches. The analysis categorized main challenges into nine categories such as Economic and Financial, Technological, Legal Contractual, Technical Cognitive, Procedural, Cultural, Geographical, Policy and Commercial. Figure 1 illustrates the methodological approach flowchart for this research.

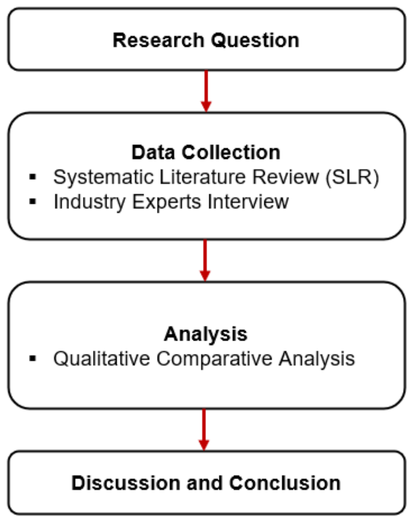

Figure1: Methodological approach flowchart

4 RESEARCH FINDINGS AND DISCUSSION

According to Abd Razak et al. (2022) most conversations around DfMA concentrate on off-site prefabrication. However, there should be guidelines for on-site fabrication and prefabrication as well, since not all projects are feasible for OSC, yet they could still gain from the principles of DfMA design. Figure 2 shows the proposed conceptual framework of DfMA challenges in OnSC projects. This conceptual framework, which consists of main DfMA challenges and their respective sub-challenges in OnSC, was developed in a prior study conducted by the authors. In this paper, we utilize the framework to aid in the comprehension of our comparative analysis. The framework categorizes the challenges into nine main categories, as shown in Figure 2, with distinctions between OnSC and OSC challenges visually indicated by a red dashed format. This delineation is critical as it underscores the unique and shared hurdles faced in both construction settings, thus providing a structured basis for our analysis.

The comparative analysis revealed several similarities and differences in the challenges in implementing DfMA implementation for OnSC and OSC in each main nine categories. Common challenges included the need for effective project planning and coordination, efficient logistics management, and skilled workforce training. However, there were also notable differences, such as the unique challenges of transporting and assembling off-site manufactured components in OSC, compared to the challenges of coordinating on-site construction activities in OnSC.

