Design for manufacturing and assembly (DfMA) and challenges of its application in on-site construction (OnSC)

by

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Conception pour la fabrication et l'assemblage (DfMA) et défis de son application dans la construction sur site (OnSC)

Sadaf MONTAZERI

RÉSUMÉ

L'industrie de la construction a depuis longtemps dû faire face à des problèmes de productivité faible, ce qui a suscité une recherche de solutions innovantes. La construction hors site (CHS) s'est imposée comme une option prometteuse pour améliorer la productivité, et l'intégration des principes de la conception pour la fabrication et l'assemblage (Design for Manufacturing and Assembly- DfMA) a suscité une attention considérable ces dernières années. Bien que l'on s'attende à ce que le DfMA soit largement adopté dans la CHS, il offre des avantages potentiels à la fois pour les activités sur site et hors site. Cependant, il existe un manque notable de recherches comparant les pratiques de DfMA dans la construction sur site et hors site.

La présente thèse basée sur des articles se penche sur le DfMA ne sert exclusivement que les projets CHS. En utilisant la méthodologie de recherche en science de la conception (DSR), nous reconnaissons que divers projets de construction, y compris les composants sur site des projets CHS, peuvent encore bénéficier des principes du DfMA. À mesure que l'adoption systématique du DfMA se propage dans le secteur de la construction, il est essentiel d'identifier et de relever les défis liés à sa mise en œuvre à différentes étapes de la construction. La revue de la littérature a d'abord évalué l'état actuel de l'adoption du DfMA dans la construction, couvrant les contextes CHS et sur site, avec une analyse bibliométrique pour explorer leur relation. Les conclusions de cette revue de la littérature offrent des informations précieuses, notamment une discussion approfondie du DfMA dans la CHS et la construction sur site, l'identification des lacunes de recherche et des recommandations pour les développements futurs dans ce domaine. Ensuite, nous nous sommes concentrés sur les aspects sur site de la construction, en examinant et en analysant 42 défis du DfMA validés regroupés en neuf catégories principales. Ces conclusions servent de base au développement d'un cadre de défis liés au DfMA. En identifiant de manière exhaustive et en comprenant ces défis dans la CHS et la construction sur site, cette étude contribue au domaine de la gestion de la construction et offre des informations précieuses aux professionnels de l'industrie, aux chercheurs et aux décideurs. En fin de compte, elle offre des orientations aux organisations souhaitant mettre en œuvre efficacement des stratégies de DfMA. Cela améliorera la productivité de la construction, sa durabilité et sa compétitivité dans l'environnement construit.

Mots-clés : Conception pour la fabrication et l'assemblage (Design for Manufacturing and Assembly- DfMA), Construction hors site (CHS), Construction sur site, Construction modulaire, Défis, Productivité de la construction, Gestion de la construction

Design for manufacturing and assembly (DfMA) and challenges of its application in on-site construction (OnSC)

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ABSTRACT

The construction industry has long had to deal with low productivity, prompting a search for innovative solutions. Off-site construction (OSC) has emerged as a promising option to enhance productivity, and the integration of Design for Manufacturing and Assembly (DfMA) principles has gained considerable attention in recent years. While DfMA is expected to find widespread adoption in OSC, it holds potential benefits for both on-site and OSC activities. However, there is a notable lack of research comparing DfMA practices in on-site construction.

The present article-based thesis delves into the misconception that DfMA exclusively serves OSC projects. Using the Design Science Research (DSR) methodology, we recognize that various construction projects, including on-site components of OSC projects, can still benefit from DfMA principles. As DfMA's systematic adoption proliferates across the construction sector, it is essential to identify and address challenges associated with its implementation at diverse construction stages. The literature review initially assessed the current state of DfMA adoption in construction, spanning OSC and on-site contexts, with a bibliometric analysis to explore their relationship. The findings from this literature review offer valuable insights, including an in-depth discussion of DfMA in OSC and on-site construction, identification of research gaps, and recommendations for future developments in this field. After that we focused on the on-site aspects of construction, examining and analyzing 42 validated DfMA challenges grouped into nine main categories. These findings inform the development of a DfMA-related challenges framework. By comprehensively identifying and understanding these challenges across OSC and on-site construction, this study contributes to the construction management field and provides valuable insights for industry professionals, researchers, and policymakers. Ultimately, it offers guidance for organizations aiming to implement DfMA strategies effectively. This will enhance construction productivity, sustainability, and competitiveness in the built environment.

Keywords: Design for Manufacturing and Assembly (DfMA), Off-site Construction (OSC), On-site Construction (OnSC), Modular Construction, Challenges, Construction Productivity, Construction Management

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LIST OF ABREVIATIONS

AECO	Architecture, Engineering, Construction, and Operations
BIM	Building Information Modelling
CCDC	Canadian Construction Documents Committee
CIRIA	Construction Industry Research and Information Association
DfA	Design for Assembly
DfM	Design for Manufacturing
DfMA	Design for Manufacturing and Assembly
DK	Design Knowledge
DSR	Design Science Research
KPMG	Klynveld Peat Marwick and Goerdeler
IoT	Internet of Things
MiC	Modular integrated Construction
MS	Mean Score
OSC	Off-Site Construction
ROI	Return of Investment
SLR	Systematic Literature Review
UK	United Kingdom
VDC	Virtual Design and Construction
VM	Value Management

LIST OF SYMBOLS

α	Internal consistency
K	Number of groups or categories
Σ	Sum over a set of values
∑s^2 y	Sum of each DfMA challenges variance
s^2 x	The variance of a sum of DfMA challenges value

INTRODUCTION

For decades, the construction industry has suffered from remarkably low productivity. Global productivity growth in the construction sector has averaged just one percent a year for the past two decades compared with world economic growth of 2.8 percent and manufacturing growth of 3.6 percent, this clearly indicates that the construction sector is underperforming (McKinsey Global Institute., 2017).

Using off-site construction (OSC) can improve construction productivity (Mao et al., 2015). OSC provides enhanced productivity through standardization, modularization, and repeated production, as well as manufacturing quality and safety, due to the reduction in outdoor work (Hyun et al., 2022). In a report published by Klynveld Peat Marwick Goerdeler (KPMG) in 2016, it is cautioned that OSC alone will not overcome all the challenges the construction industry is facing. To achieve this, an integrated design process is needed, like the Design for Manufacture and Assembly (DfMA) method. (Boothroyd, 2005) defined DfMA as a methodology that seeks to resolve the industry's fragmentation problem by connecting design, manufacturing, and construction early in the design process. Gao et al. (2020) mentioned that a survey of DfMA users conducted by Boothroyd Dewhurst Inc. found the typical DfMA benefits include: a 51% reduction in parts count, a 37% decrease in parts cost, a 50% faster time-to-market, a 68% improvement in quality and reliability, a 62% drop-in assembly time, and a 57% reduction in manufacturing cycle time.

According to Lu et al. (2021) DfMA is expected to have a wide range of applications, from one-off small-scale to large-scale construction projects, and can benefit both cast-in-situ and OSC methods. DfMA uses a series of design strategies under its guidelines and principles to achieve minimization in the part counts, standardization, and modularization, which appear to be the key characteristics associated with the DfMA principles (Gao et al., 2018).

In the most recent studies, the most widespread DfMA adoption is foreseen in OSC projects and there is a lack of research on DfMA in OnSC. In a construction process, even when referencing the highest degree of prefabrication as categorized by Gibb's (2001) taxonomy, in level 4, which denotes a fully modular building, there remain elements that necessitate on-site completion. It is inherent in the nature of construction that certain processes, adaptions, or integrations are best managed directly on the project location. This underscores the broader significance and applicability of the DfMA principles.

In the context of this research, the term "on-site construction (OnSC)" is used in two specific ways. Firstly, it refers to the work that is completed on-site as part of a larger OSC project. For instance, the Hambro composite floor system by CANAM, as shown in Figure 0.1, is a relevant example. In this scenario, a significant portion of the project involves assembling structural components at the actual site location. Secondly, it pertains to specific projects that are entirely executed at the construction site. A case in point is the GBE system, produced by GBE Innovation Company, a manufacturer and supplier based in France. This system involves creating a cast in place sandwich wall with internal insulation between two concrete skins, as depicted in Figure 0.2. The GBE Innovation Company asserts that their system serves as an outstanding substitute for insulated pre-walls (prefabricated sandwich panels) or external thermal insulation. These examples highlight the diverse applications and implementations of OnSC within this research.

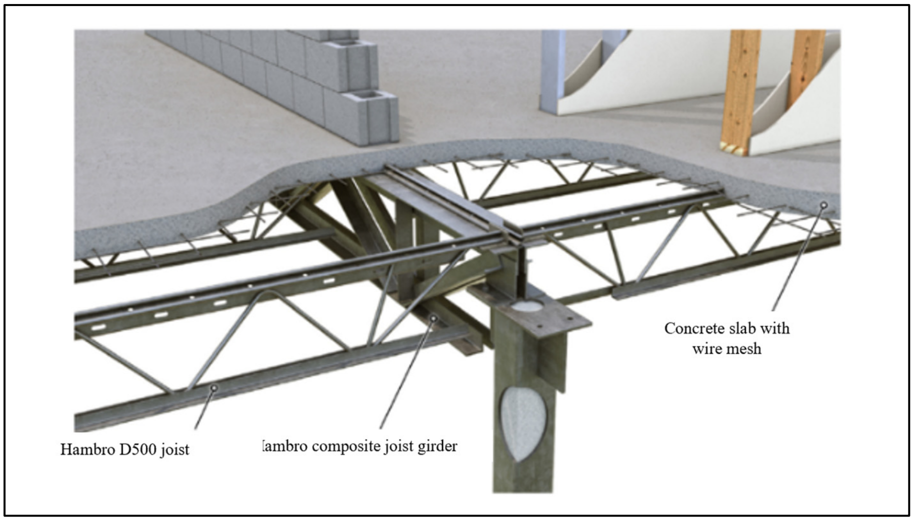

Figure 0.1 Hambro composite floor system[1]

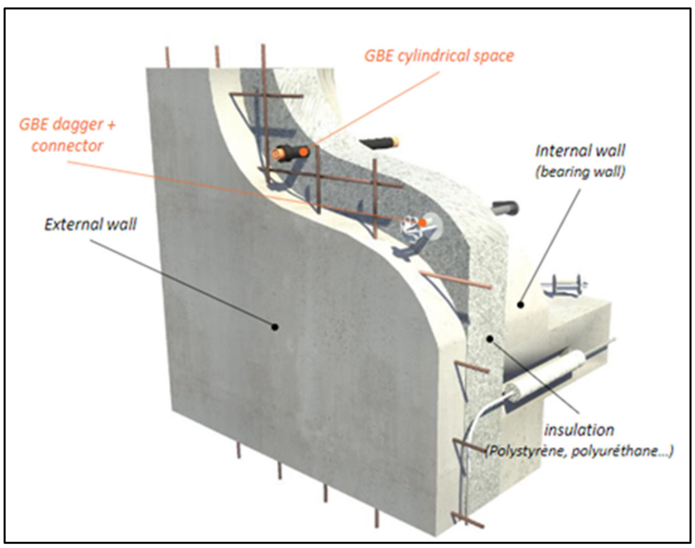

Figure 0.2 GBE wall system[2]

[1] *Source of the example: https://www.canam.com/en/document/hambro-composite-floor-system/*
[2] *Source of the example: https://www.gbe-innovation.fr*

By studying DfMA beyond the OSC, even these on-site components and activities can be streamlined, thereby maximizing efficiency and cohesion throughout the whole building process. Therefore, this research effort focuses on the application of DfMA in both OSC and OnSC and addresses the misconception that DfMA serves OSC only.

The thesis comprises four chapters, including two papers.

- Chapter 1: A comprehensive literature review;
- Chapter 2: Research methodology for this research;
- Chapter 3: A comparison between Design for manufacturing and assembly in off-site construction (OSC) and on-site construction (OnSC) (*Conference paper- presented in the Proceedings of the Canadian Society of Civil Engineering Annual Conference 2023);*
- Chapter 4: Identifying challenges for extended design for manufacturing and assembly (DfMA) in all phases of construction projects (*Journal paper- submitted to the American Society of Civil Engineers journal*).

CHAPTER 1

LITERATURE REVIEW

1.1 Design for manufacturing and assembly (DfMA)

Design for manufacture and assembly (DfMA) is an emerging approach in the AECO industry; Boothroyd. (1994) describes DfMA as a methodology which seeks to resolve the problem of fragmentation in the industry by connecting design, manufacturing, and construction from early in the design process and is a combination of design for manufacture (DfM) and design for assembly (DfA). The purpose of DfMA is to design products in a way that allows for downstream assembly and manufacturing (Gao et al., 2020).

1.1.1 Historical background and development

DfMA was first applied by Ford and Chrysler to their weapon production processes during World War II, the initial usage was founded in manufacturing industries (Lu et al., 2021). It was in the late 1960s and early 1970s that formal approaches to design for manufacturing (DFM) and design for assembly (DfA) were developed, as reflected in UK standards published in 1975 for the management of design for economic production. In the 1970s, Boothroyd and Dewhurst began exploring DfMA academically (Bogue., 2012). Lu et al. (2021) noted that in the research realm, the DfMA literature is growing, while industry leaders such as (Beatty, 2018; O'Rourke, 2013) considered DfMA to be the future of construction; hence, it is a shift from traditional, sequential design thinking to a non-linear approach.

According to Tan et al.(2020), several countries have either introduced the DfMA guide or emphasised DfMA's importance in construction; such as United Kingdom, Singapore, and Hong Kong governments.

1.1.2 Process and principles

The typical primary procedure involved in DfMA process can be arranged into stages, as summarized in Figure 1.1. It is a systematic procedure that helps companies make the fullest use of manufacturing and assembly processes (Bogue, 2012). As illustrated in Figure 1.1, the first step to the analysis of a design concept is typically the use of DFA, which provides ideas for how to simplify the design structure of a product by using fewer parts, fewer variations, and simpler assembly instructions (Boothroyd, 2005; Tasalloti et al., 2016).

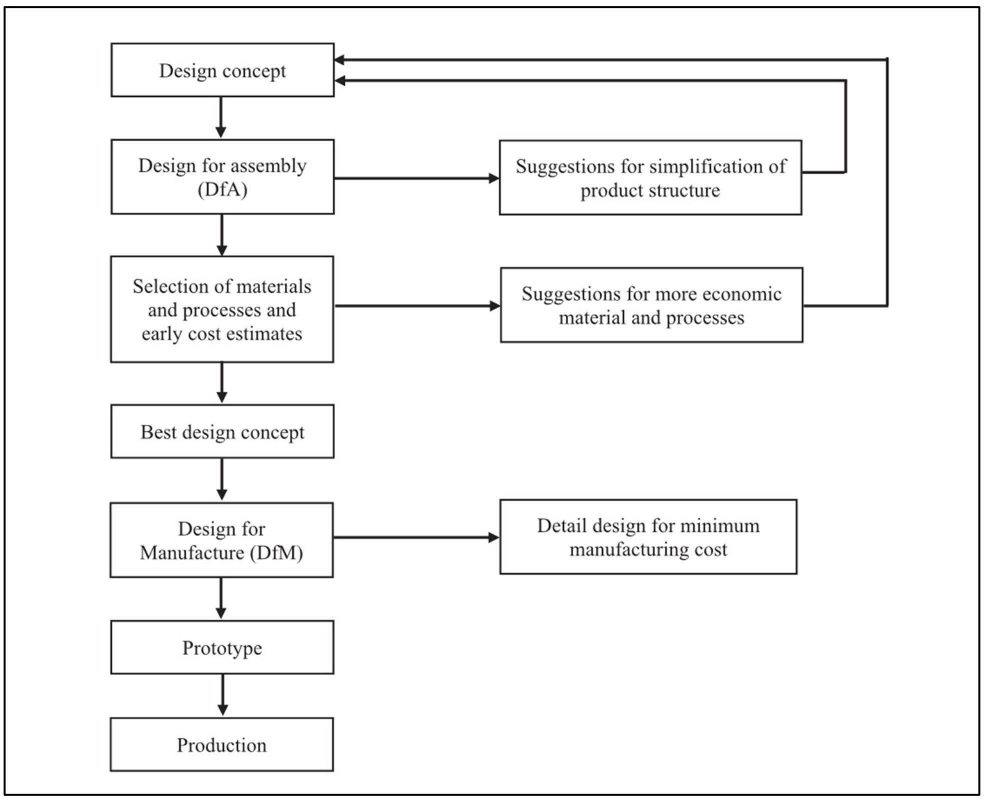

Figure 1.1 Typical stages in a DfMA procedure[3]
Taken from (Boothroyd, 2005)

[3] *Source of the example: Boothroyd (2005)*

(Gao et al., 2018) explained DfMA as a process, an evaluation method, and a technology. There has been use of DfMA since the 1980s to simplify the design of products and reduce manufacturing time and costs (Langston & Zhang, 2021). As shown in Figure 1.2, DfMA can be perceived as a systematic procedure that, when applie d as part of the design phase, would add value to the construction and production process (Abd Razak et al., 2022).

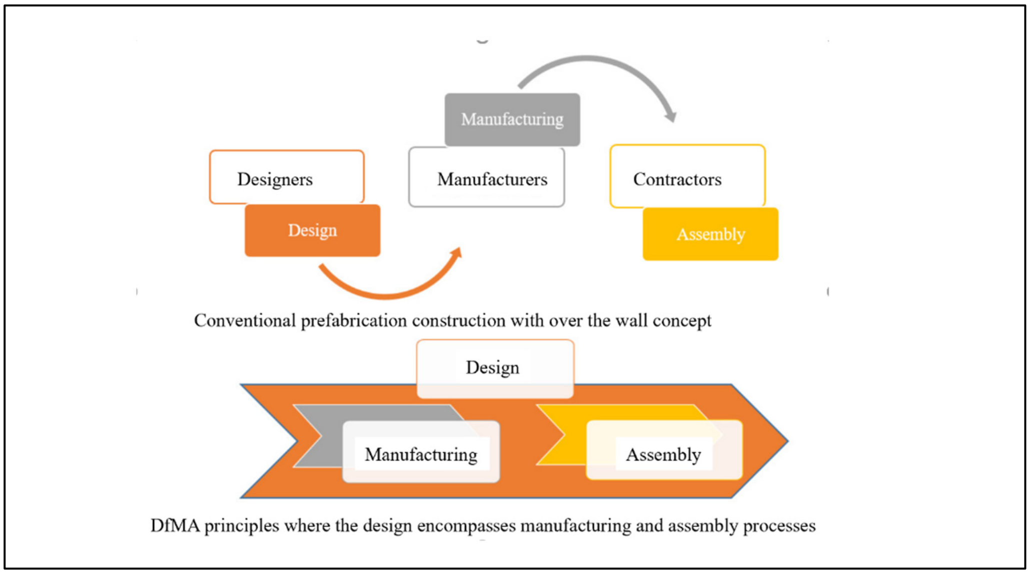

Figure 1.2 Simplified DfMA principles[4]
Taken from (Abd Razak et al., 2022)

In order to adopt DfMA in the construction industry, available guidelines from the manufacturing industry might be a good starting point. However, these guidelines should be further studied in order to better suit the needs of the construction industry (Abd Razak et al., 2022). Researchers such as (Bogue, 2012; Emmatty & Sarmah, 2012) have developed some guidelines for the application of DfMA, as shown in Table 1.1.

[4] *Source of the example: Abd Razak et al (2022)*

Table 1.1 DfMA guidelines[5]

N	Guidelines	Benefits
1	Aim for mistake-proof design	Avoid unnecessary re-work, improve quality, and reduce time and costs.
2	Design for ease of fabrication	Reduce time and costs by eliminating complex fixtures and tooling.
3	Design for simple part orientation and handling	Reduce time and costs by avoiding non-value adding manual effort.
4	Design with predetermined assembly techniques in mind	Reduce time and costs when assembling.
5	Consider modular designs	Reduce time and costs due to simplified design and assembly.
6	Consider design for mechanized or automated assembly	Improve assembly efficiency, quality and security.
7	Use standard and off-the-shelf components	Reduce purchasing lead time and costs.
8	Use as similar materials as possible	Reduce time with fewer manufacture processes and simplified jointing.
9	Use as environmentally friendly materials as possible	Reduce harm to the environment.
10	Minimize precast component types	Reduce time and costs with simplified design, manufacture, and assembly.
11	Minimize connector types and quantity	Reduce time and costs with simplified design, manufacture, assembly, repair and maintenance.
12	Minimize the use of fragile parts	Reduce costs due to fewer part failures, and easier handling and assembly.
13	Do not over-specify tolerances or surface finish	Reduce costs with easier manufacture.

