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Developing a Construction-Oriented DfMA Deployment Framework

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Abstract: Applying design for manufacture and assembly (DfMA) principles in the construction industry has gained attention in recent years. Studies convey that the application of DfMA in construction projects can significantly enhance overall productivity. However, the literature on construction-oriented DfMA is still limited, and its application in real-life projects has been stifled due to various constraints. Following a design science research method, a systematic literature review was conducted to identify the construction-oriented DfMA implementation challenges. To address these challenges, a construction-oriented DfMA framework was theorized, verified in a project-based context, and validated through focus group discussions with off-site construction industry experts. In this study, 45 challenges were identified and categorized into eight main constraint categories: contractual, technological, procedural, cultural, commercial, geographical, financial, and technical/cognitive. The foremost challenges to the adoption of DfMA in construction projects seems to relate to the contractual and operational aspects and their associated stakeholders. This study provides insight into the challenges of implementing DfMA in the construction industry. The investigated challenges contribute to the theoretical and practice-based checklists of limitations for implementing DfMA methods and can inform future research. Finally, this paper introduces a framework for implementing DfMA and provides supporting field-based evidence for its application.

Keywords: design for manufacturing and assembly; DfMA; construction; industrialized construction; off-site construction; design science research method; literature review

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1. Introduction

Design for manufacture and assembly (DfMA) is a combination of two terms: design for manufacture (DfM) and design for assembly (DfA) [1]. This approach, which is known as both a philosophy and a methodology, has existed in the manufacturing industry for decades [2]. In this method, products are designed based on maximizing their amenability for downstream manufacturing and assembly [3]. DfMA began during World War II (1939–1945), when Ford and Chrysler developed design principles in their weapon production procedures [4]. In the late 1960s and early 1970s, the formal exploration of DfMA began with the research efforts of Boothroyd and Dewhurst [5–8] and has since then remarkably developed within the manufacturing industry [9].

Despite the long-standing recognition and significant development of DfMA in manufacturing industries, it has not been widely adopted in the construction industry. Indeed, the currently available solutions fail to deliver the fully desired results [10]. The Royal Institute of British Architects (RIBA) initiated the first few studies about the application of DfMA in construction around a decade ago. In 2013, the RIBA recognized the potential of DfMA in the construction industry and added a DfMA overlay to its well-known Plan of Work for implementing the DfMA principles and guidelines [11]. Later in 2020, RIBA published a revised version of its Plan of Work, which provided an updated DfMA-based guideline for accomplishing construction projects [11]. In addition to the conceptual development, some attempts have been made to develop DfMA methods in practice. For instance, Bryden Wood developed a digital platform-based DfMA application to enable architects to design bespoke houses and apartment blocks in collaboration with manufacturing suppliers [10]. In this regard, various countries have supported similar initiatives: Singapore in 2016 (building and construction authority of Singapore's DfMA for BIM) [12], the UK in 2018 (UK government's national infrastructure and construction pipeline) [13], and Italy in 2019 (the Italian public procurement process) [3].

The construction-oriented DfMA encompasses several central criteria, such as technology rationalization, product and process integration, logistics optimization, and material specifications [14]. Gao et al. [15] categorized various interpretations of DfMA in the construction literature into three groups: a philosophy that focuses on prefabrication and modular construction; a design process for improving manufacturing assembly; and an evaluation system to evaluate the efficiency of manufacturing assembly. As a philosophy, DfMA is hardly a new concept in the construction industry, but as an empirical process, it has recently been suggested that its guidelines be implemented for the building environment [16].

1.1. Previous Studies

Although studies on DfMA have gained attention in recent years, the number of studies in the construction literature is still limited. There is a dearth of knowledge regarding the challenges of implementing DfMA methods in construction.

As a collaborative strategy, DfMA relies heavily on integration. However, the project-based nature of the construction industry with its unique characteristics such as fragmentation, contextual embeddedness, lengthy manufacturing/assembly lines, and 'one-off' endeavors, seems to oppose the widespread application of DfMA [17]. In a study conducted by [18], it was identified that unsupportive organizational, contractual, and operational systems and procedures create fragmentations of stakeholders' responsibilities, thus inhibiting the proper implementation of DfMA. According to [19], proper "stakeholders' integration" stems from three fundamental aspects: organizational structure, contractual guidelines, and operating systems and processes. Several scholars indicated that the application of concerted organizational structures, relational contracting frameworks, and integrative operational systems can improve integration, thus enhancing the implementation of collaborative strategies in the construction industry [18–22]. For instance, in integrated project delivery (IPD) studies, the early engagement of contractors to collaborate with the design professionals is stated by several scholars as a strategy that improves organizational integration [21–23]. Notwithstanding these claims, the literature reveals a lack of empirical studies about the required collaborative working environment that could enhance the enactment of DfMA in construction projects.

The construction literature shows that some scholars have conducted literature review studies on DfMA-related topics. The authors of [24] conducted a literature review study to identify the shared practices of DfMA with lean and digital fabrication, and they concluded that "design to target value" and "concurrent engineering" are shared by all three approaches. The authors of [25] conducted a systematic review and selected 23 DfMA-related articles that were published before March 2019. They concluded that in the construction domain, DfMA has been understood from three perspectives: (a) a holistic process with a set of design principles; (b) an evaluation system to assess the efficiency of manufacturing and assembly; and (c) a philosophy to enhance prefabrication and modular construction processes. According to their study, developing design guidelines, creating muti-disciplinary teams, applying virtual design and construction systems, and understanding the lean principles can enhance the successful application of DfMA in construction. In 2020, Ref. [26] reviewed the development of DfMA in manufacturing and construction and identified its similarities and differences to other concepts. They categorized the construction-related DfMA research in three directions: implementation and guidance strategies, frameworks and blueprints, and applications in on-site or off-site construction. Ref. [27] conducted a systematic literature review on DfMA-related publications in the construction literature until the year 2021. Based on the reviewed DfMA-related articles, they identified practical analogies between prefabrication and manufacturing, and provided recommendations for future opportunities to apply DfMA in construction. In 2022, Ref. [28] reviewed the relevant articles on DfMA, and identified the main benefits (reduced time, reduced cost, higher quality, and increased reliability) and barriers (inefficiencies of multi-disciplinary teams, design standardization limits, traditional contracting strategies, lack of training, lack of a suitable ecosystem, lack of early involvement of suppliers, etc.) for DfMA implementation in the construction industry. The authors also discussed the benefits of building information modeling (BIM) integration with DfMA.