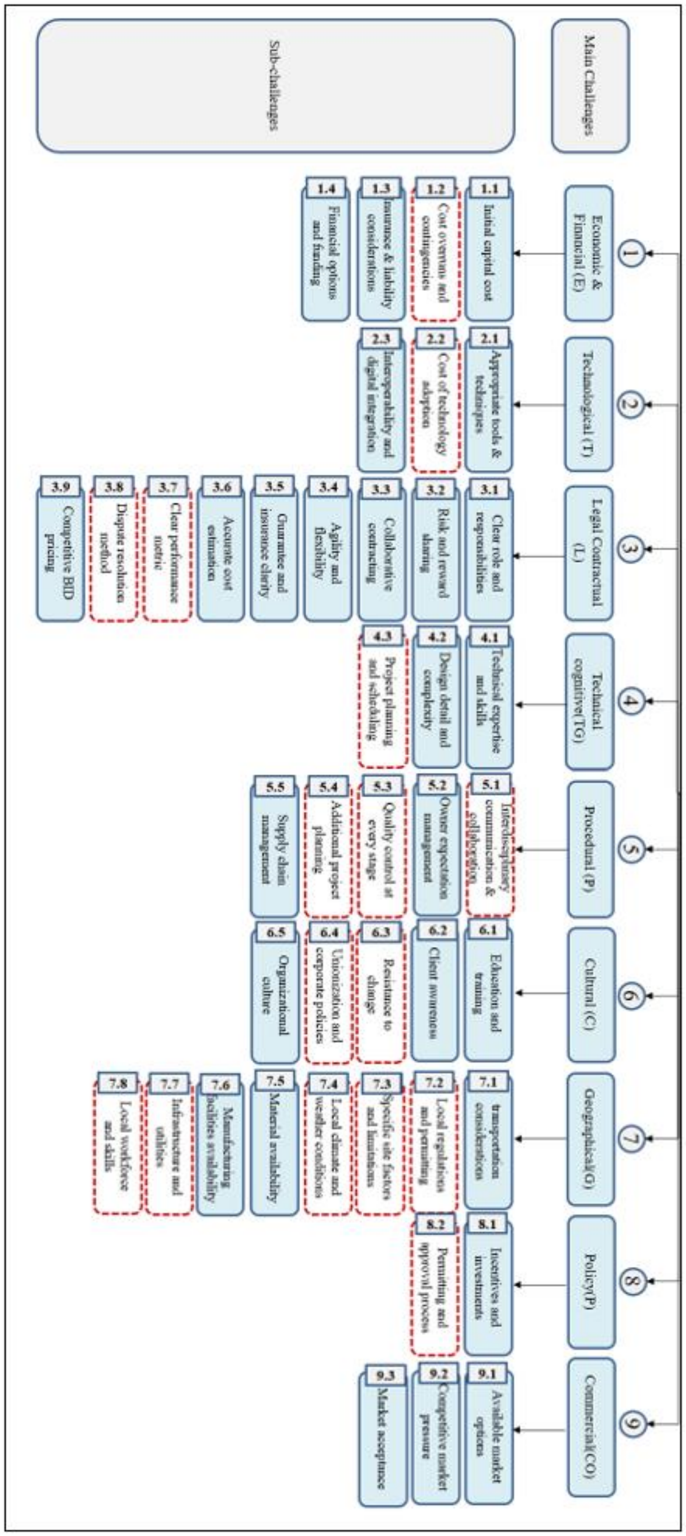

Figure 2: The proposed conceptual framework of DfMA challenges in OnSC projects (The sub-challenges marked with a red dashed format indicates ones that are different between OnSC and OSC)

4.1 Economic and Financial

The implementation of DfMA in both OSC and OnSC presents distinct economic and financial challenges. While both methods require a considerable initial investment in design, leading to higher upfront costs, the nature of the economic challenges differs between the two approaches. In OnSC, the challenges primarily revolve around the unpredictability of site conditions, such as adverse weather or unexpected site constraints, which can lead to cost overruns and require extensive contingency planning. On the other hand, OSC faces the challenge of high initial capital requirements, involving substantial investment in facilities, technology, and processes before the construction phase even begins. Both OSC and OnSC highlight the need for innovative and flexible financial strategies to accommodate the unique demands and uncertainties inherent in each construction approach. Generally, these results are consistent with the conclusions of other researchers who have identified "higher design costs" as an obstacle to the effective adoption of DfMA approaches in OSC projects (Boothroyd 1994).

4.2 Technological

Both OSC and OnSC face technological challenges in adopting DfMA. The selection of appropriate DfMA tools and techniques is crucial for enhancing construction processes in both approaches. OSC-specific challenges include managing the module configuration process and coordinating between phases and contractors due to the off-site nature of construction. On the other hand, OnSC faces challenges related to the cost of technology adoption, as implementing advanced technology directly on the construction site can be expensive and challenging. Both OSC and OnSC encounter interoperability and digital integration challenges, emphasizing the importance of seamless integration of various digital tools and systems in modern construction practices. The shared view among expert opinions and existing research, such as Gao, Low, and Nair (2018) and Lu et al. (2021), highlights the lack of appropriate tools and accessible technology as barriers to adopting DfMA in OSC projects. This emphasizes the widespread technological challenges and the need for inventive solutions to improve the adoption of DfMA practices in the construction sector.

4.3 Legal Contractual

There are several common challenges in the contractual category between DfMA implementation in OSC and OnSC, such as accurate cost estimation, clarity in terms of guarantees and insurance, contract agility, and supply chain integration. However, OSC-specific challenges primarily revolve around the integration of prefabrication and industrialized construction methods, as well as collaboration among different stakeholders. On the other hand, OnSC places more emphasis on performance metrics and dispute resolution within the construction site context. Supply chain integration is also crucial for both OSC and OnSC, but the complexities and challenges differ due to varying environmental conditions and coordination requirements. The literature suggests that successful DfMA application in OSC requires early stakeholder involvement, open communication, and thorough information sharing (Abueisheh et al. 2020; Gao, Jin, and Lu 2020; Wuni and Shen 2020).

4.4 Technical Cognitive

DfMA implementation in both OSC and OnSC involves common concerns such as the need for specialized expertise, complexity of design, and stakeholder awareness. However, there are distinct challenges in each approach. OSC heavily relies on the standardization of details, emphasizing uniformity and predictability (Jin et al. 2018). On the other hand, OnSC demands a higher degree of flexibility and adaptability to unique site-specific challenges. Technical proficiency and increased awareness among stakeholders are essential for both OSC and OnSC, despite their differing approaches and specific challenges.