[5] *Source of the example: Bogue (2012) and Emmatty & Sarmah (2012)*

According to (Bogue, 2012) there are three means of applying a DfMA process;

1. First is to follow a general set of non-specific and qualitative rules or guidelines and require someone (most likely designers and engineers) to interpret and apply them in each individual case. The aim is to encompass a diversity of products, processes and materials. Table 1.1 provides an example of such DfMA guidelines and their associated benefits;

2. Second method employs a quantitative evaluation of the design. The rationale is that each part of the design can be rated with a numerical value depending on its 'assemblability'(Bogue, 2012). Subsequently, the numbers can be summed for the entire design and the resulting value is used as the guide to evaluate the overall design quality;

3. Another evaluation tool is based on a 100-point method with demerit marks being given for factors which hamper the ease of assembly. The third approach which is most recently developed is the automation of the entire process. It relies on computer software.

1.1.3 Research themes

In a research recently conducted by Rankohi et al.(2022), four themes are identified for DfMA in construction. These themes- technology, application, project lifecycle, and prefabrication- are all illustrated in figure1.3.

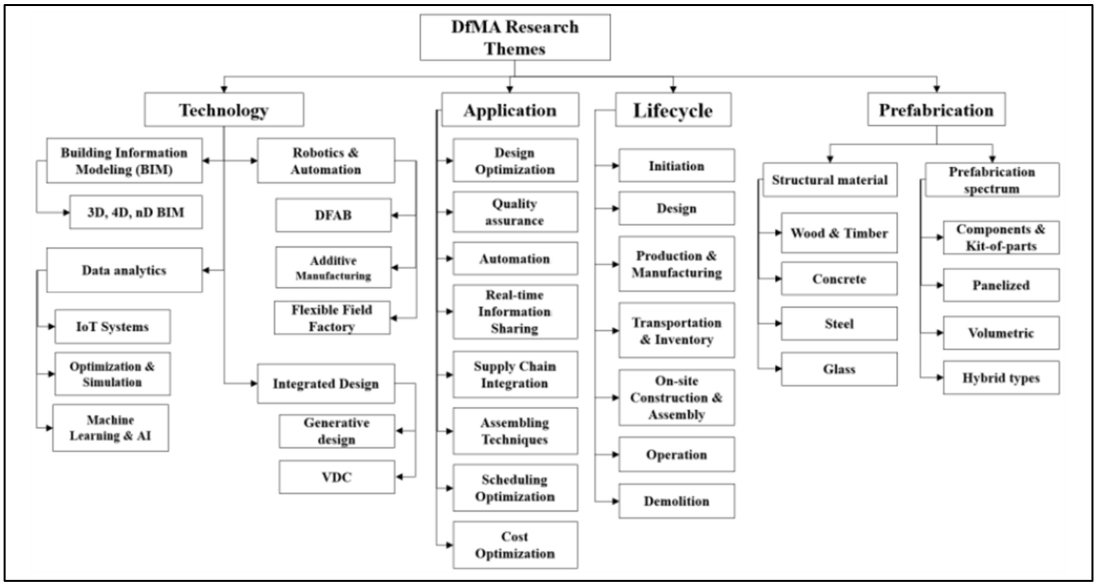

Figure 1.3 Identified themes in DfMA literature [6]
Taken from Rankohi et al.(2022)

1.1.3.1 DfMA technologies

According to (Abd Razak et al., 2022) even though the application of DfMA is not necessarily digitalised, it is clear from the majority of studies that there are a multitude of technological requirements that need to be addressed when DfMA is used in construction project (FAVI et al., 2017; Marinelli et al., 2022; Wasim et al., 2020). Bakhshi et al. (2022) grouped the technology applications as follows: visualization or simulation, real-time information sharing, communication or collaboration, and training or safety.

To expand DfMA's use, other authors have integrated it with emerging technologies. Among these technologies are Modular integrated Construction (MiC), Virtual Design and Construction (VDC), the Internet of Things (IoT), Building Information Modeling (BIM), prefabrication, and smart construction (Lu et al., 2021), volumetric modular construction (Wasim et al., 2022), additive manufacturing, and digital fabrication (Tuvayanond & Prasittisopin, 2023). According to most studies, it has been demonstrated that BIM has the

[6] *Source of the example: Rankohi et al. (2022)*

potential to enhance DfMA in most cases (Abd Razak et al., 2022). In a work by (Tan et al., 2020), it is revealed that in the context of DfMA, BIM can serve three functions: it can enable the DfMA process, serve as a tool for utilizing DfMA techniques, and produce a DfMA information model.

1.1.3.2 DfMA application area

DfMA is a procedure that considers manufacturing and assembly processes during the initial planning and design stages to eliminate potential production problems, thereby optimizing quality, time, and total cost (Roxas et al., 2023). Many studies have discussed the application areas of the DfMA method in construction projects and they have provided case study examples of evidence to support their findings. These are some of the most frequently cited areas of application: 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).

1.1.3.3 DfMA and project lifecycle

A construction project's life cycle consists of a series of stages to be completed to achieve the project's objectives (Rankohi, Carbone, et al., 2022). RIBA 2020 defines these stages as: definition, preparation and briefing, concept design, spatial coordination, detailed design, manufacturing/construction, handover, and use/operation. The majority of studies reviewed the impact of the DfMA method during various project phases, with most attention focused on the design, manufacturing, and site assembly phases (Alfieri et al., 2020; Gao et al., 2020; Lu et al., 2021; Wuni & Shen, 2020b). As part of product design, DfMA focuses on optimizing manufacturing and assembly stages. However, in order to apply DfMA to the design stage, most studies state that the guidelines are necessary to ensure the method is used appropriately (Roxas et al., 2023).

1.1.3.4 DfMA and prefabrication

There has been a comprehensive review of the use of prefabrication, or otherwise known as off-site manufacturing, without taking into account DfMA from various perspectives by other researchers (Wasim et al., 2022). However, a report from KPMG (2016) cautioned “off- site manufacturing alone will not overcome the challenges the construction industry is facing, to do so requires a partnership with an integrated design process, like the Design for Manufacture and Assembly (DfMA) method”. As it is commonly known, DfMA is the process of evaluating and improving the design of products both for their economic manufacturing and assembly (Gao et al., 2020). The literature demonstrates that DfMA principles have been employed across a range of prefabricated projects involving different materials, with numerous studies addressing their application in prefabricated and offsite construction endeavors (Bao et al., 2022; Tan et al., 2020).

A report by the Building and Construction Authority described DfMA as a game-changing methodology closely associated with prefabrication ongoing evolution (O’Rourke, 2013). DfMA addresses challenges by engaging manufacturers and technicians early in the design phase, making it a pivotal element in the prefabrication process. DfMA solves problems by involving manufacturers and technicians upfront at the design stage, and it is considered a crucial step in the prefabrication process (Langston & Zhang, 2021)

1.1.4 Key benefits and challenges

The advantages of DfMA are multifaceted (Langston & Zhang, 2021) and 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. Studies have shown that the DfMA can improve the quality of construction projects from the design phase to the manufacturing and construction phases (Bao et al., 2022; FAVI et al., 2017). DfMA optimization helps lower construction project costs, supported by numerous studies showcasing its cost-reduction impact (Lu et al., 2021; Tan et al., 2020; Wasim et al., 2020). The largest benefit reported by (O'Rourke, 2013) was program time reduction, which was also mentioned in several other studies (Qi et al., n.d.; Yin et al., 2019; Yuan et al., 2018). The application of DfMA, as indicated by literature (Bakhshi et al., 2022b; Machado et al., 2016), leads to increased labor productivity by reducing or eliminating labor-intensive activities on-site, consequently resulting enhancements in health and safety during onsite assembly. Finally, few studies explored DfMA in construction projects with regards to sustainability and environmental impacts (FAVI et al., 2017; Gao et al., 2018).

Despite the importance of DfMA in the construction industry, researchers have identified a number of challenges based on their investigations (Langston & Zhang, 2021). Guidelines, standards, and affordable technologies are not available in the global industry for better adoption of DfMA (Lu et al., 2021), knowledge limitation (Gao et al., 2020; Gerth et al., 2013), community resistive mindset, social attitudes, and user acceptance (Lu et al., 2021; Montali et al., 2018), insufficient supply chain management (Langston & Zhang, 2021; Tan et al., 2020), At an early stage, DfMA adoption can be costly, as new technologies and an ecosystem require additional investment (Langston & Zhang, 2021; Lu et al., 2021; O'Rourke, 2013), and lack of suitable technical requirements (Bakhshi et al., 2022).

1.2 DfMA overlaps with other concepts

Apart from the DfMA process, principles, and guidelines, and considering the advantages and challenges of DfMA adoption, it is crucial to examine DfMA and its similar value-adding concepts which has been introduced to improve the AECO productivity and efficiency (Lu et al., 2021), such as buildability, value management, and lean construction, to understand how the DfMA philosophy is reflected in various construction practices (Lu et al., 2021). Figure 1.4 illustrates this DfMA overlaps with the other concepts. This section discusses the similarities, differences, and linkages between the concepts and DfMA.

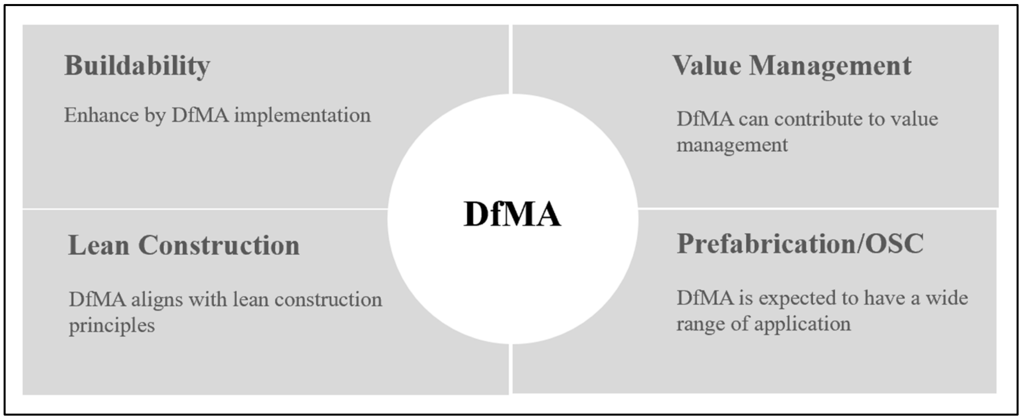

Figure 1.4 The Overlap of DfMA with Other Key Concepts in Construction

1.2.1 DfMA and buildability

Buildability defined by CIRIA 1983 as "the extent to which the design of a building facilitates ease of construction, subject to the overall requirements for the completed building". In this way, buildable designs have improved quality and safety performance, improved productivity levels, and mitigated the risk associated with unforeseen issues in the construction industry (Lam & Wong., 2011). In the process of design for buildability, the initial focus is on various external elements like site geotechnical conditions, site access and movement, and the resources, skills, and technology. Afterwards, the approach involves implementing standardization, simplicity, integration, and prefabrication techniques to achieve the desired level of buildability (Lu et al., 2021).

In buildability and DfMA, there are both similarities and differences. First and foremost, both aimed to simplify manufacturing and building processes from the beginning of the design phase. This is to improve quality, cost, productivity, and safety performance. Second, both follow the standardization principle for the design, and third, both encourage integration and prefabrication. It has become evident that the buildability of buildings can be enhanced by the implementation of DfMA, prefabricated construction, and technologies for virtual and automated construction (Gao et al., 2018).

1.2.2 DfMA and value management

Value Management (VM) is a philosophy and management approach aimed at improving stakeholder decision-making. It involves conducting value studies to optimize organizational decisions and performance through a structured value-based methodology that includes key stakeholders (Kelly et al., 2014). It is possible to trace back the origins of both VM and DfMA to the manufacturing industry. It should be noted that VM, as with DfMA, is the result of integration and cooperation among members of a multidisciplinary team.

DfMA and VM have some obvious differences that are worth pointing out. To begin with, they have different goals and objectives. VM looks at all functionality and finance of a building, not just manufacturing and assembly phases, while DfMA focuses on two main functions which are manufacturing and assembly. Furthermore, they use different methods to achieve their respective goals. VM is a methodology that makes use of team-based, process-driven approaches, including function analysis, to analyze and deliver projects for optimized whole-life performance and cost, and without compromising quality at any point in their lifecycle (Male et al., 2007). On the contrary, DfMA uses a series of design strategies that are in line with its guidelines and principles as a means to improve the manufacturing and assembly process (K. Chen & Lu, 2018; Gao et al., 2018).

While DfMA focuses on specific technical details, such as component size, building materials, and connection method, VM begins with the architectural function and applies a series of management techniques (Lu et al., 2020). As Lu et al.(2020) explains, it is worth noting that VM represents a project management perspective whereas DfMA puts more emphasis on a product design perspective. However, they can work together so that more efficient construction practices can be achieved.

1.2.3 DfMA and Lean Construction

Lean construction is defined as a way 'to design production systems to minimize the waste of materials, time and efforts to generate the maximum possible amount of value' (Koskela, 1992). According to (Gao et al., 2020; Gbadamosi et al., 2020) DfMA and lean construction principles are interrelated , and can help the AECO industry achieve maximum shared value, such as reducing construction cost and efforts, and increasing productivity (Lu et al., 2021).

DfMA aligns with lean construction by targeting waste reduction, particularly inefficient motions and non-value adding activities, drawing from principles like minimizing parts and enhancing ease of handling and assembly (Gerth et al., 2013). Despite their similarities, the two principles are conceptually different, with different working scopes and focuses. The objective of lean construction is to eliminate construction waste, effort, and time through the design of a proper production and delivery system over a supply chain. Several lean principles are critical for preventing overstock and increasing cash flow, such as a flexible workforce and just-in-time delivery. Comparatively, In contrast, DfMA principles are intended to reduce manufacturing and assembly costs from the very beginning of the design process (Gao et al., 2018). In this process, a series of measures are taken to optimize design, but workforce flexibility and warehousing level are not as heavily considered as they would be in lean construction (Lu et al., 2021).

1.3 Status quo of DfMA in construction

DfMA has been widely used since the 1980s as a tool for simplifying product design and maximizing time and cost efficiency in manufacturing for more than 50 years. This method offers promise to achieve a more sustainable and productive construction industry (Langston & Zhang, 2021).

Roxas et al. (2023) explained that based on the studies discussed in the various pieces of literature on DfMA, it is evident that it has many advantages. In addition, it has been proven in many studies that the application of DfMA to construction projects can enhance productivity and quality, and has presented directions for applying DfMA to construction projects as well (Gbadamosi et al., 2020; Hyun et al., 2022; Kim et al., 2016). Despite the growing research literature in the field of DfMA, it is still considered by many industry leaders such as (Beatty, 2018; O'Rourke, 2013) to be the future of construction. According to Lu et al. (2020), in the construction industry, DfMA is still at an infancy stage of adoption and there is still a considerable amount of work to be done in order to ensure the construction industry adopts DfMA. Roxas et al. (2023) also explained construction must adopt techniques to promote DfMA adoption.

1.4 Conclusion

The literature review conducted a comprehensive review of DfMA within the realm of construction industry. Emerging as a transformative approach, DfMA encompasses both design for manufacture (DfM) and design for assembly (DfA), aiming to bridge the gaps between design, manufacturing, and construction phases. DfMA's historical evolution, process, principles, and research themes have been extensively explored. From its origins in World War II in manufacturing to its present-day adoption as a potential game-changer in the construction domain, DfMA has evolved to address challenges such as fragmentation and inefficiency in the construction industry.

According to the literature review, DfMA offers a wide range of benefits, ranging from enhanced quality and reduced costs to improved safety, sustainability, and productivity across the project lifecycle. There are, however, a number of challenges that have to be overcome in the implementation of DfMA in construction. A lack of guidelines, technological tools, and a resistant mindset within the industry pose challenges. Moreover, the initial investment required and the need for specialized technical requirements are major obstacles. The integration of DfMA with emerging technologies such as BIM, IoT, and prefabrication presents a promising growth path for the construction industry.

In addition, the review explores the intersections and differences between DfMA, buildability, value management, and lean construction concepts. These concepts share the goal of optimizing efficiency and value, however, they differ in their scope and approach. In its role as a bridge between design and construction, DfMA can streamline processes, enhance collaboration, and lead the industry toward a sustainable and productive future. It is clear, despite all the challenges, that DfMA has a lot to offer the construction industry in the near future.

1.5 Potential area for future research

The prioritization of OnSC application in my research stems from a critical observation within the literature and industry practices that reveal a significant emphasis on specific OnSC projects and integrating DfMA principles in such linds of projects. This focus has inadvertently left a gap in understanding how DfMA can be effectively applied in situations where OSC is not feasible or ideal. Considering the construction industry's broader context, including its low productivity rates and the increasing demand for innovative solutions to enhance efficiency, quality, and sustainability, addressing the challenges of OnSC DfMA implementation emerges as an important area of study.

The prioritization for future research, based on the identified gaps, could be suggested as follows:

On-site construction (OnSC) application: The critical observation from the collective literature reveals that most DfMA dialogues revolve around OSC. However, it is essential to recognize that not every project aligns with OSC, yet they can still benefit from the advantages of DfMA design paradigms. In line with the insights of Abd Razak et al. (2022), there could be significant research potential in developing guidelines specifically for on-site fabrication, ensuring that projects unsuitable for OSC can still benefit from DfMA methodologies.

Integration with emerging technologies: As the second priority, the focus on integrating DfMA with technologies like BIM, IoT, and VDC is crucial. The review mentioned that as DfMA gradually aligns with the advent of progressive technologies such as BIM, IoT, and VDC, it becomes important to understand how to integrate these technologies to enhance DfMA efficacy in construction projects. Researchers might consider formulating holistic technological solutions that naturally integrate DfMA principles into the digital construction landscape.

Sustainability and circular economy: Given the increasing emphasis on sustainability, future research can investigate how DfMA can contribute to sustainable construction practices. This may include assessing the environmental impact of implementing DfMA approaches, exploring methods to reduce waste and promote recycling in construction, and quantifying the long-term sustainability benefits of DfMA application.

Guidelines and standards: Review of different literature highlighted the lack of guidelines and standards as a challenge in DfMA adoption. Future research could focus on developing comprehensive guidelines and standards specifically for the construction industry. These guidelines should cover not only the technical aspects but also the managerial and organizational aspects of implementing DfMA methodology.

Supply chain management: Explore ways to improve supply chain integration in DfMA processes. Research can examine how DfMA impacts the relationships between suppliers, manufacturers, and construction teams and identify best practices for optimizing the supply chain in DfMA for different types of projects ranging form OnSC to OSC.

Case studies and real-world applications: More in-depth case studies and real-world applications of DfMA in construction projects can provide valuable insights into its effectiveness, challenges, and lessons learned. Researchers can collaborate with industry partners to gather data and feedback from ongoing DfMA projects in the industry.

Life cycle analysis: Conducting comprehensive life cycle assessments of DfMA projects can provide a deeper understanding of their environmental and economic impacts over time. This research field can support the case for DfMA in terms of long-term benefits and sustainability.

Global adoption and policy: Investigate the global adoption of DfMA and the role of government policies and regulations in promoting its use. It can offer insights into how different regions are advancing and what barriers remain. The comparative studies across different countries and regions can also offer insights into the variations in implementing DfMA.

By maintaining OnSC application as the primary focus, the research directly addresses a significant gap in the current body of knowledge and practice. This focus does not diminish the importance of the other identified gaps; rather, it underscores the necessity of a foundational shift in the construction industry towards more innovative, efficient, and sustainable practices that can only be achieved by addressing the challenges of OnSC DfMA implementation.

CHAPTER 2

RESEARCH OBJECTIVES AND METHODOLOGY

2.1 Introduction

In order to expand knowledge and make a meaningful contribution to theory and practice in this field, this study adopted an exploratory research strategy to investigate the challenges affecting the adoption of DfMA in OnSC, with the aim of developing DfMA challenges related frameworks. To accomplish this objective, a multi-step research approach known as Design Science Research (DSR) was employed.