4.5 Procedural

Both OSC and OnSC share common procedural challenges related to DfMA implementation, such as additional project planning and interdisciplinary communication and collaboration. However, the specific areas of emphasis differ between the two approaches. According to different literature (Jin et al. 2018;

Rankohi et al. 2023) OSC requires additional project planning to ensure smooth transportation and assembly of prefabricated components. OnSC also necessitates additional project planning, with a primary focus on scheduling and coordinating various on-site activities. Effective coordination between design, manufacturing, and construction teams is crucial in OSC (Gao, Low, and Nair 2018), while OnSC involves a broader spectrum of on-site trades and subcontractors, making interdisciplinary communication and collaboration more critical. Quality control also differs, with OSC focusing on ensuring factory-produced components meet required standards (Alazzaz and Whyte 2014), while OnSC emphasizes the quality of installation and workmanship.

4.6 Cultural

From the cultural perspective, both OSC and OnSC face cultural challenges in DfMA adoption, but the nature and emphasis of these challenges differ. According to our analysis, clients may be more familiar with OnSC practices and may need more education on the benefits of DfMA, while OSC may face skepticism or resistance from clients familiar with OnSC. OSC's challenges often revolve around aligning stakeholder communication, supply chain collaboration, and transforming perceptions of industrialized construction (Abd Razak et al. 2022). OnSC's challenges are more focused on internal cultural shifts, adapting to new practices, and addressing resistance within existing teams.

4.7 Geographical

While both OSC and OnSC share some common challenges in DfMA implementation, the differences primarily stem from the distinct nature of each approach. OSC encounters challenges associated with centralized manufacturing in a controlled factory environment, transportation of components, and ensuring code compliance across regions (Gao, Low, and Nair 2018). On the other hand, OnSC deals with site-specific factors, local workforce and regulatory considerations, and the necessity to adapt to existing infrastructure. Navigating local regulations and permitting is also a challenge for both OSC and OnSC, but the variations across different geographic locations add complexity to OnSC projects.

4.8 Policy

Both OSC and OnSC face DfMA policy-related challenges, but the details differ. OSC's challenges revolve around the complexities of prefabrication, transportation, and assembly (Gao, Low, and Nair 2018; Langston and Zhang 2021), while on-site DfMA focuses on integrating techniques compliant with existing on-site regulations. Both approaches emphasize the need for proactive government incentives to facilitate growth within the sector. OSC seeks legislation support that accommodates the unique needs of factory-made components and their transport, while OnSC focuses on facilitating designs and methods specific to the technique and coordinating site issues.

4.9 Commercial

Comparing the challenges of DfMA between OnSC and OSC reveals striking parallels in the commercial domain. Both OSC and OnSC encounter similar hurdles when implementing DfMA methodologies. These challenges predominantly revolve around market dynamics, competition intensity, and market acceptance levels. The convergence of these commercial obstacles underscores a common area of focus and concern across different construction modalities regarding DfMA application. This alignment is primarily attributed to the introduction of DfMA as a novel methodology in both sectors, necessitating collective efforts to educate the market and overcome any resistance or uncertainty surrounding this modern construction approach. Notably, detailed comparative analyses emphasize the minimal differences in sub-challenges within the commercial category of OSC and OnSC, providing a visual representation of the shared obstacles encountered in these construction methodologies.

5 CONCLUSION

The comparative analysis of DfMA implementation challenges in OSC and OnSC reveals distinct challenges in each approach across various categories, including economic and financial, technological, legal contractual, technical cognitive, procedural, cultural, geographical, and policy challenges. Understanding these challenges is crucial for developing strategies and solutions that address the unique demands and characteristics of each construction approach, ultimately improving the adoption and implementation of DfMA practices in the construction industry. This comparative analysis provides valuable insights into the evolving nature of DfMA practices in response to the demands and characteristics of both OSC and OnSC. The findings highlight the importance of considering the specific challenges associated with each construction approach when implementing DfMA. By understanding these challenges, construction professionals can make informed decisions and develop strategies to overcome barriers to DfMA adoption, ultimately improving construction project outcomes in terms of efficiency, productivity, and quality.

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