Central to the choice of employing a mixed-method approach, combining both quantitative and qualitative research methods, was the recognition of the complex, multifaceted nature of the challenges surrounding DfMA adoption. According to (Heyvaert et al., 2011) the use of mixed methods approaches has seen a notable rise in popularity, with an increasing trend of integrating both qualitative and quantitative research elements at the core stage of empirical studies. This approach was selected to leverage the strengths of both quantitative methods (e.g., the ability to generalize findings from a larger sample) and qualitative methods (e.g., the depth of understanding and context-specific insights they provide). Therefore, this section initiates by providing a clear definition of the utilized research methodology. It then proceeds to explore the motivations behind the research, identify the research problems, and outline the research objectives. Ultimately, it ends with the development of the artifact (a conceptual framework, in our case), its subsequent demonstration, and a discussion on the contributions made by this research.

2.2 Design Science Research (DSR) methodology

Design Science Research (DSR) is a problem-solving paradigm that seeks to enhance human knowledge via the creation of innovative artifacts (Brocke et al., 2020). DSR seeks to enhance human knowledge with the creation of innovative artifacts and the generation of design knowledge (DK) via innovative solutions to real-world problems (Hevner, March, Park, & Ram 2004).

This DSR process includes six steps: problem identification and motivation, definition of the objectives for a solution, design and development, demonstration, evaluation, and communication. In this chapter, the different steps of the DSR methodology are explained in the context of this research.

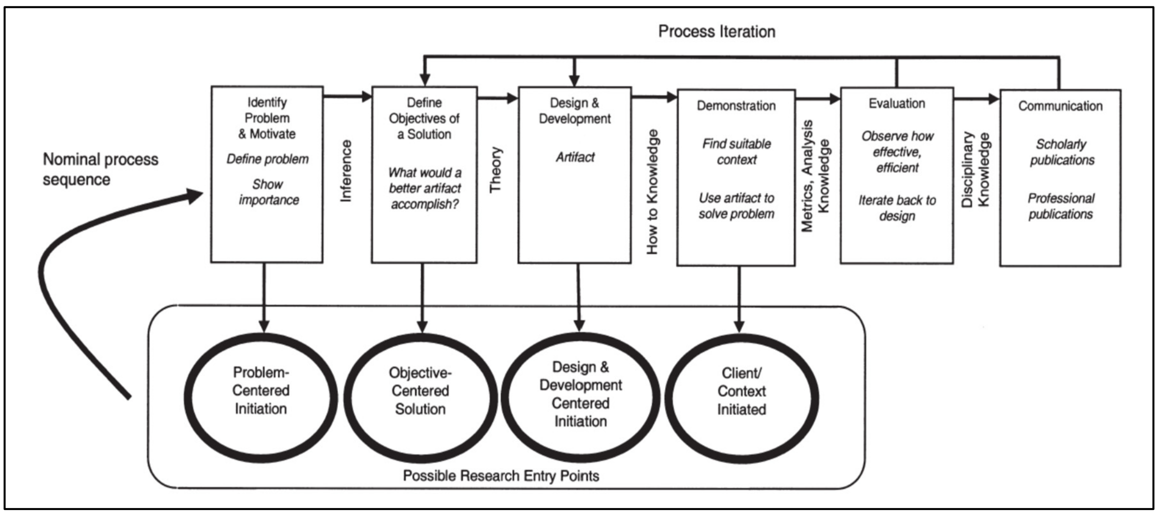

Figure 2.1 Design Science Research Methodology Process Model[7]
Taken from(Peffers et al., 2007)

2.2.1 Research motivation

The construction industry has suffered from remarkably low productivity. Global productivity growth in the construction sector has averaged just one percent a year for the past two decades compared with world economic growth of 2.8 percent and manufacturing growth of 3.6 percent, this clearly indicates that the construction sector is underperforming (McKinsey Global Institute., 2017). So, the motivation for researching and extend DFMA in in the whole lifecycle of a construction project is driven by the desire to improve construction processes,

[7] *Source of the example: Peffers et al. (2007)*

and enhance quality. In addition, by reviewing the literature and identifying research gaps that emphasize on more research studies on DfMA applications in on-site parts of the construction, since not all the projects are applicable for OSC or a project cannot be fully OSC.

Furthermore, this study was partly inspired by a real-world industrial application, introduced through a Mitacs project in collaboration with GBE innovation company, a manufacturer and supplier based in France. GBE is known for producing cast-in-place concrete walls with integrated insulation, a process they believe to be a novel and updated approach in the construction industry which is an excellent alternative to insulated double walls (prefabricated sandwich panels) or external thermal insulation. The implementation of the GBE® process necessitates exacting accuracy, especially during the simultaneous continuous pouring of self-compacting concrete on both sides. It was observed that the vast majority of this process was executed on-site, emphasizing the critical nature of onsite operations in its success. This insight into GBE's practices underscores the relevance of examining the importance of OnSC, particularly those processes that are thought to be innovative yet remain heavily reliant on traditional on-site methods.

Indeed, developing frameworks for identified challenges of DfMA implementation in OnSC would have a significant practical impact. The proposed conceptual framework can assist researchers and practitioners in identifying the root causes of barriers to implementing DfMA strategies in OnSC projects and directing them towards implementing remedial measures to address these hindrances based on the stakeholders involved. By comparing the DfMA challenges in OSC and OnSC, industry professionals can make informed decisions to optimize construction projects based on their specific requirements and goals.

2.2.2 Problem statement, research questions, and hypothesis

The problem addressed in this research study is misconceptions regarding the adoption of DfMA practices within the construction industry. Specifically, there exists a common belief that DfMA primarily serves OSC processes. This misconception has led to the lack of application of DfMA principles and guidelines in situations where OSC is not the sole method employed. This is even when considering projects with a high degree of OSC. However, it is essential to recognize that certain aspects of construction projects continue to be executed on-site, presenting opportunities for applying DfMA principles and guidelines. Therefore, this research aims to investigate and clarify how DfMA can benefit construction projects that incorporate both off-site and OnSC methods, thereby addressing misconceptions and optimizing DfMA adoption in the whole lifecycle of the construction industry. Based on the problems identified in the industry and by the existing body of knowledge, we have developed some research questions based on those concerns, which are as follows:

1. What does DfMA mean in the context of OnSC?
2. How can DfMA be implemented effectively in on-site part of the constructions?

To answer the first question, we conducted a systematic literature review to identify the state-of the-art for DfMA implementation in OSC and OnSC. We have extensively examined scholarly papers in this direction in order to identify what is the current status of DfMA in OSC and OnSC. The conference paper provides detailed information on this topic in Chapter 3.

In response to the second research question, the second paper in chapter 4 (submitted) identifies, verifies, and analyzes DfMA challenges in OnSC and makes a comparison with DfMA challenges in OSC. In this paper, a conceptual framework on the challenges for the implementation of DfMA in OnSC is developed, based on nine main challenges categories and their sub-categories. In Paper 2, we addressed one of the research gaps identified in the conclusions of paper 1, stemming from the systematic literature review, which is the absence of specific guidelines for OnSC projects, making certain that projects appropriate for OnSC are equally able to take advantage of DfMA methodologies.

The statement of the problem, as well as the proposition of research questions, and hypotheses, leads to the defining of the research objectives, which is the second step within the DSR.

2.2.3 Research objectives

The comprehensive literature analysis indicated ambiguity concerning DfMA's application in both OSC and OnSC. Consequently, this study's primary aim was to examine the present status of DfMA within the OSC and OnSC fields. Notably, given the limited literature on DfMA in OnSC, challenges to DfMA's implementation in this context were identified. Essentially, this research endeavors *to establish a conceptual framework outlining the challenges of DfMA in OnSC, thus facilitating a comparison with the challenges within OSC*.

2.2.4 Artifact development

To answer the first question and to gain insights into the existing status of DfMA implementation in both OSC and OnSC, we conducted a comprehensive systematic literature review. This effort consisted of an extensive review of scholarly publications, providing an overview of DfMA's most recent developments in construction. Our findings, methodologies, and analysis are extensively documented in Chapter 3, which is a published paper dedicated to this topic.

Based on our literature review, we sought to delve deeper into the specific challenges faced during DfMA implementation in OnSC. This led to the development of a comprehensive framework aimed at ranking and analyzing these existing challenges. Notably, this framework was specifically developed to emphasize the on-site phases of construction when adopting the DfMA methodology. The outcome of this research is presented in our second paper, which is currently under review. By strategically adopting the DSR methodology, we plan to foster a better comprehension of the complexities surrounding DfMA in the construction industry. We hope that our contributions will significantly aid future research and practical applications in this domain.

2.2.5 Evaluation

While our primary focus in this research was on the artifact (conceptual framework) development phase, leading to the comprehensive framework for DfMA challenges in OnSC, it is essential to acknowledge the importance of the evaluation stage in the DSR methodology. Part of our results was indeed assessed for internal consistency using Cronbach's Alpha, which provides preliminary validation of our findings.

Potential evaluation methodologies for future research could include case study implementations by using the framework in real construction projects and documenting its impact and relevance, expert reviews by inviting professionals and researchers in the field of DfMA to evaluate and provide feedback on the framework, and simulation-based evaluations by testing the framework's assumptions and outcomes in a controlled, simulated environment.

2.2.6 Research communication

During the concluding phase of the DSR method, effective communication of research findings is essential, targeting the specific audience identified by (De Sordi, 2021), which comprises professionals and fellow researchers. To facilitate this communication, this thesis is organized into two articles, and the subsequent section provides concise summaries of these articles.

2.2.6.1 Article 1: A comparison between DfMA in OSC and on-site construction – A systematic literature review (SLR) (Conference publication)

This article initiated this research by addressing the first step of the DSR methodology. It presented an SLR through Chapter 3. In particular, Article 1 focused on exploring the most recent publications from 2010 to 2022 that delve into the implementation of DfMA in the construction industry. This investigation allowed for the categorization of articles into various themes, shedding light on the current state of DfMA adoption in both OSC and OnSC. The findings from this work offer valuable insights for researchers and industry experts, addressing the initial research question. It's worth noting that Article 1 was presented at the Canadian Society of Civil Engineering Annual Conference in 2023.

2.2.6.2 Article 2: Identifying challenges for extended design for manufacturing and assembly (DfMA) adoption in all phases of a construction project (Journal paper - Submitted)

This article serves as the central communication within the thesis, prominently featured in Chapter 4. Within this article, a conceptual framework addressing the challenges associated with DfMA in OnSC projects is introduced. The primary objective of this article is to both identify and rank these challenges specifically for OnSC projects. Through this process, it seeks to make a meaningful contribution to the field of construction management, offering valuable insights to a diverse audience including industry professionals, researchers, and policymakers.

Ultimately, the study's findings, as presented in Article 2, have the potential to guide organizations in the effective implementation of DfMA strategies. This, in turn, can lead to improvements in construction productivity, sustainability, and competitiveness within the built environment. It is important to note that Article 2 has been submitted to the American Society of Civil Engineers (ASCE) journal.

CHAPTER 3

A COMPARISON BETWEEN DESIGN FOR MANUFACTURING AND ASSEMBLY (DFMA) IN OFF-SITE CONSTRUCTION (OSC) AND ON-SITE CONSTRUCTION – A SYSTEMATIC LITERATURE REVIEW

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Paper presented at *the Canadian Society of Civil Engineering (CSCE) Annual Conference*, May 2023

3.1 Abstract

The construction industry has long been criticized for low productivity problems. Using off-site construction (OSC) provides an opportunity to improve construction productivity. In terms of OSC adoption, various studies represent the construction projects ranging from entire on-site to complete OSC Applying design for manufacturing and assembly (DfMA) principles in the building has recently gained industry attention. DfMA as a systematic procedure is expected to be widely adopted in OSC. According to the literature, it can, however, benefit both on-site and OSC activities. This study is based on mixed- method review of 40 selected articles by keywords search of DfMA in OSC and OnSC. There has been insufficient research comparing these practices more specifically in DfMA in OnSC. This literature review aims to assess the current state of the DfMA in construction and its adoption in OSC and OnSC. In order to study the relationship between these practices, a bibliometric analysis was conducted. The contribution to the body of knowledge will be the outcome of this literature review including an in-depth discussion on DfMA in OSC and OnSC, research gaps, and recommendations for near-future perspectives in this field. The results of this paper can help

researchers as well as professionals. It can also guide interested stakeholder groups in implementing DfMA within their projects and reduce the impression that DfMA is only applicable to OSCs.

Keywords: Design for Manufacturing and Assembly (DfMA); Off-site Construction (OSC); On-site Construction (OnSC); Modular Construction; Construction Productivity

3.2 Introduction

During the last couple of decades, industry practitioners have experienced poor performance and low productivity in the construction sector due to various factors (Q. Chen et al., 2018). Using OSC provides an opportunity to improve construction productivity (Mao et al., 2015). OSC offers a new construction approach by moving the building construction process away from the job site into a controlled factory environment (Yuan et al., 2018). According to Gao et al. (2020) many studies have explored various aspects of OSC, including its barriers and constraints, benefits, and opportunities.

In a report published by KPMG in 2016, it is cautioned that OSC alone will not overcome all the challenges the construction industry is facing, in order to achieve this, an integrated design process is needed, like the Design for Manufacture and Assembly (DfMA) method. (Boothroyd, 2005) defined DfMA as a methodology that seeks to resolve the industry's fragmentation problem by connecting design, manufacturing, and construction from early in the design process. According to the research theory of Lauri Koskela, DFMA can also be introduced into the construction industry to improve the current design system or process. (Gao et al., 2020) mentioned that a survey of DfMA users conducted by Boothroyd Dewhurst Inc. found the typical DfMA benefits include: a 51% reduction in parts count, a 37% decrease in parts cost, a 50% faster time-to-market, a 68% improvement in quality and reliability, a 62% drop-in assembly time, and a 57% reduction in manufacturing cycle time, Figure 3.1. DfMA, as a design methodology, is based on the concept of optimization and the goal is to maximize the delivery process for clients by designers. Obviously, this includes all activities, from concept to automation to logistics (Abrishami & Martín-Durán, 2021).

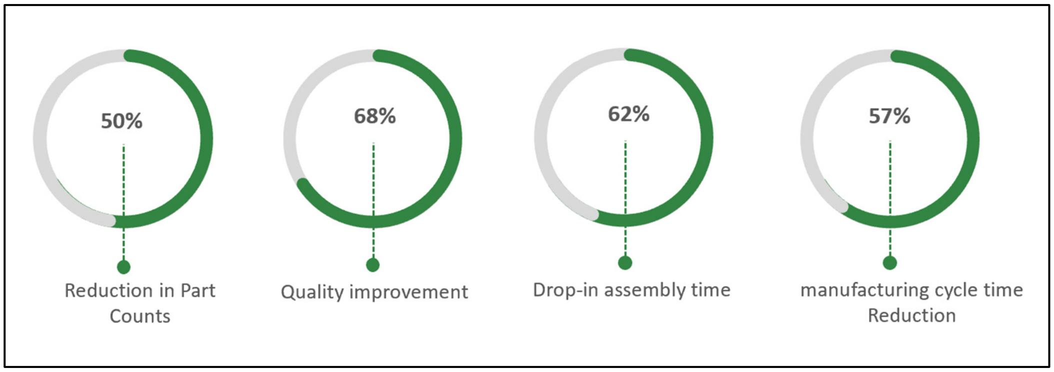

Figure 3.1 Overview of Key Benefits Associated with DfMA

According to (Lu et al., 2021) DfMA is expected to have a wide range of applications, from one-off small-scale to large-scale construction projects, and can benefit both cast-in-situ and OSC methods. DfMA uses a series of design strategies under its guidelines and principles to achieve better manufacturability and assimilability. Minimization, standardization, and modularization appear to be the key characteristics associated with the DfMA principles (Gao et al., 2018).

In relation to OSC, many designers and researchers have implemented a BIM parametric structure and utilized its data exchange capability to enhance design information production quality and design information transfer, thus improving the quality of all the design processes (Bakhshi et al., 2022b). An integration of DfMA and the capabilities of BIM tools in the design stage could both facilitate the design process and increase the efficiency of the manufacturing and assembly stages in OSC (Abrishami & Martín-Durán, 2021; Bakhshi et al., 2022b).

In order to identify areas of research that require further investigation. This literature review aims to investigate the most current practices in the field of DfMA, OSC, OnSC, and their integration with BIM as a VDC technologies. In the most recent studies, the most widespread DfMA adoption is foreseen in OSC projects and there is a lack of research on DfMA in OnSC. Currently, DfMA was closely associated with OSC and in different kinds of literature, they have been used interchangeably.

In this review, our focus will be on highlighting the application of DfMA in OSC and OnSC, and BIM as a virtual design tool, highlighting the existing gaps in research and providing recommendations regarding future research in this area. It is part of a broader research project comparing DfMA in OSC and OnSC.

3.3 The systematic literature review methodology

In this study, a comprehensive review of the existing literature is conducted in order to identify the state-of-the-art of DfMA in OSC and OnSC and its integration with BIM.

The methodological approach of this study is based on a mixed- method approach, which combines quantitative and qualitative methods. To conduct a comprehensive review and identify areas of research that require further investigation a systematic literature review (SLR) method was applied. A quantitative review by bibliometric approach and a qualitative review to provide a deeper understanding of the research topics. Conducting literature reviews systematically can enhance the quality, replicability, reliability, and validity of the review (Xiao & Watson, 2019). For analyzing and synthesizing relevant information (Sandelowski et al., 2006 ; Heyvaert et al., 2011) offered helpful insights into combining mixed methods research and combining quantitative and qualitative studies. We selected Scopus for conducting a comprehensive study of journal papers in English between 2010 and 2022. The initial keywords were selected based on the previous studies.

After data cleaning, analyzing, and synthesizing of the available studies, for the presentation of results we used the Bibliometric mapping approach with the VOS viewer computer program. VOS viewer is a freely available computer program developed for constructing and viewing bibliometric maps. The functionality of VOS viewer is especially useful for displaying large bibliometric maps in an easy-to-interpret way (Abd Razak et al., 2022).

Figure 3.2 shows the diagram for literature searches of DfMA in OSC and OnSC and the evaluation for the inclusion process. It shows the initial DfMA search, which was filtered by searching DfMA in the construction field. In the next step, by searching OSC and OnSC within the initial search results, the total number of related articles filtered to 46.

In this stage, according to Linnenluecke et al. (2020) we checked the title, abstract, and keywords of each record, and for some publications, main body skim-reading was done to determine the suitability of the publication for inclusion in the review, we also excluded any duplication, conference proceeding, book chapter, and editorial letter. As suggested by Bakhshi et al. (2022), backward and forward searches were conducted to identify relevant literature. Finally, a total of 40 journal papers were selected as key articles.

The articles were categorized into four themes, namely: DfMA, OSC/Prefabrication, OnSC, and BIM. Table 3.1 shows the summary of 40 key articles categorized based on these research themes and method type.

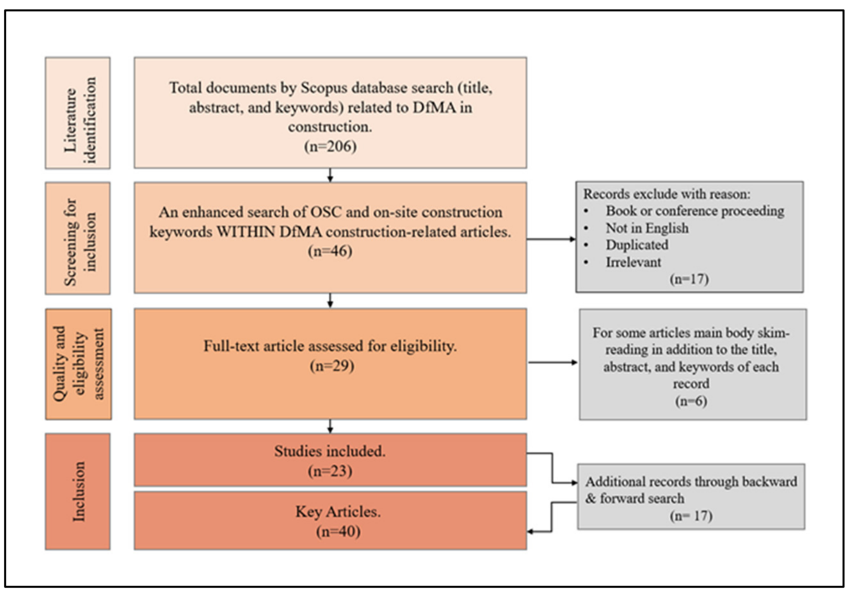

Figure 3.2 Literature search and evaluation for inclusion

Table 3.1 Comprehensive table of key articles, categorized by research themes and methodological approaches

A comparison between design for manufacturing and assembly (DfMA) in OSC and OnSC							
	Author	**year**	**Research themes**				**Method type**
			DfMA	**Prefabrication**	**On-site**	**BIM**	
1	Abd Razak et al.	2022	○	○	○	○	Review
2	Abrishami & Martín-Durán	2021	○	○		○	Develop a Framework
3	Alfieri et al.	2020	○	○			Frameworks Comparison & Process Matrix
4	Antoniou & Marinelli	2020	○	○			Introduce Standardization Proposal
5	Bakhshi et al.	2022	○	○		○	Develop a Framework
6	Banks et al.	2018	○	○		○	Case Study
7	Bao et al.	2021	○		○	○	Qualitative Research
8	Bogue	2012	○				Technical Paper

Table 3.1 Comprehensive table of key articles, categorized by research themes and methodological approaches (cont'd)

A comparison between design for manufacturing and assembly (DfMA) in OSC and OnSC							
	Author	**year**	**Research themes**				**Method type**
			DfMA	**Prefabrication**	**On-site**	**BIM**	
10	FAVI et al.	2017	○				Develop Design Approach
11	Formentini et al	2022	○				Review
12	Gao et al.	2019	○	○		○	Review
13	Gao et al.	2018	○	○		○	Questionnaire Survey
14	Gbadamosi et al.	2019	○	○		○	Develop a Design Assessment and Optimization System
15	Gbadamosi et al.	2020	○	○		○	Propose a Framework
16	Gerth et al.	2013	○	○	○		Develop a Method

Table 3.1 Comprehensive table of key articles, categorized by research themes and methodological approaches (cont'd)

A comparison between design for manufacturing and assembly (DfMA) in OSC and OnSC							
	Author	**year**	**Research themes**				**Method type**
			DfMA	**Prefabrication**	**On-site**	**BIM**	
19	Hu & Chong	2019		○		○	Review
20	Hyun et al.	2022	○	○		○	Suggest a Design Process
21	Jalali Yazdi et al.	2021	○	○			Develop a Framework
22	Jin et al.	2018	○	○		○	Review
23	Jung & Yu	2022	○	○		○	Develop a DfMA Checklist
24	Leminen et al.	2013					Develop a Checklist
25	Liew et al.	2019	○	○		○	Introduce a Novel System, Develop techniques
26	Liu et al.	2021	○	○		○	Propose a Framework
27	Lu et al.	2021	○	○	○	○	Comparative Analyses
28	Mao et al.	2014		○		○	Factor Analysis
29	Marinelli	2021	○			○	Develop Goals

Table 3.1 Comprehensive table of key articles, categorized by research themes and methodological approaches (cont'd)

A comparison between design for manufacturing and assembly (DfMA) in OSC and OnSC							
	Author	**year**	**Research themes**				**Method type**
			DfMA	**Prefabrication**	**On-site**	**BIM**	
31	Qi et al.	2021	○	○		○	Review
32	Shang et al.	2020	○	○		○	Questionnaire Survey
33	Tan et al.	2020	○				Proposed Guidelines
34	Tinder	2018	○	○	○	○	Interview & Case study
35	Vaz-Serra et al.	2021	○	○		○	Case Study
36	Wasim et al.	2020	○	○	○	○	Develop a tool
37	Wasim et al.	2022	○	○	○	○	Review
38	Wuni & Shen	2020		○			Questionnaire Survey
39	Yin et al.	2019	○	○		○	Review
40	Yuan et al.	2018	○	○	○	○	Develop a Design Approach

3.4 Quantitative analysis

To identify publications related to DfMA, a search in Scopus for articles from the year 2010 to 2022 was conducted. The set of keywords used in this search was:

"DfMA" OR "Design for Manufacturing and Assembly" OR "Design for Manufacturing" OR "Design for Assembly" AND "Construction".

The results of the above-mentioned initial search were then filtered to search OSC and OnSC within the DfMA cluster. A total of 206 articles were selected as the most related publications for further qualitative analysis. Figure 3.3 shows the number of publications related to DfMA in construction by year (2010–2022) and by journals. The maximum percentage of papers in a single year was published in 2022 (23.5%) and the majority of the articles in DfMA in construction are published in Automation in Construction journal. It is worthy to note neither of these journals focuses on investigating the DfMA in OnSC. Accordingly, this fact confirms that the use of DfMA in OnSC is something that needs more attention and focuses in future studies.

To identify pioneer researchers of DfMA in construction, a bibliometric analysis was conducted and the key authors were identified. In Figure 3.4, we show the results for authors with more than three publications in this area.

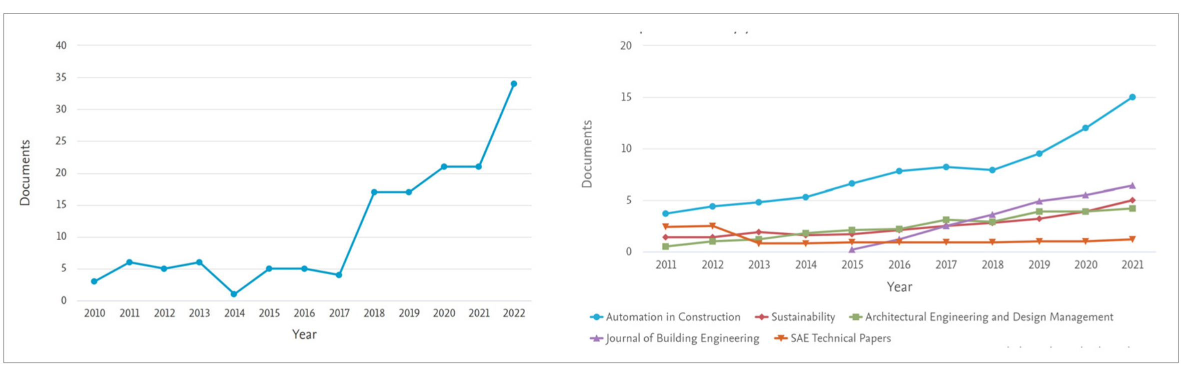

Figure 3.3 Left: Total number of articles by year;
right: Total number of articles by journal

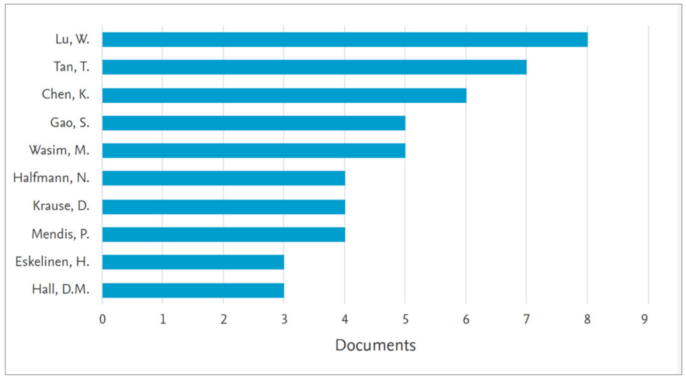

Figure 3.4 Pioneer authors with a minimum of
3 publications in DfMA in construction

The following keywords were used in a bibliometric search in Scopus, to identify the related articles published from 2010 to 2022. All non-related subject areas were excluded, and the search was limited to English articles only. The set of keywords used for the initial search is as follows:

("DfMA" OR "Design for Manufacturing and Assembly" OR "Design for Manufacturing" OR "Design for Assembly") AND ("OSC" OR "Off site construction" OR "off-site construction" OR "offsite construction" OR "On-site" OR "On-site construction" OR "Onsite construction" OR “Off-site manufacture” OR “Off-site manufacturing”) AND "Construction".

Data was exported from Scopus to VOS viewer for bibliometric analysis to identify related keywords in this domain. Figures 3.5 and 3.6 were generated by VOS viewer software. Figure 3.5 shows the country mapping for DfMA in OSC and OnSC -related articles and Figure 3.6 shows the results for the keywords that occur more than 3 times.

Figure 3.5 Country mapping for DfMA in construction related articles

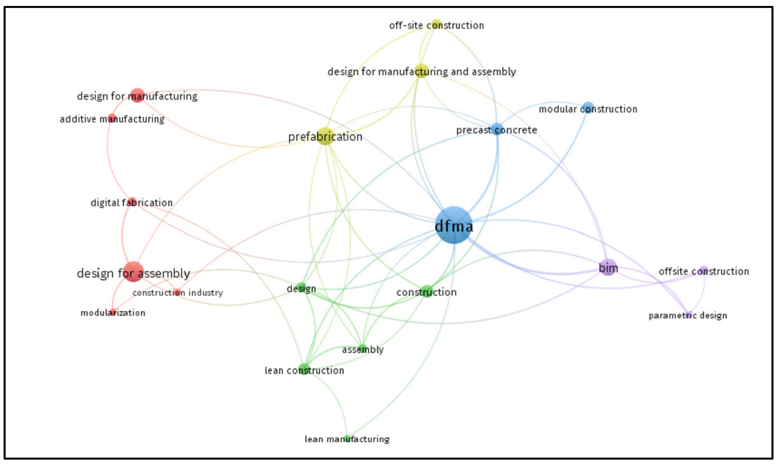

Figure 3.6 DfMA in construction keywords mapping

Country mapping for DfMA in construction reveals the influential countries in the domain as well as direct and indirect relationships in terms of the information flow and closeness among countries. As shown in Figure 3.5, the United Kingdom, Canada, Italy, Switzerland, and the United States are productive with direct and indirect relationships with each other, and the United Kingdom is the only country that connects with all countries and the most prominent country in this field. Co-authorship analysis of countries can contribute to redefining strategies and establishing policies to improve productivity (Karimi & Iordanova, 2021). Table 3.2 completes this analysis by showing countries with more than 5 publications related to DfMA in construction.

According to Su & Lee (2010) in bibliometric studies, the analysis of keywords provides insight into the extent of a research domain and marks its boundaries. In keywords mapping, the cluster density view is particularly useful to get an overview of the assignment of items to clusters and how clusters of items are related to each other (van Eck & Waltman, 2010), which shows the relationships among subdomains existing in the studied field (Karimi & Iordanova, 2021).

Keywords represent the key contents of existing research and depict the areas studied within the boundaries of a given domain (Su & Lee, 2010). A network of keywords shows the knowledge in terms of relationships, patterns, and intellectual organization of research themes (van Eck & Waltman, 2010).

Table 3.2 Countries with more than 5 publications in DfMA in construction

Country	Number of articles	Citations	Total length strength
United Kingdom	36	557	24
Australia	24	470	18
China	15	457	20
United States	13	138	5
Germany	13	34	0
Hong Kong	9	161	14
India	8	3	0
Canada	6	94	6
Singapore	6	159	4
Italy	6	156	2
Switzerland	5	49	3
Poland	5	11	0
South Korea	6	8	0

Figure 3.6 shows that apart from the DfMA-related keywords, which are the central field of this literature review, “prefabrication”, “off-site construction/offsite construction”, and “BIM” attracted higher attention. In addition, analysis of the node weight degree reveals that these

research areas have much higher relative importance compared to all the others. On the other hand, regardless of BIM, less attention has been paid to other aspects of technological application concepts (parametric design, additive manufacturing) in DfMA, which indicate that researchers investigated these research areas less frequently within the body of the existing literature. More importantly, OnSC is not one of the keywords, so it can be concluded that there is a lack of research in DfMA in OnSC and this domain requires more attention from researchers. This is supported by Table 3.3, which shows DfMA keywords that occur more than three times.

Table 3.3 Top 15 high occurrence keywords in DfMA in construction

Ranking	**Occurrence**	**Total Link Strength**	**Keyword (total 532)**
1	37	42	DfMA, Design for Manufacturing and Assembly
2	13	4	Design for Assembly
3	11	18	Prefabrication
4	10	17	BIM
5	9	15	Off-site construction, Offsite Construction
6	8	4	Design for Manufacturing
7	7	19	Construction
8	7	17	Precast Concrete
9	8	4	Design for Manufacturing
10	6	6	Modular Construction
11	5	16	Design
12	4	5	Digital fabrication
13	4	3	Additive Manufacturing
14	3	6	Parametric Design
15	3	4	Modularization

3.5 Qualitative analysis

The qualitative analysis discussed in this study is part of an ongoing research project, which aims to investigate the DfMA in OSC and OnSC. Section 3 of the current literature helps to identify trends and the current status of the DfMA in construction and its application in OSC and OnSC and the role of BIM as a virtual design tool. Based on table 1, the most relevant articles to the research topic were identified to be examined in greater detail. Using the literature review as a guide, a majority of studies discussed different DfMA-related categories like definition (Boothroyd, 2005; Gerth et al., 2013; Gao et al., 2018; Marinelli et al., 2022), guidelines (Bogue, 2012; Gao et al., 2018), process (Gao et al., 2018), methods for applying (Gao et al., 2018), benefits (Gao et al., 2018; Yuan et al., 2018 ; Yin et al., 2019; Marinelli et al., 2022), hindrance factors, (Q. Chen et al., 2018; Lu et al., 2020; Bao et al., 2022) technological requirements (Gao et al., 2018; Jin et al., 2018; Bao et al., 2022;) , and enabling factors (Abd Razak et al., 2022; Pasco et al., 2022). In the following sections we are going to qualitatively analyze and highlight our findings in three categories:

3.5.1 DfMA and OSC

DfMA and OSC are currently closely associated (Gao et al., 2020; Lu et al., 2020), and in Various studies we reviewed their terminology used interchangeably (O'Rourke, 2013; Gao et al., 2020; Abd Razak et al., 2022). According to (Abd Razak et al., 2022) few studies have addressed the linkage between DfMA and OSC. Based on the literatures reviewed we are going to compare these two terminologies, DfMA and OSC and clarify their similarities and differences in the following aspects:

Historical background: Formal approaches to DFM and DFA emerged in the late 1960s and early 1970s, and DfMA has its origin in the manufacturing industry (Bogue, 2012). A variety of countries began using prefabricated buildings in 1940, and the concept quickly spread around the globe (Yuan et al., 2018). According to Lu et al. (2021), the empirical implementation of many DfMA guidelines and OSC technologies has begun in the AECO industry in the recent decade. So, we would argue that DfMA and OSC are not entirely new in construction.

Definition: Goulding et al. (2015) defined DfMA as a systematic procedure, which can add value to the construction/production process by standardizing components and reducing variables, while OSC is a construction approach in which building elements are manufactured in a place other that their final installation location (Pasco et al., 2022). According to the definitions and as confirmed by Bakhshi et al. (2022) and Abd Razak et al. (2022) it can be argued that DfMA has the potential as a design approach and as a tool to be used in OSC designs to respond to the complexity of the construction industry and to maximize the full advantage of OSC as a whole.

Objectives: Based on studies by Gao et al. (2020) and Lu et al. (2020), DfMA aims to improve manufacturability and assimilability from the early stage of design. Yuan et al. (2018) also described OSC's main objectives as standardization, industrial production, and assembly construction. The studies show that the benefits of DfMA and OSC may look similar since both aim for the same objective.

Methods to achieve: As stated by Lu et al. (2021), DfMA uses a series of design strategies under its guidelines and principles to achieve better manufacturing and assembly. OSC can be achieved by designing, manufacturing transporting, and installing the construction components (Mao et al., 2015). So, as mentioned before, DfMA as a tool can be used in the OSC design process to ensure high quality in all stages of building construction (Bakhshi et al., 2022).

3.5.2 DfMA and On-site construction

DfMA is expected to have a wide range of applications, from one-off small-scale to large-scale construction projects, and can benefit both cast in-situ and OSC methods (Lu et al., 2021). Most discussions about DfMA are focused on OSC (Abd Razak et al., 2022). While Gao et al. (2020) stated that construction is moving towards a combination of OSC and on-site assembly. Thus, there should also be guidelines for on-site fabrication and prefabrication since not all projects are suitable for OSC, but can still benefit from DfMA design principles (Abd Razak et al., 2022). The limited examples reported in the literature give the impression that DfMA serves OSC only. So, as Lu et al. (2021) also mentioned, more research studies on DfMA applications in OnSC are recommended.

3.5.3 DfMA and BIM

Abrishami & Martín-Durán (2021) Considered BIM as a virtual design and construction (VDC) technology that facilitate DfMA implementation from different aspects, BIM can link DfMA activities like procurement, fabrication, transport, installation to upstream activities such as briefing, appraisals, and conceptual design, thereby improving communication and collaboration with stakeholders. In addition, BIM has a role in making the project less risky by allowing the project team to simulate the construction virtually to identify potential pitfalls way before the actual construction begins.

Our research indicates that while there is a considerable focus on the BIM-DfMA approach, there remains a significant research gap concerning how this approach should be adopted in the contexts of OnSC as defined in this study. Firstly, in scenarios where on-site work is part of a larger OSC project, such as the assembly of the Hambro composite floor system by CANAM, where structural components are assembled on the actual site. Secondly, in projects entirely executed on-site, like the GBE system by GBE Innovation Company, involving the creation of a cast-in-place sandwich wall with internal insulation between two concrete skins. The GBE system, as an innovative substitute for insulated pre-walls or external thermal insulation, exemplifies the varied applications and realizations of OnSC that are yet to be fully explored in the realm of the BIM-DfMA approach.

3.6 Conclusion and future work

This paper discusses how DfMA research has evolved in construction over the past decade. This study is required in order to understand DfMA in construction, its applications in OSC and OnSC, and its integration with BIM as a virtual design tool. Here, we conducted a systematic literature review based on publications in the Scopus database. The review was restricted to journal publications from 2010 to 2022. With the help of the quantitative method, the bibliometric analysis of DfMA in construction enabled the identification of the most recent subfields of study, including DfMA, OSC/Prefabrication, OnSC, and BIM. In addition, to analyze qualitatively, key publications relevant to DfMA's application in OSC and on-site construction were selected from the dataset. The classification of key articles shed light on how DfMA and OSC are similar and different in terms of historical background, definition, objectives and methods to achieve. The Categorization also shows that the literature on DfMA is limited in OSC and there has been insufficient research on the application of DfMA in OnSC. In exploring the integration of DfMA with BIM as a digital technology, in addition to its benefits, there is a lack of research regarding how this approach should be adopted during the whole lifecycle of a construction project. Further research is required to investigate the lack of on-site DfMA based prefabrication for construction components rather than OSC, and studying the integration of DfMA with emerging technologies like BIM during the whole lifecycle of a construction project.

3.7 Acknowledgement

The authors would like to gratefully thank Mitacs Acceleration Program and the École de technologie supérieure (ÉTS) for their support and financial contribution.

CHAPTER 4

IDENTIFYING CHALLENGES FOR EXTENDED DESIGN FOR MANUFACTURING AND ASSEMBLY (DfMA) IN ALL PHASES OF A CONSTRUCTION PROJECT

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4.1 Abstract

Design for Manufacturing and Assembly (DfMA) has emerged as a promising approach to enhance productivity in the construction industry. In recent studies, the most widespread DfMA adoption is foreseen in off-site construction (OSC). This creates a misconception that DfMA serves OSC only, while not all projects are suitable for full OSC, but they can still benefit from DfMA design principles. In this context, "on-site construction (OnSC)" refers to work completed on-site as part of an OSC project, as well as OnSC using specific realization methods. Since the adoption of DfMA as a systematic procedure is anticipated to be widespread within the construction sector, it is crucial to identify challenges associated with its implementation in the different stages of the construction process. This article aims to identify, verify, and analyze the challenges to the adoption of DfMA with a focus on the on-site parts of the construction. The study utilized a mixed-method approach, comprising of an extensive review of the literature and industry expert interviews. The information gathered was analyzed and synthesized using NVivo 14 Pro and prioritized using the mean score (MS) analysis and weighting function. Based on the research methodology, 42 DfMA challenges were validated and grouped into 9 Main categories. Further analysis concluded that the three most important challenges in implementing DfMA in on-site parts of the construction are economic and financial, technological, and legal contractual challenges. They formed the basis for developing a conceptual framework representing DfMA-related challenges. By identifying and understanding the challenges for DfMA adoption in both OSC and OnSC, this article aims to contribute to the body of knowledge in construction management and provide valuable insights for industry professionals, researchers, and policymakers. Ultimately, the findings of this study can guide organizations in effectively implementing DfMA strategies in all stages of a project, leading to enhanced construction productivity, sustainability, and competitiveness in the built environment.

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

4.2 Introduction

For decades, the construction industry has suffered from remarkably low productivity. Global productivity growth in the construction sector has averaged just one percent a year for the past two decades compared with world economic growth of 2.8 percent and manufacturing growth of 3.6 percent, this clearly indicates that the construction industry is underperforming (McKinsey Global Institute., 2017).

In the past few decades, OSC has grown in popularity in the construction sector, and various studies have recommended it as a way to boost productivity (Barlow et al., 2004; Alazzaz & Whyte, 2014; Li et al., 2022). In a 2016 report by KPMG, it was highlighted that OSC could not address all the challenges of the construction industry; hence, an integrated approach like Design for Manufacture and Assembly (DfMA) was considered essential. DfMA, initially developed in the manufacturing industry, has now become a significant approach in construction, enhancing the process through the standardization of components and the reduction of variables. It offers the potential to enhance productivity, efficiency, and quality (Goulding et al., 2015).

Different studies have been conducted on the use of DfMA methods in OSC projects leading to the misconception that DfMA only serves OSC. However, according to Lu et al. (2021) the use of DfMA is expected to have a wide range of applications, ranging from one-off small-scale to large-scale construction projects, benefitting both OnSC and OSC methods.

This study was partly inspired by a real-world industrial application, introduced through a Mitacs project in collaboration with GBE innovation company, a manufacturer and supplier based in France. GBE is known for producing cast-in-place concrete walls with integrated insulation, a process they believe to be a novel and updated approach in the construction industry which is an excellent alternative to insulated double walls (prefabricated sandwich panels) or external thermal insulation. The implementation of the GBE® process necessitates exacting accuracy, especially during the simultaneous continuous pouring of self-compacting concrete on both sides. It was observed that the vast majority of this process was executed on-site, emphasizing the critical nature of onsite operations in its success. This insight into GBE's practices underscores the relevance of examining the importance of OnSC, particularly those processes that are thought to be innovative yet remain heavily reliant on traditional on-site methods.

In the broader context of construction, even the highest degree of prefabrication, as classified by Gibb's (2001) taxonomy (level 4, indicating a fully modular building), involves elements that require on-site completion. It is a fundamental aspect of construction that some processes, adaptations, or integrations are more effectively managed directly at the project site. This reality brings into focus the significance and applicability of the DfMA principles beyond the OSC, reveals opportunities to streamline even those on-site components and activities. This approach aims to enhance efficiency and coherence throughout the entire building process, merging innovative methods like those of GBE with on-site techniques.

There have been numerous challenges identified and documented with regard to DfMA methods in OSC projects in previous studies. In addition, some strategies were suggested to facilitate DfMA's application in OSC, However, based on the literature review, none of these studies conducted a comprehensive study to identify the existing challenges, focusing on all phases of construction projects to consist of both OSC and OnSC parts. Even in the literature with a focus on the DfMA challenges in OSC the impact and the importance of the identified challenges are not investigated.

This article begins by defining DfMA, as a methodology that simplifies and optimizes the manufacturing and assembly processes of various components used in construction. The study then aims to identify the challenges hindering the adoption of DfMA methodology beyond the boundaries of OSC, focusing on OnSC parts. By integrating insights from a comprehensive literature review and interviews with industry experts, the article delves into the current state of knowledge surrounding DfMA. It focuses on uncovering and discussing the key barriers and difficulties that currently impede its widespread implementation in the construction sector. By shedding light on the challenges related to DfMA adoption, the article contributes to construction management knowledge. It provides valuable guidance for researchers and practitioners, facilitating quicker investigation of the root causes of barriers in implementing DfMA strategies across various construction projects. Additionally, it assists in addressing these hindrance factors by suggesting appropriate remedial measures.

This paper is structured in a way that facilitates a comprehensive understanding of the subject matter. It begins with the 'Research Background' section, offering an in-depth overview of DfMA in construction. Following this is the 'Methodology' section, detailing the research approach and the techniques employed for data collection and analysis. The 'Discussion and Research Findings' section comes next, where the analysis of the data is explored, highlighting key results and their implications. An additional section, 'Compare DfMA in OSC and On-site,' is included to specifically focus on the comparative analysis of DfMA in OSC versus traditional on-site methods. The paper concludes with the 'Conclusion' section, summarizing the study's main insights and contributions, and emphasizing significant findings from the data analysis.

4.3 Research Background

DfMA as a methodology, emphasizing simplicity and minimizing the use of materials, labor, and manufacturing-related activities (Wasim et al., 2020). It was in the late 1960s and early 1970s that formal approaches to design for manufacture (DfM) and design for assembly (DfA) were developed, which were reflected in 1975 British standards on managing design for economic production. With Boothroyd and Dewhurs' practice and research, DfMA also became an academic field in the 1970s. Since the 1980s, it has been extensively used to streamline product design and cut down on manufacturing time and costs (Langston & Zhang, 2021).

DfMA is a tool that is used to illustrate how an approach that was previously sequential and conventional is now taking a non-linear and iterative approach (Tuvayanond & Prasittisopin, 2023). Various researchers Bogue (2012), Boothroyd (1994), and Vaz-Serra et al. (2021) mentioned that DfMA, as a methodology, is based on certain guidelines, standards, and rules; and diverse policies have been introduced to enable efficient implementation of DfMA. In general, common guidelines for DfMA encompass minimization, standardization, and modularization (Song et al., 2022).

According to Gao et al. (2018), for the construction industry in particular, there are three views on the adoption of DfMA: DfMA as a systematic process combining design, manufacture, and assembly to enhance value of the overall process; DfMA as an evaluation system that can assess the efficiency in manufacturing and assembly, integrating with virtual design and construction; and DfMA as a technology which is a revolutionary approach linked with evolving prefabrication and modular construction techniques.

Numerous studies have emphasized the benefits of DfMA such as; reduce cost and time (Tan et al., 2020; Wasim et al., 2020; Lu et al., 2021), enhance quality (FAVI et al., 2017; Bao et al., 2022), reduced construction labor (Machado et al., 2016; Bakhshi et al., 2022), enhanced sustainability and circular economy during asset's lifecycle (FAVI et al., 2017; Gao et al., 2018), and enhancing waste management (Roxas et al., 2023). According to Lu et al. (2021), if we take a closer look at DfMA and its similar concepts, such as buildability, value management, and lean construction, we can see that the DfMA philosophy is reflected in various construction practices throughout the industry.

As reported in the literature by Bao et al. (2022) and Wasim et al. (2020), DfMA applications are still limited, and not much information is available on DfMA adoption in the construction industry. However, in different research there are several challenges associated with the adoption of DfMA in the construction industry including resistance to change and a preference for traditional methods (Montali et al., 2018; Langston & Zhang, 2021), lack of government support and incentives (Chen et al., 2017), lack of planning and building codes alignment (Bao et al., 2022), higher costs, government regulations, risk aversion (Langston & Zhang, 2021), lack of suitable technical requirements (Bakhshi et al., 2022). It is important to recognize that each of these challenges has a complex environment for the widespread adoption of DfMA in the construction industry. This underscores the need for coordinated efforts from industry stakeholders, government agencies, as well as the construction industry to ensure that these issues are addressed and DfMA's benefits are promoted positively.

While the existing literature provides insights into the use of DfMA in OSC, a significant gap remains in understanding its challenges and opportunities in OnSC contexts. As outlined earlier 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. This gap is particularly notable given the construction industry's chronic underperformance in productivity compared to other sectors. Moreover, while DfMA's potential in enhancing productivity, efficiency, and quality in OSC is acknowledged, its broader application in OnSC – where processes and integrations often require direct management on project sites – is less explored. This paper aims to bridge this gap by specifically focusing on the challenges of implementing DfMA beyond the OSC environments.

The objectives of this study are: to begin with, conducting a comprehensive investigation into the current challenges hindering DfMA's adoption in OnSc, a facet less emphasized in existing studies. This involves analyzing both the challenges documented in the context of OSC and identifying unique challenges pertinent to OnSc. Next, the paper seeks to evaluate the impact and significance of these challenges, providing insights into their relative importance and potential implications for the construction industry. By addressing these objectives, this study endeavors to extend the existing body of knowledge on DfMA and its applicability, offering practical recommendations for overcoming barriers and promoting the wider adoption of DfMA principles in both OnSc and OSC projects.

4.4 Methodology

This study was conducted using a mixed method research approach consisting of quantitative and qualitative research design as the methodological framework in the pursuit of creating a comprehensive understanding of the studied phenomenon. According to Boswell & Cannon (2022), due to the complexity of today's problems, the rise of qualitative research, and the need for diverse audiences to be served by various forms of data, mixed methods research is becoming increasingly important; so, in order to provide a complete analysis of problems, quantitative and qualitative data must be combined. Figure 4.1 shows the multistage methodological approach flowchart for this research.

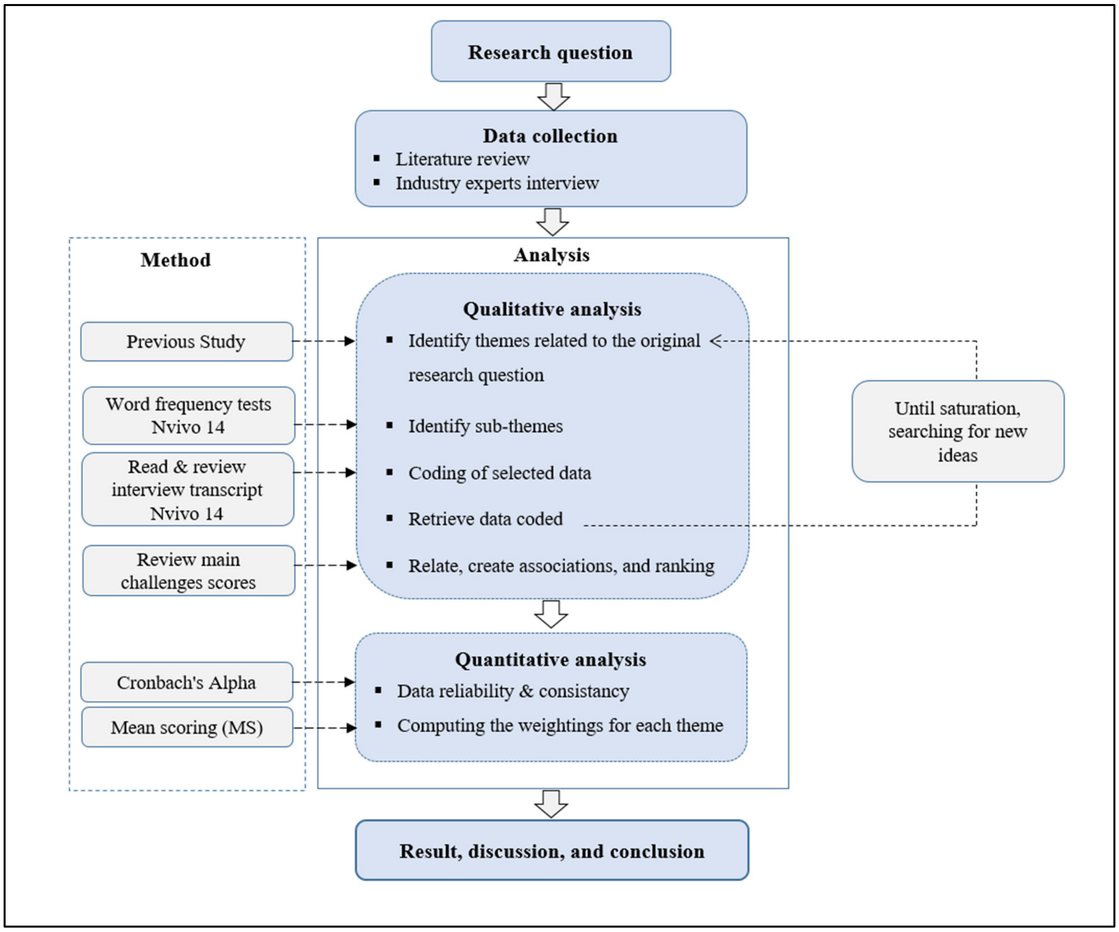

Figure 4.1 Multistage methodological approach flowchart

4.4.1 Data collection

First, a review of the previous literature was conducted in section 2, as part of the overall multistage methodology in order to assess the current state of the DfMA in construction and its adoption in OSC and OnSC. The literature review shed light on the fact that the literature on DfMA is limited in OSC and there has been insufficient research on the application of DfMA in OnSC (Lu et al., 2021).

To identify DfMA challenges in OnSC, we used the opinion and experience of industry experts. It is very common to conduct interviews in order to gather data (Taylor, 2005), and semi- structured interviews are the most commonly used interview technique in qualitative research (DiCicco-Bloom & Crabtree, 2006). A semi-structured interview approach was applied, where we asked open-ended questions within a specific theme as described by (Denzin & Lincoln, 2011). This method, as mentioned by Kallio et al. (2016), helped us gathered reliable and comparable data; It also gave us flexibility to ask more questions on the spot and plan out the main topics in advance. The study employed a comprehensive questionnaire, it was designed to cover a broad spectrum of potential challenges in DfMA implementation, derived from both literature review and preliminary expert feedback. This iterative design process ensured the questionnaire's relevance and comprehensiveness. The questionnaire comprised of four sections. The first section, titled 'Expert's Profile and Professional Experience,' requested participants to share their occupational background and their experience in construction. The second section, served as an introduction to the questionnaire, setting the context for the subsequent queries. The third section delved into "OnSC Project Description" which included detailed examples of some of these specific OnSC projects like GBE process. Finally, the fourth section, "DfMA Challenges Interview Questions" encompassed a series of questions categorized into nine different sections according to previous study. The questionnaire probed into various aspects of DfMA implementation in OnSC. Questions covered legal and contractual considerations, such as contract drafting and negotiation factors. Technological inquiries focused on tools and bottlenecks in DfMA application, including automation and robotics. Procedural barriers, including scheduling and workforce coordination. Cultural factors, like stakeholder communication and social attitudes. Commercial challenges, geographical influences, and economic and financial impacts, such as cost and Return of Investment (ROI), were also discussed. The questionnaire delved into technical cognitive aspects like project planning and labor requirements. Finally, policy and regulatory barriers, alongside unforeseen challenges like weather and site constraints, were also addressed. Additionally, this section concluded with an open-ended query inviting respondents to share any further insights or points not covered in the interview, emphasizing the value of their unique perspectives. The questionnaire is attached in Appendix 1 for reference.

Noble and Smith (2015) emphasized the importance of truth value in qualitative studies, such as semi-structured interviews, for ensuring the credibility of results and the representation of samples. This study conducted ten interviews, using the purposive sampling technique and thematic analysis, until reaching saturation. Saturation is achieved when new data no longer provides significant new insights, as outlined by Saunders et al. (2018).

4.4.2 Semi-structured interviews

We conducted interviews with a diverse group of ten industry experts from various professional backgrounds, each possessing varying years of experience within the construction industry. All interviews were conducted online for maximum accessibility and convenience for the participants, with interview durations ranging from 30 minutes to one hour. Table 1 indicates the profile of respondents in the interview. In order to prevent ethical issues, the interviewees were informed that their names and companies were kept anonymous. As well, interviewees were free to quit at any time. All interviews were audio-recorded and transcribed accurately in Microsoft Word documents. The transcripts of each single-person interview were imported as single documents into the NVivo 14 project. This computer-assisted qualitative data analysis software (CAQDAS) was developed by QSR International (Melbourne, Australia), the world's largest qualitative research software developer. By using this software, one can perform qualitative inquiry beyond mere coding, sorting, and retrieval of data. A key feature of the software is its ability to integrate coding with qualitative linking, shaping, and modeling (Wong, 2008).

Table 4.1 Interviewees' profile

Interviewee	professional role	Type of company	Industry experience (years)	Interview duration
Int-1	Project manager	Manufacturer	10	55 min
Int-2	Project manager	Structural engineering	8	32 min
Int-3	Director	General contractor	10	38 min
Int-4	Design director	General contractor	20	40 min
Int-5	Project manager	Structural engineering	13	30 min
Int-6	Architect	Manufacturer	20	35 min
Int-7	Director	Architecture	10	45 min
Int-8	Digital construction director	General contractor	15	30 min
Int-9	Director	General contractor	10	30 min
Int-10	Architect	Architecture	4	50 min

4.4.3 Data analysis

According to Wong (2008) in the qualitative data analysis process, the process of coding or categorizing the data is the most important part of the procedure; which involves subdividing a huge amount of raw information or data and subsequently assigning the collected information or data to different categories. NVivo enhances research quality by simplifying the data analysis process that would typically be done manually. It saves time, facilitates the identification of trends and themes, and makes qualitative data analysis more systematic (Wong, 2008).

As proposed by Lewins and Silver (2007), qualitative studies should reflect on how the coding themes were chosen in analyzing interview transcripts. The coding process for this research followed the approach used by Dransfield et al. (2004) involving two steps:

Initially, NVivo codes were established by conducting a thorough review of the existing literature, particularly focusing on the research that served as the theoretical foundation for this study. This included an in-depth analysis of challenges to the implementation of DfMA in OSC, as outlined by Rankohi et al. (2023). These challenges were categorized into eight groups: legal contractual, technological, procedural, cultural, commercial, geographical, economic and financial, technical cognitive. The codes were further classified into nine categories. These categories are directly related to the challenges associated with DfMA in the OnSC process. The identified categories, considered as parent codes, include: (1) legal contractual, (2) technological, (3) procedural, (4) cultural, (5) commercial, (6) geographical, (7) economic and financial, (8) technical cognitive, and (9) policy. Employing such a technique ensures a clear link between the research questions and the data. It also facilitates the generation of new insights, as highlighted by Bazeley (2013). Secondly, after importing interview transcripts into NVivo 14 using the code functions, we looked for repetitions and regularities by running word frequency tests. According to Ryan & Bernard (2003), discovering concepts and themes in texts can be done most efficiently by analyzing the frequency of words or the number of repetitions. Similarly, Bazeley (2019) mentions people repeating ideas of significance to them, and identifying these repetitions can provide insight into the context in which they are used. So, Sub-themes were meticulously defined by conducting separate word frequency queries in NVivo for each main theme. This process involved analyzing the query results, which included the frequency of each word's occurrence in the text, its weighted percentage, and its synonymous terms Figure 4.2 is a screenshot of word frequency queries. Based on these comprehensive data, we systematically delineated sub-themes for each main theme.

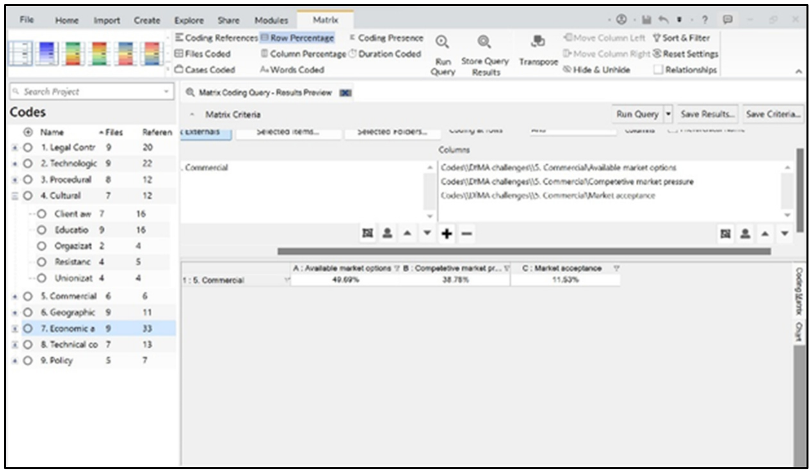

Figure 4.2 Matrix coding query for one of the main DfMA challenges and the sub- categories by NVivo 14

Finally, a total of 42 challenges were reviewed and discussed by 10 interviewees across 9 categories of the DfMA implementation with a focus in OnSC, who agree that these challenges have adversely affected the implementation of the DfMA in construction projects. Table 4.2 shows the DfMA challenges for the on-site part of the constructions identified through industry expert interviews.

Table 4.2 On-site construction (OnSC) DfMA challenges

N	Categories	Code	Challenges
1	Legal Contractual (L)	L1	Accurate cost estimation
		L2	Agility and flexibility
		L3	Clear performance metric
		L4	Clear role and responsibilities
		L5	Collaborative contracting
		L6	Competitive BID pricing
		L7	Dispute resolution method
		L8	Guarantee and insurance clarity
		L9	Risk and reward sharing

Table 4.2 On-site construction (OnSC) DfMA challenges (cont'd)

N	Categories	Code	Challenges
2	Technological (T)	T1	Cost of technology adoption
		T2	Identifying appropriate tools and techniques
		T3	Interoperability and digital integration
3	Procedural (P)	P1	Additional project planning
		P2	Interdisciplinary communication and collaboration
		P3	Owner expectation management
		P4	Quality control at every stage
		P5	Supply chain management
4	Cultural (C)	C1	Client awareness
		C2	Education and training
		C3	Organizational culture
		C4	Resistance to change
		C5	Unionization and corporate policies
5	Commercial (CO)	CO1	Available market options
		CO2	Competitive market pressure
		CO3	Market acceptance
6	Geographical (G)	G1	Infrastructure and utilities
		G2	Local climate and weather conditions
		G3	Local regulations and permitting
		G4	Local workforce and skills
		G5	Logistics and transportation considerations
		G6	Manufacturing facilities availability
		G7	Material availability
		G8	Specific site factors and limitations

Table 4.2 On-site construction (OnSC) DfMA challenges (cont'd)

N	Categories	Code	Challenges
7	Economic and financial (E)	E1	Cost overruns and contingencies
		E2	Financial options and funding
		E3	Initial capital cost and automation
		E4	Insurance and liability considerations
8	Technical cognitive (TG)	T1	Design detail and complexity
		T2	Project planning and scheduling
		T3	Technical expertise and skills
9	Policy (P)	P1	Incentives and investments
		P2	Permitting and approval process

After conducting a qualitative analysis using NVivo on the interview transcripts, and identifying the primary challenges, each main challenge was ranked on a scale of 1 to 5 based on its significance through the reviewing the interview transcripts.

Various methods were employed to assign scales based on expert opinions gathered during interviews and through the analysis of transcripts. The first approach involved direct inquiry into factors commonly identified in the list and sought the opinions of experts. These experts were requested to assess the significance of challenges in implementing DFMA. These factors could include aspects such as Accurate cost estimation (L1), Initial capital cost (E3), Permitting and approval process (P2), or the Local regulations and permitting (G3). The experts were then asked to assess the significance of these challenges on a scale ranging from 1 to 5.

The subsequent method involved evaluating the frequency of the topic and the degree of emphasis placed on specific factors in terms of repetition and the time experts dedicated to discussing each factor. In this method, the researchers analyzed the transcripts of interviews to evaluate the frequency of certain topics and the degree of emphasis placed on specific factors by the experts. This involved identifying how often certain challenges were discussed, and the amount of time dedicated to each factor during the interviews. The goal is to assign a numerical value on the scale of 1 to 5, where 1 indicates "Not at all important" and 5 indicates "Very important." Table 4.3 used to assign the degree of importance based on transcription:

Table 4.3 Degree of importance

Scale	1	2	3	4	5
Frequency	Never mentioned during the interview.	The category was discussed, but the specific factor was indirectly mentioned.	The category and factor were discussed directly once	The category and factor were discussed directly more than once.	Experts directly emphasized the importance and elaborated on it further

The scale is interpreted as follows: 1 = Not at all important, 2 = Slightly important, 3 = Important, 4 = Fairly important, and 5 = Very important. We continued by analyzing the data set using Statistical Package for the Social Science (IBM SPSS v.25), and Cronbach's Alpha was used to evaluate both the data reliability as well as the reliability of the survey instrument. According to Tavakol & Dennick (2011) for evaluating the internal consistency of the answers, Cronbach's alpha was employed, a scale from 0 to 1. A Cronbach's alpha of 0.7 signifies an acceptable level of reliability, with 0 denoting no reliability and 1 signifying absolute reliability (Tavakol & Dennick, 2011). The assessment resulted in a Cronbach's alpha score of 0.804, surpassing the acceptable limit and indicating a dataset of high reliability. Table 4.4 illustrates the variable and internal consistency values based on Cronbach's alpha.

$$\alpha = \frac{K}{K-1}\left[1 - \frac{\sum S^2 y}{S^2 x}\right] \tag{4.1}$$

Taken from Tavakol & Dennick (2011)

Table 4.4. Internal consistency

Variable	Description	Value	Internal consistency
K	Number of DfMA challenges	9	0.804
$\sum \mathbf{s^2y}$	Sum of each DfMA challenges variance	4.87	
$\mathbf{s^2x}$	The variance of a sum of DfMA challenges value	17.09	

4.4.3.1 Mean scoring and ranking of DfMA challenges

We computed the mean scores (MS) for the identified DfMA challenges on a 5-point grading scale. This approach can be applied as a result of the work of researchers (Wuni & Shen, 2020; Attouri et al., 2022), that they all used the MS in order to form the basis for evaluating the ranking and prioritizing different factors in their research. We used the following formula to compute MS (mi).

$$\text{MS} = \frac{\sum(E \times F)}{N}, \; (1 \leq \text{MS} \leq 5) \tag{4.2}$$

Taken from Tavakol & Dennick (2011)

Where E is a score given to each challenge based on the analysis with NVivo, ranging from 1 to 5; F is the frequency of each rating (1–5) for each challenge; and N represents the total number of industry experts. Among challenges, those with the highest score were regarded as the major challenges that influenced the adoption of DfMA in on-site part of the constructions. Table 4 displays the mean scores (MS) analysis results.

Table 4.5 DfMA challenges ranking (Based on MS)

Categories	MS	Rank
Economic and financial (E)	4.6	1
Technological (T)	4.4	2
Legal Contractual (L)	4.3	3
Technical cognitive (T)	4.2	4
Procedural (P)	4.1	5
Cultural (C)	3.6	6
Geographical (G)	3.1	7
Policy (P)	2.6	8
Commercial (CO)	2.2	9

In the process of ranking the sub-categories pertinent to DfMA challenges, our methodology employed a matrix coding query. As delineated by Bazeley (2018), this technique enables the creation of a matrix or table, providing a visual intersection of various codes or themes. Such an approach is instrumental in unveiling underlying patterns and relationships within the dataset. Specifically, this method facilitates the observation of recurring themes across different data sources, such as interviews, or the frequent co-occurrence of certain themes. To enhance our analysis, we utilized the row percentage feature, which displays the proportion of words coded in each category as a percentage of the total words in that row. This was complemented by a thorough screening of the text to verify the accuracy of these percentages. The culmination of this meticulous process is reflected in the sub-category rankings presented in Table 4.6.

Table 4.6 DfMA Sub-category challenges ranking for on-site construction

	Categories	Code	Sub-categories	Row percentage (%)	Rank
1	Economic and financial (E)	E1	Cost overruns and contingencies	25.92	2
		E2	Financial options and funding	18.69	4
		E3	Initial capital cost	33.54	1
		E4	Insurance and liability considerations	21.85	3
2	Technological (T)	T1	Cost of technology adoption	31.4	2
		T2	Identifying appropriate tools and techniques	45.89	1
		T3	Interoperability and digital integration	22.71	3
3	Legal contractual (L)	L1	Accurate cost estimation	9.66	6
		L2	Agility and flexibility	13.51	4
		L3	Clear performance metric	6	7
		L4	Clear role and responsibilities	20.3	1
		L5	Collaborative contracting	15.24	3
		L6	Competitive BID pricing	2.27	9
		L7	Dispute resolution method	4.43	8
		L8	Guarantee and insurance clarity	11.76	5
		L9	Risk and reward sharing	16.83	2
4	Technical cognitive (TG)	T1	Design detail and complexity	23.15	2
		T2	Project planning and scheduling	18.97	3
		T3	Technical expertise and skills	57.88	1

Table 4.6 DfMA Sub-category challenges ranking for on-site construction (cont'd)

	Categories	Code	Sub-categories	Row percentage (%)	Rank
5	Procedural (P)	P1	Additional project planning	16.2	4
		P2	Interdisciplinary communication and collaboration	35.87	1
		P3	Owner expectation management	25.11	2
		P4	Quality control	19.51	3
		P5	Supply chain management	5.11	5
6	Cultural (C)	C1	Client awareness	25.51	2
		C2	Education and training	32.46	1
		C3	Organizational culture	10.76	5
		C4	Resistance to change	13.36	3
		C5	Unionization and corporate policies	17.91	4
7	Geographical (G)	G1	Infrastructure and utilities	3.72	7
		G2	Local climate and weather conditions	6.42	4
		G3	Local regulations and permitting	20.15	2
		G4	Local workforce and skills	0.26	8
		G5	Logistics and transportation considerations	52.12	1
		G6	Manufacturing facilities availability	3.47	6
		G7	Material availability	4.36	5
		G8	Specific site factors and limitations	9.5	3
8	Policy (P)	P1	Incentives, Investments	82.74	1
		P2	Permitting and approval process	17.26	2
9	Commercial (CO)	CO1	Available market options	49.69	1
		CO2	Competitive market	38.78	2
		CO3	Market acceptance	11.53	3

4.5 Discussion and research findings

The nine challenges categories and their sub-categories were used to create a conceptual framework for DfMA challenges in the field of OnSC. The framework is illustrated in figure 4.3. The importance and ranking of the DfMA challenges have the potential to guide industry experts to have an ideal implementation scheme for DfMA in their construction projects.

Overall, economic and financial-related challenges, such as initial capital costs, cost overruns and contingencies, insurance and liability considerations, and financing options and funding are considered the most important and relevant challenges for implementing DfMA in OnSC for building projects. In contrast, commercial-related factors, such as available market options, competitive market pressure, and market acceptance have the least influence on the implementation of DfMA in OnSC projects. Figure 4.3 shows the conceptual framework of DfMA challenges in OnSC projects based on MS with the sub-challenges that differ between OSC and OnSC highlighted in a red dashed format for easy identification and comparison. In the following sections, more details will be provided about the first three most significant challenges associated with DfMA in OnSc, along with a comparison of these challenges to those in OSC.

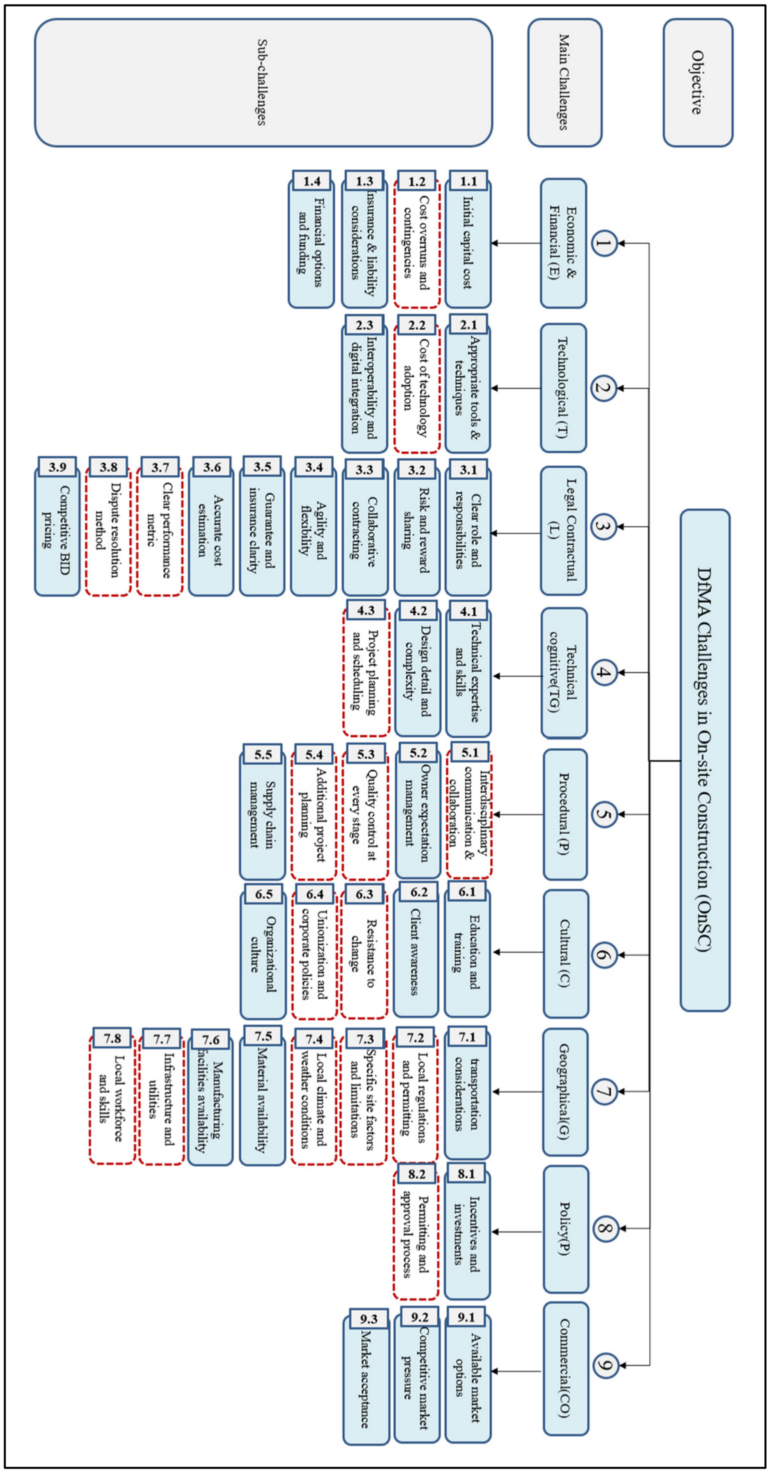

Figure 4.3 The proposed conceptual framework of DfMA challenges in OnSC projects
(The sub-challenges marked with a red dashed format indicate ones that are different between OnSC and OSC)

4.5.1 Economic and financial

The economic and financial aspects of DfMA in OnSC are identified as the most important challenges by scoring a total mean of 4.6 (Table 4.5). The discussion highlights various factors that contribute to the economic and financial considerations in implementing DfMA such as initial capital cost, cost overruns and contingencies, insurance and liability considerations, and financing options and funding.

An expert opinion suggests that "*Initial capital costs are a critical factor in DfMA implementation in OnSC. Acquiring technology and equipment for design, fabrication, and installation involves significant upfront expenses. This can pose a challenge, especially for smaller firms or projects with limited budgets. The accuracy of initial budget estimation is crucial to avoid financial setbacks*" *(Int-2)*. This emphasizes the significance of estimating the budget accurately at the project's outset, and considering all capital costs. The interviewees also noted that "*cost overruns are often underestimated, especially by those new to DfMA" (Int-2).* This observation is particularly significant in light of the NVivo analysis, which ranks cost overruns and contingencies as the second most prominent economic and financial challenges in DfMA implementation in OnSC. The focus on contingencies echoes the literature's recognition of the need for risk management in the initial phases. According to an expert opinion, "*Stakeholders often perform a thorough return of investment (ROI) analysis to assess whether the long-term benefits of DfMA, such as reduced construction time and operational efficiency, outweigh the initial capital costs" (Int-8).*

As a general summery of the conducted interviews, the economic and financial challenges of adopting DfMA primarily involve the trade-off between initial capital investments in technology and equipment and the potential for long-term labor cost savings. This balance between upfront expenditures and future efficiencies is crucial in decision-making for DfMA projects. Stakeholders must carefully consider these trade-offs, as the shift towards DfMA requires reallocating funds from traditional labor to capital investments, impacting the project's financial strategy and necessitating a thorough analysis to fully understand the economic implications of DfMA in OnSC.

The availability of financing options and funding sources plays a pivotal role in DfMA adoption from the industry experts' viewpoint as one mentioned "*Access to favorable financing or funding mechanisms can influence the decision to invest in DfMA. Government projects or those aligned with societal needs may attract more funding which makes them more likely to implement new methodologies like DfMA" (Int-4).*

In General, these findings are aligning with the findings of other scholars who have identified "higher design costs" compared to traditional methods as a barrier to the proper implementation of DfMA methods in OSC projects (Boothroyd, 1994). This comparison underscores the consistency of challenges faced across different construction methods and emphasizes the universal nature of economic and financial hurdles in the implementation of DfMA methodologies.

4.5.2 Technological

The technological challenges in DfMA implementation in OnSC can be categorized into three main areas: identification of appropriate tools and techniques, the cost of adopting new technologies, and issues related to interoperability and digital integration. Our data analysis reveals that these technological challenges are the second highest among the nine challenges faced in DfMA implementation in OnSC.

A significant challenge identified through NVivo analysis is the selection of the right tools and technologies for each project phase. Experts particularly emphasize "the *importance of specific software for different tasks like precise estimation and quality control. However, the unfamiliarity with these software tools necessitates training, highlighting a knowledge gap in the industry*" *(Int-5).*

Through qualitative analysis, it was revealed that the cost of technology adoption ranked second among the technological challenges in OnSC. The expert specifically mentions, "*high initial investment required for advanced technologies could be considered as a challenge, particularly for smaller construction firms. Implementing cutting-edge technology directly at the construction site can be both costly and complex. This involves not just the financial aspect of having and integrating different equipment, but also encompasses the challenges of training personnel, adapting existing processes, and ensuring compatibility with site-specific conditions. Additionally, maintaining advanced technology in a dynamic on-site environment adds to the complexity, requiring robust support systems and contingency planning to mitigate potential disruptions. "(Int-9)*. This acknowledges that financial constraints may hinder the adoption of technologies, potentially impacting efficiency and project outcomes. The interoperability issue, ranked third in technological challenges, industry expert interview emphasizes "the *complexity of integrating diverse technologies and the critical need for streamlined digital communication for the successful implementation of DfMA in different stages of OnSC projects" (Int-7)*.

The common thread between the expert's insights and existing literature such as Gao et al. (2018) and Lu et al. (2021) discussed about not having the right tools and affordable technology hindering the adoption of DfMA in OSC projects. This underscores the global nature of technological challenges and the necessity for innovative solutions to enhance DfMA practices adoption in the construction industry.

4.5.3 Legal contractual

Legal contractual challenges have been ranked as the third most significant barrier in implementing DfMA in OnSC with a total MS of 4.3, which shows that integrating DfMA principles into OnSC projects requires careful consideration of various legal and contractual factors. These challenges encompass several sub-categories, including: Clear role and responsibilities, Risk and reward sharing, Collaborative contracting, Agility and flexibility, Guarantee and insurance clarity, Accurate cost estimation, Clear performance metrics, Dispute resolution methods, and Competitive bidding prices. In our analysis, we have selected the first three sub-categories for their significant comprehensiveness and relevance, as indicated by the interviewees. These sub-categories are: clear role and responsibilities, risk and reward sharing, and collaborative contracting.

Based on the direct interviews, it is evident that clarity in roles and responsibilities is a priority in implementing DfMA. One interviewee emphasizes the necessity of "*clear requirements, Role and responsibilities mentioned in the contract"(Int-4)*, highlighting the question: "*Who's going to do what?"(Int-4)*. This correlates with the prevailing literature that identifies clarity in roles as essential for successful project execution when implementing DfMA in OSC (Rankohi et al., 2023). Such clarity ensures that there is no ambiguity about each party's duties, which can lead to confusion and disputes.

Risk and reward sharing is about defining how the different parties (owners, designers, contractors) share the risks and potential rewards associated with DfMA (Scott et al., 2013). One interviewee discussed the subject of "*risk allocation"(Int-8)* and queried*, "if [DfMA] failed… Who's gonna take care of this? Who's gonna pay for it?*"(Int-8). According to the industry expert interviews, it can be concluded that such queries reflect concerns in the industry about unforeseen issues and the subsequent financial implications.

Collaborative contracting is essential for implementing DfMA in construction projects, promoting cooperation among all project stakeholders from the very beginning (Langston & Zhang, 2021). One interviewee emphasized "*The early involvement of all parties, including suppliers and subcontractors, is crucial. This initial collaboration is a key for ensuring optimal design and precise product specifications are achieved efficiently" (Int-10).* However, according to *(Int-1)* there is an inherent challenge here: "*OnSC procurement rules, especially in government-funded projects, sometimes hinder this early, integrated collaboration due to rigid tendering processes and strict compliance requirements that limit flexibility and hinder the adoption of more collaborative, innovative approaches. These regulations often emphasize* *competitive bidding and cost minimization over the potential long-term benefits of early stakeholder integration, thereby restricting opportunities for open communication and joint planning in the initial stages of the project*" *(Int-1).* Finally, the collaborative contracting section can be completed by the *(Int-2)* opinion "*for DfMA projects to truly flourish, stakeholders must prioritize collaboration over competition, ensuring that the best ideas, materials, and methods are utilized to their fullest potential" (Int-2).*

As supported by the literature, for DfMA to be effectively applied in OSC, early stakeholder involvement, open communication, and comprehensive information sharing are necessary (Abueisheh et al., 2020; Gao et al., 2020; Wuni & Shen, 2020). Traditional project delivery methods that exclude stakeholders during design stages hinder DfMA application, in line with opinions from interviewees who emphasized the significance of collaborative contracting and early engagement.

4.6 Compare DfMA challenges in OSC and OnSC

In this section, we will conduct a comparative analysis of DfMA challenges identified in OnSC with challenges identified in previous studies for OSC. By examining these challenges, we aim to gain a comprehensive understanding of the similarities and differences of DfMA adoption for OSC and its implementation when we are extending it to all the phases of a construction project - also considering the on-site parts. This comparative assessment will shed light on how DfMA practices are evolving and adapting in response to the unique demands and characteristics of both OSC and OnSC, contributing valuable insights to the field of construction management and innovation.

4.6.1 Economic and financial

The implementation of DfMA in OSC and OnSC presents distinct economic and financial challenges. As outlined in Section 4.1 (Int-2), and also according to different literature (O'Rourke, 2013; Lu et al., 2021) DfMA necessitates a considerable initial investment in design, leading to higher upfront costs for both construction methodologies OSC and OnSC. Even though both methods share this initial cost factor, the nature of the economic challenges varies between the two. For considering DfMA in OnSC, the challenges are predominantly centered around the unpredictability of site conditions. Unforeseen issues such as adverse weather or unexpected site constraints can lead to cost overruns and require extensive contingency planning. These factors introduce significant financial uncertainties and can escalate overall project costs beyond initial projections. In contrast, OSC DfMA's primary challenge lies in its high initial capital requirements. This involves substantial investment in facilities, technology, and processes before the construction phase even begins. Despite these differing points, both OSC and OnSC underscore the need for innovative and flexible financial strategies. This includes preparing for higher initial expenditures and emphasizes the importance of adaptable financial management among stakeholders to accommodate the unique demands and uncertainties inherent in each construction approach. Figure 4.4 graphically shows the economic and financial challenges associated with the OSC and OnSC.

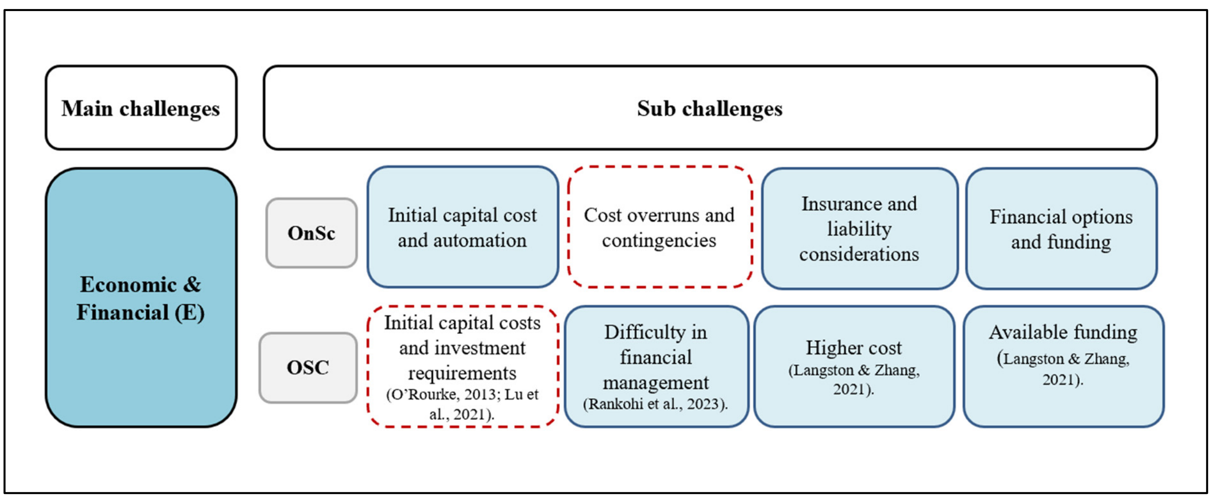

Figure 4.4 Comparative analysis of economic and financial challenges in implementing DfMA in OnSC and OSC (Sub-challenges in blue are specific to each construction method, and red dashes marking differences between OnSC and OSC)

4.6.2 Technological

In terms of technological challenges for DfMA adoption, as stated in the research of Gao et al. (2018) and as mentioned by (Int-5), both OSC and OnSC face the challenge of identifying appropriate DfMA tools and techniques. This highlights the importance of selecting the right technology and methodologies to enhance construction processes. According to Rankohi et al. (2023) OSC-specific challenges include managing the module configuration process, and coordinating between phases and contractors. These challenges arise due to the off-site nature of construction in OSC, where modules are manufactured separately and assembled on-site, while according to the expert overviews (Int-9), what is important from the technological perspective in OnSC is that this construction method specifically faces the challenge of the cost of technology adoption. This is because implementing advanced technology directly on the site location can be expensive and challenging. Both contexts encounter interoperability and digital integration challenges. Ensuring that various digital tools and systems work seamlessly together is essential in modern construction practices. Figure 4.5 provides a visual representation of the comparative analysis outlined in this section.

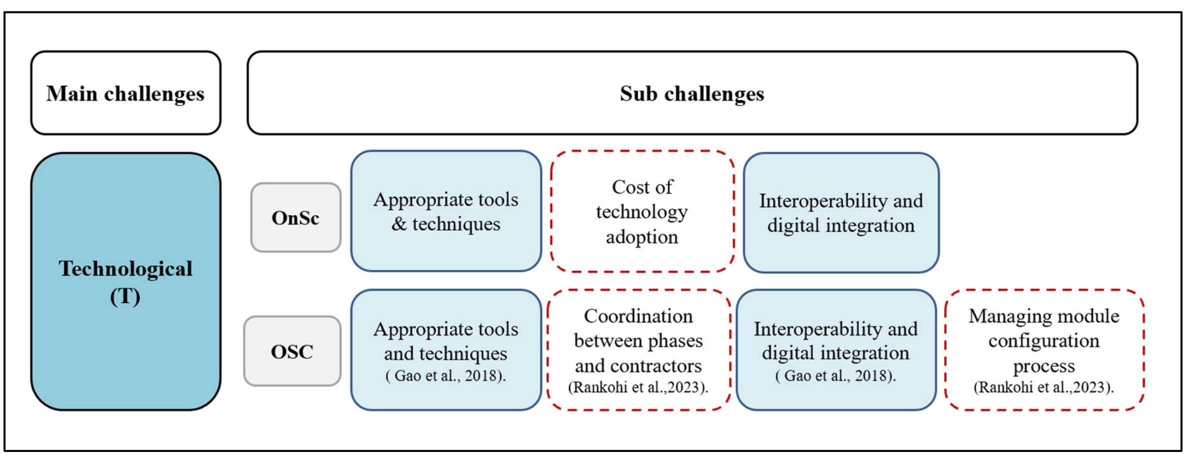

Figure 4.5 Comparative analysis of technological challenges in implementing DfMA in OnSC and OSC (Sub-challenges in blue are specific to each construction method, and red dashes marking differences between OnSC and OSC)

4.6.3 Legal contractual

There are several common challenges in the contractual category between implementation of DfMA in OSC and OnSC, such as accurate cost estimation, clarity in terms of guarantees and insurance, contract agility, and supply chain integration. However, as indicated by Langston & Zhang (2021) and Lu et al. (2021) OSC-specific legal contractual challenges primarily are related to the integration of prefabrication and industrialized construction methods, and different stakeholders' collaboration. While, the insights from industry expert interviews suggest that OnSC may place more emphasis on performance metrics and dispute resolution within the construction site context (Int-3). It is also important to mention the emphasis on supply chain integration, which underscores its significance in ensuring that the coordination and flow of resources align with the specific needs and challenges of both OSC and OnSC (Gao et al., 2018). This is especially true for the mentioned specific OnSC projects, which typically involve numerous variables, such as varying weather conditions, site-specific challenges, coordination of multiple trades, and unforeseen issues that may arise during construction. These complexities make supply chain integration more challenging compared to the controlled environments found in OSC facilities (Int-2). Figure 4.6 depicts a comparative analysis of the main and sub challenges associated with implementing DfMA across the two construction methods.

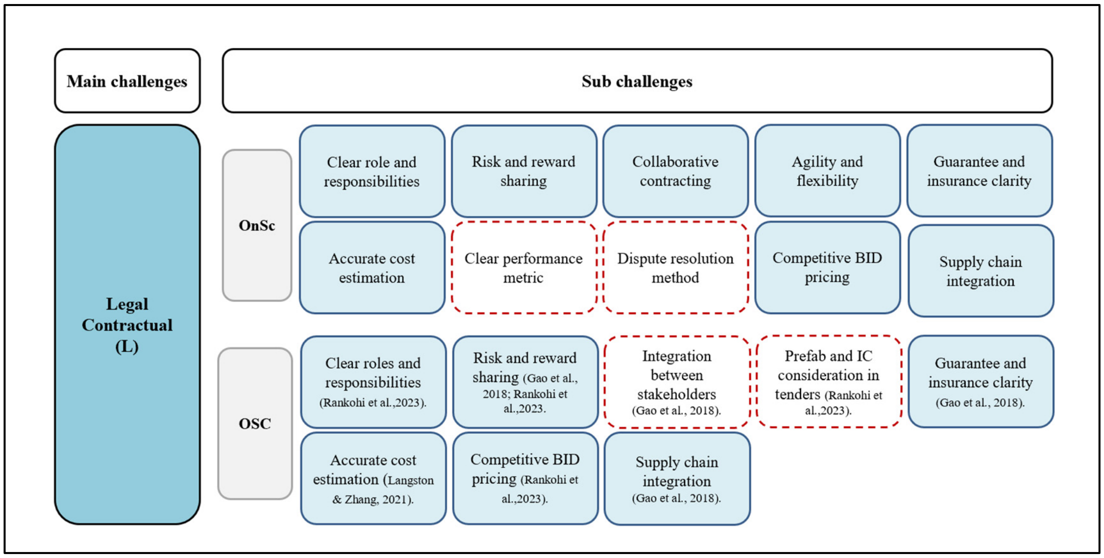

Figure 4.6 Comparative analysis of legal contractual challenges in implementing DfMA in OnSC and OSC (Sub-challenges in blue are specific to each construction method, and red dashes marking differences between OnSC and OSC)

4.6.4 Technical cognitive

Although DfMA in both OSC and OnSC within the technical cognitive category exhibit common concerns such as the need for specialized expertise, the complexity of design, and stakeholder awareness, industry expert interviews and a review of various literatures reveal distinct challenges in each approach. OSC heavily relies on the standardization of details, as pointed out by Jin et al. (2018), emphasizing uniformity and predictability. In contrast, OnSC DfMA demands a higher degree of flexibility, necessitating adaptability to unique site-specific challenges, as noted in interview Int-8. Both Jin et al. (2018) and the insights from Int-8 converge on the conclusion that technical proficiency and increased awareness among stakeholders are essential for both OSC and OnSC, despite their differing approaches and specific challenges. Figure 4.7 provides a visual comparison of the technical cognitive challenges encountered in implementing DfMA in both OSC and OnSC, delineating the specific sub-challenges unique to each construction approach.

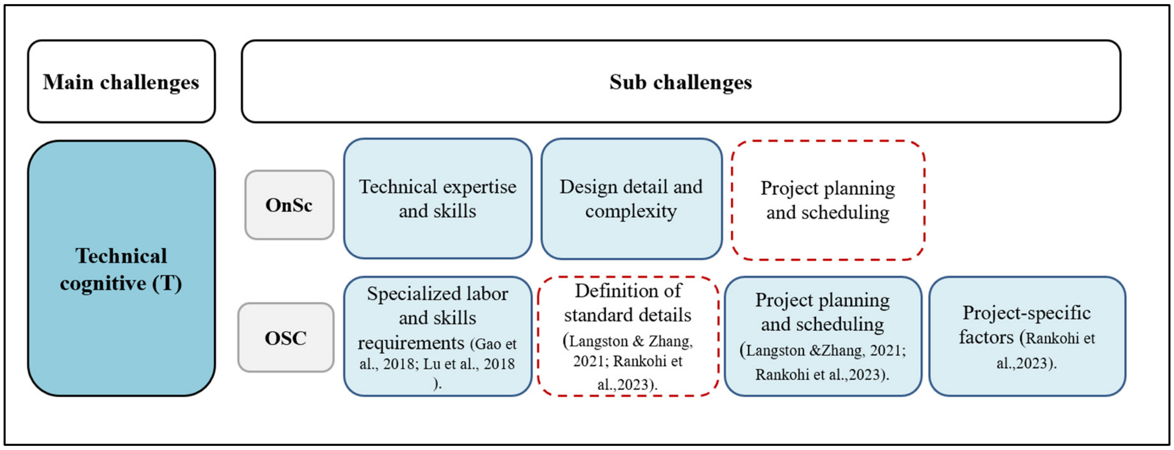

Figure 4.7 Comparative analysis of technical cognitive challenges in implementing DfMA in OnSC and OSC (Sub-challenges in blue are specific to each construction method, and red dashes marking differences between OnSC and OSC)

4.6.5 Procedural

According to the interview analysis and reviewing the literature both OSC and OnSc share some common procedural challenges related to DfMA implementation, such as additional project planning and interdisciplinary communication and collaboration, and they differ in their specific areas of emphasis. For example, in OSC the additional project planning is required to ensure smooth transportation and assembly of prefabricated components (Jin et al., 2018; Rankohi et al., 2023). OnSC also necessitates additional project planning, but its primary focus may revolve around scheduling and coordinating various on-site activities (Int-8).

Furthermore, in terms of communication and collaboration, OSC places a high premium on effective coordination between design, manufacturing, and construction teams to guarantee the seamless fit of prefabricated components on-site (Gao et al., 2018). On the other hand, OnSC may involve a broader spectrum of on-site trades and subcontractors, making interdisciplinary communication and collaboration more critical (Int-7). In terms of quality control, it is essential in OSC to ensure that factory-produced components meet the required standards before transportation to the construction site (Alazzaz & Whyte, 2014), as stated by Int-8 the quality control for OnSC would be more rigorous and the focus may shift towards the quality of installation and workmanship. Figure 4.8 presents a comparative analysis, illustrating the divergent aspects between OSC and OnSC.

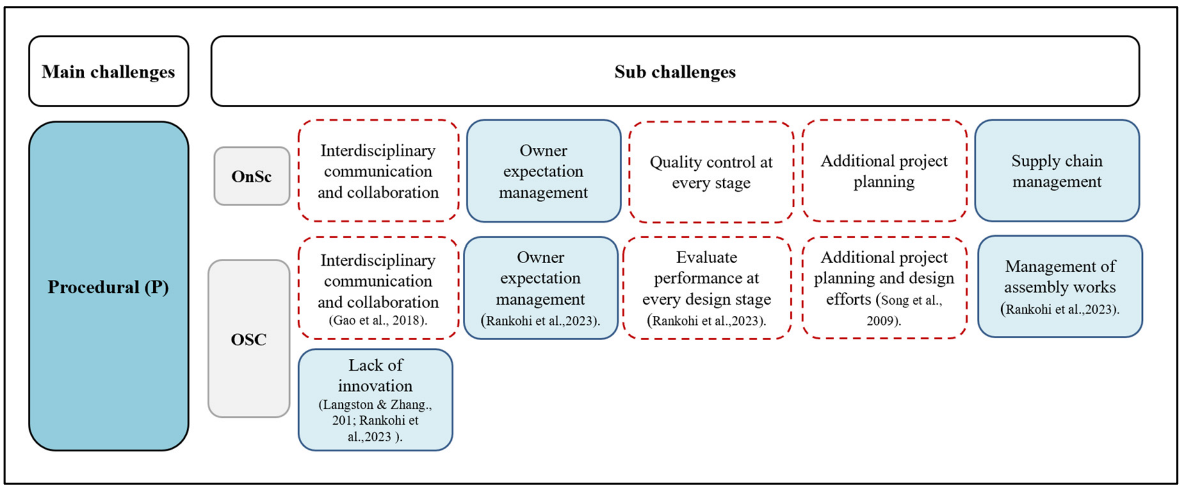

Figure 4.8 Comparative analysis of procedural challenges in implementing DfMA in OnSC and OSC (Sub-challenges in blue are specific to each construction method, and red dashes marking differences between OnSC and OSC)

4.6.6 Cultural

Both OSC and OnSC face cultural challenges in DfMA adoption, but the nature and emphasis of these challenges differ due to the distinct characteristics of each construction approach. 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 to OnSC in its own nature.

OSC's challenges often center around aligning stakeholders communication, supply chain collaboration (Abd Razak et al., 2022), and transforming perceptions of industrialized construction (Rankohi et al., 2023). OnSC's challenges are more focused on internal cultural shifts, adapting to new practices, and addressing resistance within existing teams (Int-10). Figure 4.9 displays the comparative analysis, highlighting the distinct areas of OSC and OnSC.

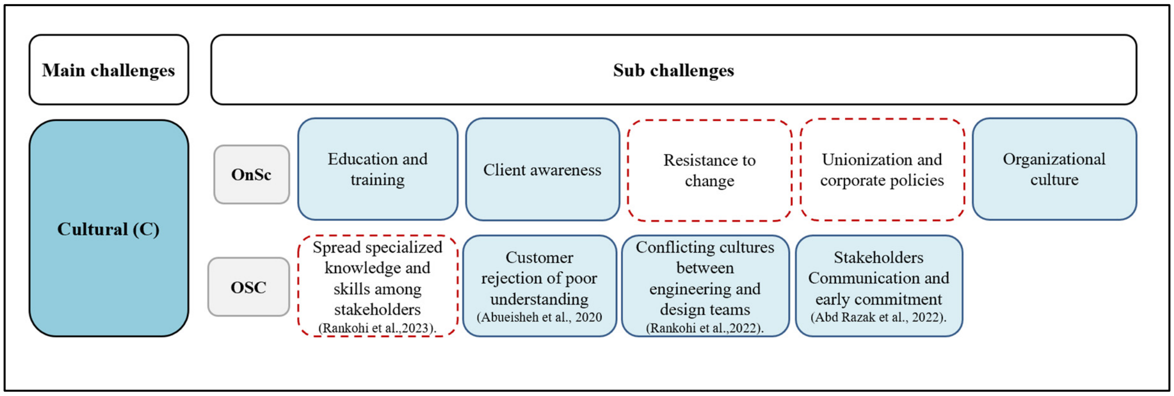

Figure 4.9 Comparative analysis of cultural challenges in implementing DfMA in OnSC and OSC (Sub-challenges in blue are specific to each construction method, and red dashes marking differences between OnSC and OSC)

4.6.7 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, the transportation of various components (Gao et al., 2018; Rankohi et al., 2023), and the need to ensure code compliance across regions (Rankohi et al., 2023) . Conversely, OnSC deals with site-specific factors (Int-4), local workforce (Int-2) and regulatory considerations (Int-4; Int-8), and the necessity to adapt to existing infrastructure (Int-1). It is important to note that OnSC also requires navigating local regulations and permitting (Int-4), which can exhibit significant variations across different geographic locations.

The Figure 4.10 underscores that while some challenges are shared—such as material availability and the necessity to navigate local regulations—there are distinct differences. OSC's challenges are largely logistic and regulatory due to the nature of prefabrication and transportation, while OnSC's challenges are more focused on the immediate physical and regulatory environment of the construction site.

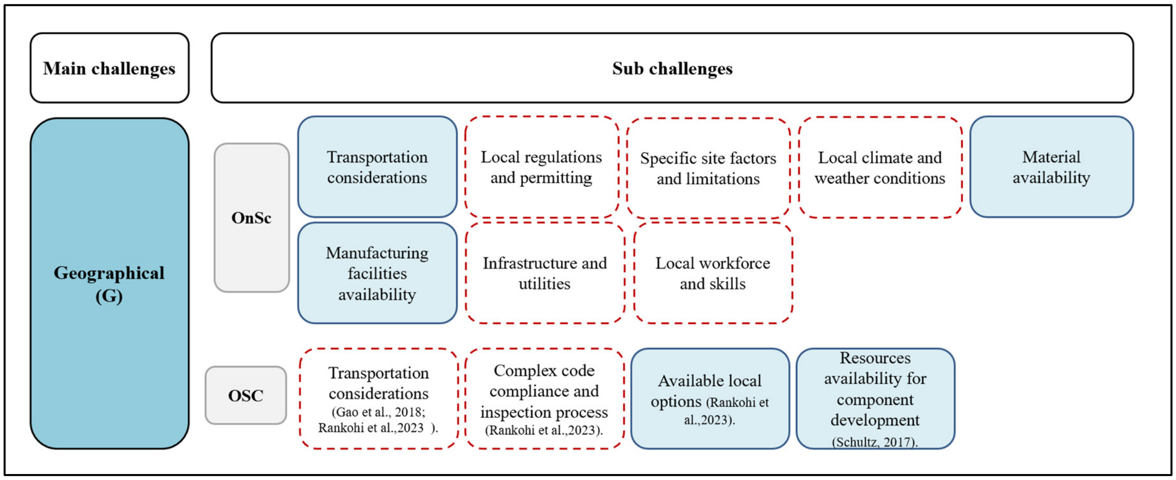

Figure 4.10 Comparative analysis of geographical challenges in implementing DfMA in OnSC and OSC (Sub-challenges in blue are specific to each construction method, and red dashes marking differences between OnSC and OSC)

4.6.8 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 et al., 2018; Langston & Zhang, 2021), while on-site DfMA's challenges are more about integrating DfMA techniques into construction environments in a manner compliant with existing on-site regulations (Int-4). For instance, Gao et al. (2018) provide insights from the OSC perspective, while Interviewee 8 (Int-8) offers a viewpoint from OnSC, indicating that in the realm of DfMA, there is an expectation for government involvement that extends beyond mere policy support. Both sources underscore the necessity for proactive government incentives aimed at facilitating growth within the sector. This highlights a shared understanding across both OSC and OnSC that government engagement should not be limited to policy formulation but should also include tangible incentives to catalyze the advancement of DfMA practices.

While OSC is looking for legislation support that accommodates the unique needs of factory-made components and their transport (Gao et al., 2018), the on-site DfMA focuses on the facilitation of designs and methods specific to the technique and coordinating the actual site issues (Int-3). Both, however, need governmental incentives. Figure 4.11 provides a clear visual comparison of DfMA in OSC and OnSC, focusing on the specific sub-challenges that differentiate these two construction methods. This illustration simplifies the understanding of how DfMA challenges vary between OSC and OnSC, making it easier to grasp the unique aspects of each approach.

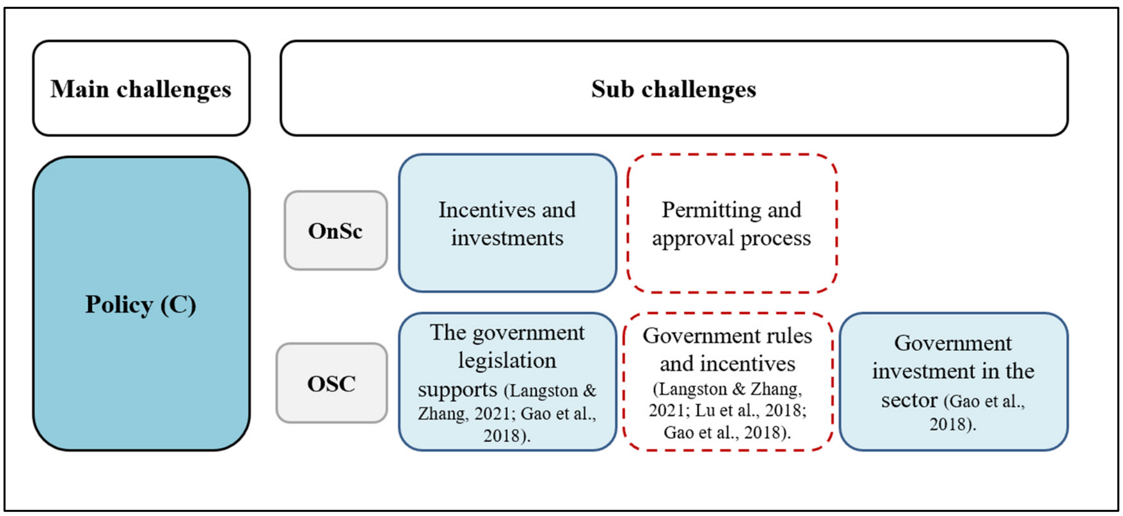

Figure 4.11 Comparative analysis of policy challenges in implementing DfMA in OnSC and OSC (Sub-challenges in blue are specific to each construction method, and red dashes marking differences between OnSC and OSC)

4.6.9 Commercial

Drawing from the scholarly discussion on DfMA implementation in OSC (Hall et al., 2018; Lu et al., 2018; Rankohi, Bourgault, et al., 2022), as well as the outcomes of our interview analysis, it is evident that both OSC and OnSC encounter parallel challenges in the commercial sphere when applying DfMA methodologies. These challenges predominantly center around the dynamics of available market options, the intensity of competition, and the degree of market acceptance. It can be concluded that this convergence in commercial obstacles highlights a shared area of focus and concern in the broader context of DfMA application across different construction modalities.

Regardless of whether the focus is on OSC solutions or OnSC methods. This alignment is primarily driven by the introduction of DfMA as a new and innovative methodology in both sectors, leading to a shared need to educate the market and address any resistance or uncertainty surrounding this modern approach to construction (Int-7). Figure 4.12 presents a detailed comparative analysis, underscoring the earlier discussion that the sub-challenges within the commercial category of OSC and OnSC exhibit minimal differences. This illustration serves to visually encapsulate the nuanced similarities in commercial challenges faced by both OSC and OnSC in the realm of DfMA, providing a clearer understanding of the shared obstacles in these construction approaches

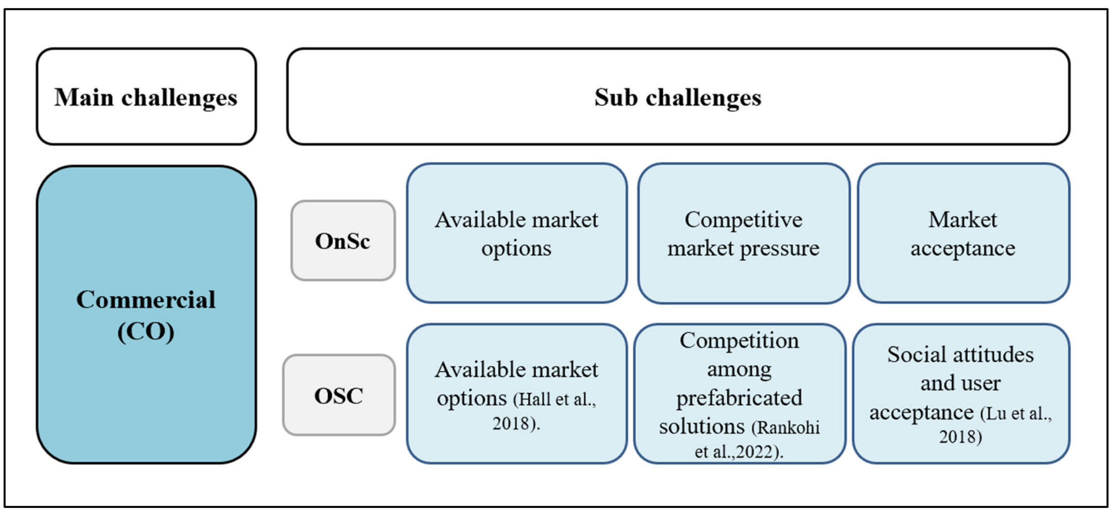

Figure 4.12 Comparative analysis of commercial challenges in implementing DfMA in OnSC and OSC (Sub-challenges in blue are specific to each construction method, and red dashes marking differences between OnSC and OSC)

4.6.10 Summary

The comparative analysis between DfMA challenges in OnSC and OSC underscores the inherent complexities and multifaceted nature of implementing DfMA techniques. When focusing on the on-site component of construction, it becomes evident that DfMA's scope expands beyond OSC, taking on broader meanings and contexts. This expansion necessitates a deeper consideration of specific site conditions, such as accessibility, existing infrastructure, and environmental factors. These factors influence construction outcomes. Moreover, this extended focus on the on-site aspects of DfMA implies that while the principles and guidelines established for OSC offer a foundation, they are insufficient by themselves. To ensure the holistic and effective application of DfMA in OnSC scenarios, the formulation of revised guidelines applicable to its broader context becomes critical. Embracing this detailed approach ensures DfMA's potential is maximized across the entire construction lifecycle. This allows for more streamlined, efficient, and adaptable construction practices in the future.

4.7 Conclusion

In conclusion, this paper focuses on DfMA within the construction industry, shedding light on its potential to enhance productivity and efficiency. While DfMA has often been associated with OSC, this study challenges the misconception that it focuses exclusively on OSC projects. Instead, it highlights the applicability of DfMA principles across a wide spectrum of construction projects, including on-site components and activities.

Through an in-depth mixed-methods research approach, combining a comprehensive literature review with interviews with industry experts, this study has identified, verified, and analyzed 42 DfMA challenges, categorizing them into nine main challenge categories. Furthermore, this research has extended beyond the prevailing focus on OSC and delved into the challenges specific to OnSC, contributing to a deeper understanding of the obstacles faced in the field.

The findings of this study have identified economic and financial challenges as the most critical barriers to DfMA implementation in OnSC, emphasizing the importance of budget accuracy, cost overruns, and funding availability. Technological challenges, including tool selection, technology adoption costs, and interoperability, have emerged as the second most significant hurdles. Furthermore, legal contractual challenges, encompassing role clarity, risk and reward sharing, and collaborative contracting, emphasizing the importance of clear contractual frameworks and early stakeholder engagement. As DfMA's relevance stretches beyond just OSC, the study underscores the need for a deeper understanding of on-site-specific factors like accessibility, infrastructure, and environmental considerations. While The existing DfMA-OSC guidelines provide a foundation, they alone do not suffice for the broader OnSC scenarios. This research aims to serve as a roadmap for the construction industry, guiding towards improved productivity and sustainability while laying groundwork for future studies. The conceptual framework developed in this study serves as a valuable guide for researchers, practitioners, and policymakers in understanding and addressing the challenges associated with DfMA adoption in OnSC. By recognizing and mitigating these challenges, the construction industry can move closer to achieving enhanced productivity, sustainability, and competitiveness in the built environment.

In summary, this research contributes to the construction management field by providing insights into the DfMA challenges specific to OnSC and lays the foundation for future studies and strategies aimed at overcoming these obstacles. Ultimately, it is hoped that the knowledge generated through this study will facilitate the widespread adoption of DfMA principles, leading to a more efficient and productive construction industry.

CONCLUSION

In the comprehensive analysis presented through this thesis, the two individual articles work together to offer a deep exploration into the application and challenges of DfMA within the construction industry. The journey through the articles illustrates a significant academic attempt to clarify the complexities of DfMA, a methodology associated with OSC. It also broadens its recognized applicability and potential to OnSC environments.

The first article provides a valuable bibliometric analysis of DfMA over the past decade, highlighting the evolution of research in the area and identifying gaps that call for further exploration, particularly regarding the application of DfMA in OnSC and its integration with BIM throughout the lifecycle of a construction project. It underscores the emerging stage of DfMA within on-site contexts and the lack of extensive research in this domain, indicating the necessity for in-depth academic and practical investigation.

In continuation of the first article, the second article takes a critical step forward by challenging the assumptions about the limitations of DfMA's applicability. It extends beyond OSC boundaries to showcase how DfMA principles can be applied in OnSC. The identification and categorization of 42 DfMA challenges into nine main categories offers an empirical basis for recognizing and confronting multifaceted barriers to DfMA implementation. The study addresses economic, technological, and legal contractual challenges, among others. It paints a comprehensive picture of the obstacles that impede DfMA's efficiency and productivity.

Overall, this thesis contributes to the academic and professional community on DfMA by illuminating the methodology's expansive reach. It also provides actionable insights into construction industry challenges. It promotes a shift in perspective, advocating for the integration of DfMA in both off-site and OnSC, with an emphasis on the need for a customized approach sensitive to the unique demands of on-site application. The conceptual frameworks and categorizations derived from this research serve as crucial stepping-stones for industry professionals, researchers, and policymakers in refining strategies that embrace DfMA principles for enhanced construction productivity and sustainability.

This master's thesis provides findings and discussions that not only advance the understanding of DfMA's current state but also encourage progressive thought for future research directions. They suggest that by embracing the diversity of challenges and the dynamism of construction environments, the industry can innovatively apply DfMA to achieve enhanced efficiency, cost-effectiveness, and environmental sustainability. In summary, this thesis presents a vision for a future where the integration of DfMA into construction processes is seamless, barriers are systematically addressed, and the full potential of this approach is realized for the betterment of the industry and the built environment.

RECOMMENDATIONS

As we move from the detailed analysis and insights generated from this research to practical applications, future plans need to be developed. As a result of our findings, we are presenting the following recommendations for more effective implementation of DfMA in the construction industry. These suggestions aim to address the identified gaps, overcome the challenges, and maximize the full potential of DfMA within both the OSC and OnSC realms. They guide researchers, practitioners, and policymakers toward fostering an environment conducive to innovation, collaboration, and advancement in the construction process. As a result, DfMA benefits can be realized on a larger scale and can contribute to the revolution in building practices. With a focus on actionable strategies, the ensuing recommendations are developed to translate the academic content of this thesis into tangible improvements in construction.

Further Research into DfMA Application Across Construction Phases: Encourage academic research focusing on the end-to-end application of DfMA in construction, especially studies that consider the integration of DfMA with BIM throughout the entire lifecycle of a project.

Investigate the potential for on-site DfMA-based prefabrication, to understand how its application could be expanded and optimized for efficiency.

Development of DfMA Best Practices and Guidelines: Develop comprehensive guidelines that address the specific needs of on-site DfMA application, including best practices for integration with existing site conditions and operations.

Create a standardized framework for evaluating the economic and financial viability of DfMA projects, to aid in decision-making and investment.

Investment in Technology and Training: Recommend investment in the development and adoption of new technologies that facilitate the use of DfMA, with a focus on improving interoperability between different digital tools.

Promote training programs for construction professionals to develop expertise in DfMA methodologies, ensuring the workforce is prepared to implement these practices effectively.

Industry-Academia Collaboration: Foster collaborations between industry practitioners and academic researchers to bridge the gap between theoretical knowledge and practical application of DfMA.

Encourage joint research initiatives and pilot projects to test the feasibility of innovative DfMA applications in real-world settings.

Policy and Regulatory Support: Urge policymakers to provide incentives for projects that incorporate DfMA, such as tax benefits, subsidies, or fast-tracked permitting processes, to encourage industry adoption.

Recommend the creation of a legal and contractual framework that supports DfMA, addressing issues like risk sharing, reward mechanisms, and collaborative contracting.

Promotion of Sustainable and Efficient Practices: Advocate for the integration of sustainable materials and practices within the DfMA process to enhance environmental performance.

Encourage the construction industry to adopt DfMA as part of a broader commitment to reducing waste and improving resource efficiency.

Enhanced Stakeholder Engagement: Highlight the importance of early and continuous engagement of all stakeholders, including owners, contractors, designers, and regulators, to ensure the successful adoption of DfMA.

Develop tools and platforms that facilitate stakeholder communication and collaboration throughout the DfMA process.

Case Studies and Success Stories: Compile and disseminate case studies of successful DfMA projects to serve as models for the industry, demonstrating the tangible benefits and overcoming skepticism through proven results.

Establish a repository of DfMA resources, including case studies, guidelines, and tools, accessible to industry professionals and researchers alike.

APPENDIX I

DfMA CHALLENGES QUESTIONAIRE

Section 1: Expert's Profile and Professional Experience

- How many years of experience do you have in the field of construction?
- Please describe your organization in terms of its operational activities, i.e. client, consultant, contractor, manufacturer.
- Please describe your professional role at your company.
- Please describe the percentage of OSC and on-site implementation in your organization.

Section 2: Introduction

Dear Mr/Mrs:

I would like to express my sincere gratitude for taking the time to participate in this interview and share your insights on the challenges related to Design for Manufacture and Assembly (DfMA) in on-site construction (OnSC). Your expertise and contribution are invaluable to the success of my thesis research.

I would like to assure you that your identity will remain confidential throughout the research process. Additionally, please be informed that your participation is entirely voluntary, and you have the right to withdraw at any point, even after the interview has taken place. Your comfort and privacy are of utmost importance, and your decision will be respected.

In this study, I aim to delve into the complexities of DfMA and its implications within the realm of OnSC. DfMA, or Design for Manufacture and Assembly, is a methodology that emphasizes the integration of manufacturing and assembly considerations into the design process of a product or structure. DfMA uses a series of design strategies under its guidelines and principles to achieve better manufacturability and assimilability. Minimization, standardization, and modularization appear to be the key characteristics associated with the DfMA principles.

In the most recent studies, the most widespread DfMA adoption is foreseen in OSC, so there is a misconception the DfMA serves OSC only, while not all projects are suitable for OSC, but can still benefit from DfMA design principles. In this context, "on-site construction (OnSC)" refers to

- Work completed on-site as part of an off-site construction project.
- specific projects that are carried out at the actual location. The examples of some of these projects are further detailed in the following section.

Section 3: OnSC Project Description

1.GBE innovation company

A manufacturer and supplier in France that produce cast in place sandwich wall with internal insolation between the two concrete skins.

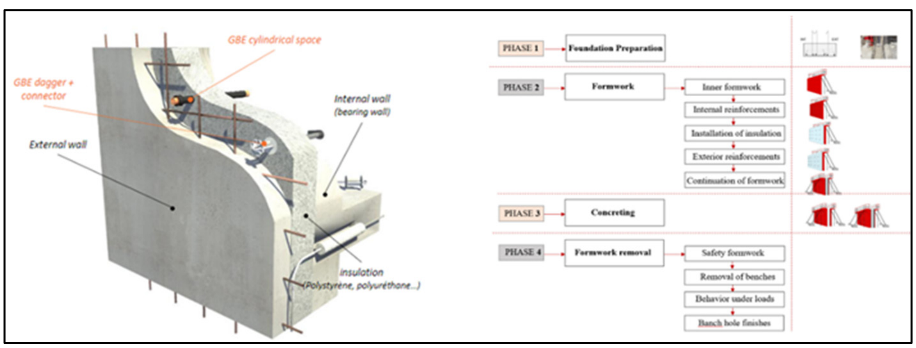

Figure-A I-1 left: GBE wall system, right: GBE process workflow[8]

2.Upbrella company

A sheltered construction service in Canada. A multi-story building construction whit out crane and starting with the roof.

3.Hambro by Canam

A composite floor system in Canada. A composite joist girder and a transfer slab system.

[8] *Source of the example: //www.gbe-innovation.fr/*

Section 4: DfMA Challenges Interview questions

In the following section, we will explore the core challenges of DfMA within the context of OnSC. Through a series of insightful questions, we aim to uncover your expertise and experiences in navigating the complexities of DfMA implementation.

Legal Contractual

1. When integrating DfMA principles into OnSC projects, what are some of the important factors relating to contract drafting and negotiation that might impact the implementation of DfMA in OnSC? (The legal contractual factors include cost estimation, BID pricing, risk/reward sharing in contracts, guarantees and insurance clarity, contractual agility and flexibility and etc.)

Technological

2. What are the appropriate tools/techniques for implementing DfMA in each phase of an OnSC project?
3. Are there any particular technological bottlenecks that you've observed when attempting to optimize the OnSC through implementing DfMA techniques?
4. Can you mention any technological barriers that may arise when incorporating automation and robotics in DfMA implementation for OnSC?

Procedural

5. When integrating DfMA principles into OnSC projects, what are the procedural barriers that construction teams might encounter in different phases? (The procedural factors include scheduling, workforce coordination, task allocation, quality control, communication, information sharing, documentation and reporting and etc.)

Cultural

6. In your experience, what cultural factors have you observed that can impact the implementation of DfMA in OnSC projects? (The cultural factors include stakeholder communication, unionization and corporate politics, social attitudes and user acceptance, etc.)

Commercial

7. From a commercial standpoint, what are some significant challenges that project stakeholders might encounter when integrating DfMA principles into OnSC projects? (The commercial factors include available market options, competitive market and etc.)

Geographical

8. What geographical specific factors might influence the effective implementation of DfMA principles during OnSC? (The geographical factors include site specific factors and limitations, logistic consideration, transportation complexities, local conditions and constraints, etc.)

Economic and Financial

9. In the context of your projects, what economic factors could impact the decision-making process for adopting DfMA techniques? (Economic factors include initial capital cost, potential cost overruns, and return on investment, etc.)

10. Are there any hidden or unforeseen costs associated with DfMA implementation in OnSC that project stakeholders should be aware of?

Technical cognitive

11. When considering the technical cognitive aspects, what are the potential barriers for adapting DfMA principles during OnSC? (The technical cognitive factors include Project Planning and Scheduling, technical expertise and skills, labour requirement, design detail, regulatory compliance and etc.)

Policy

12. From a policy and regulatory perspective, can you identify any governmental or policy-related barriers that might affect the adoption of DfMA in OnSC? (The policy factors include government legislation, incentives, and investment and etc.).

13. Could you discuss any unforeseen challenges that have emerged due to the dynamic nature of OnSC, such as weather, site-specific constraints, or logistical considerations, in the context of DfMA implementation?

Other

Is there anything else you would like to share or any other points worth mentioning that we have not covered in this interview? Your insights are greatly appreciated.

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