1.2. Research Objectives

Previous studies have documented and recognized a scattering of challenges constraining DfMA methods in construction projects. Some also suggest strategies to facilitate DfMA's application. However, to the best of the authors' knowledge, none of these studies conducted a comprehensive study to identify the existing challenges and propose organizational, contractual, and operational strategies to address them. To fill this gap, this study explores the emerging organizational, contractual, and operational tools and strategies that can address the challenges and facilitate the adoption of construction-oriented DfMA. The main goal of this study is to improve the current construction-oriented DfMA theorization and applications. This paper will address the following two objectives:

- Objective 1: To identify and categorize the principal challenges in implementing DfMA in construction projects.
- Objective 2: To develop a construction-oriented DfMA framework and propose recommendations for tackling the identified challenges.

2. Methodology

To develop knowledge and contribute to the body of theory and practice in this field, this study adopted an exploratory research approach for examining the current challenges of applying DfMA in construction and investigating and proposing alternate courses of action. To achieve this goal, we followed a design science research (DSR) approach, which is a multi-step research method, consisting of systematic literature reviews, focus group discussions, and case studies [19]. Deriving from the community of practice, DSR is an analytical and creative approach that develops exploratory and instrumental research techniques to achieve practical desired outcomes [29]. In this technique, a constructivist, action-oriented, and interpretive qualitative research strategy is applied in the construction of an artefact such as a framework or an algorithm [19]. The DSR method involves people exploring, inducing, developing, and testing models around user-centered values, interests, challenges, and concerns [19]. To validate the outcomes, we adopted a focus group discussion (FGD) method over semi-structured interviews. The FGD method is an exploratory practice in which a group of experts collectively interact and share opinions in a dynamic and interactive group discussion [19]. According to [19], each focus group consists of 5 to 25 experienced experts in the area of study. This method has been widely adopted for qualitative research [29] and is recommended to be used for studies in which interactions, exchanges of ideas, and multiple perspectives of diverse stakeholders about a topic are required [19].

Two focus groups (FDGs #1 and #2) were selected for this study, consisting of 10 and 14 participants, respectively. We used two different focus groups to identify and validate the different results of this study. The first group validated the extracted list of challenges from the literature and developed the primary framework; the second group discussed and validated the framework developed by the first group. These two groups had similar participants in terms of their job titles and work experiences. To ensure sufficient diversity of opinion, focus group participants were selected from all types of stakeholders including owners, design professionals (i.e., architects, structural and mechanical engineers, etc.), general contractors, sub-contractors, suppliers, and university professors in the construction engineering domain. The participants had knowledge and experience in both on-site and off-site construction projects and were familiar with DfMA method and principles. The experts selected for focus group discussions represented intermediate- to senior-level construction industry practitioners in Canada. Experts with between five and twenty years of successful experience in the construction industry were selected. The general characteristics of the focus group participants are provided in Table 1. A total of four FGDs were conducted per group, and each lasted between 90 and 120 min. Both groups were led by facilitators, who encouraged participants to interact and contribute constructively. The goal of the study was explained at the onset of FGD. During the discussions, participants were provided with the study results, and the results were validated through focus group discussions by the panel experts.

Table 1. Profile of focus group participants.

Participant	Focus Group #1		Focus Group #2	
	Number of Experts	**Years of Experience**	**Number of Experts**	**Years of Experience**
Owner				
Project manager	0	NA	2	5–20
Director	1	10–20	0	NA
Academia				
Professors	1	10–20	1	10–20
Consultant				
Architect	2	10–20	2	5–10
Engineer	2	10–20	2	5–10
Contractor				
Site supervisor	0	NA	1	5–10
Project manager	1	10–20	2	5–10
Supplier				
Fabricator	3	10–20	3	10–20
SC manager	0	NA	1	5–10
Total	10	10–20	14	5–20

Figure 1 illustrates the stages of the DSR research approach that have been conducted in this study. As shown, this study follows a problem-centered DSR path in two steps.

2.1. Step 1: Identification of Challenges

The first step is to identify the challenges of DfMA adoption in construction projects. To conduct a rigorous review and extract challenges, a systematic literature review (SLR) method was applied. SLR enables the collection of the most comprehensive and relevant knowledge created in a specific area of study [30]. The results of this SLR led to the extension of knowledge in the construction-oriented DfMA research domain. A detailed explanation of the SLR approach is provided in Section 3. Following the systematic literature review, the identified challenges were discussed, studied, and categorized with a panel of industry experts in focus group #1. In focus group discussions (FGDs), participants provide their opinions, and the whole group gains an overall perspective of the research roadmap. The discussions of focus group #1 were conducted for the following objectives: (1) to validate the extracted challenges from the literature; (2) to associate the identified challenges to the related stakeholders and phases; and (3) to discuss and develop strategies to address them. The FGD process is non-linear, and several iterations were performed to validate the results.

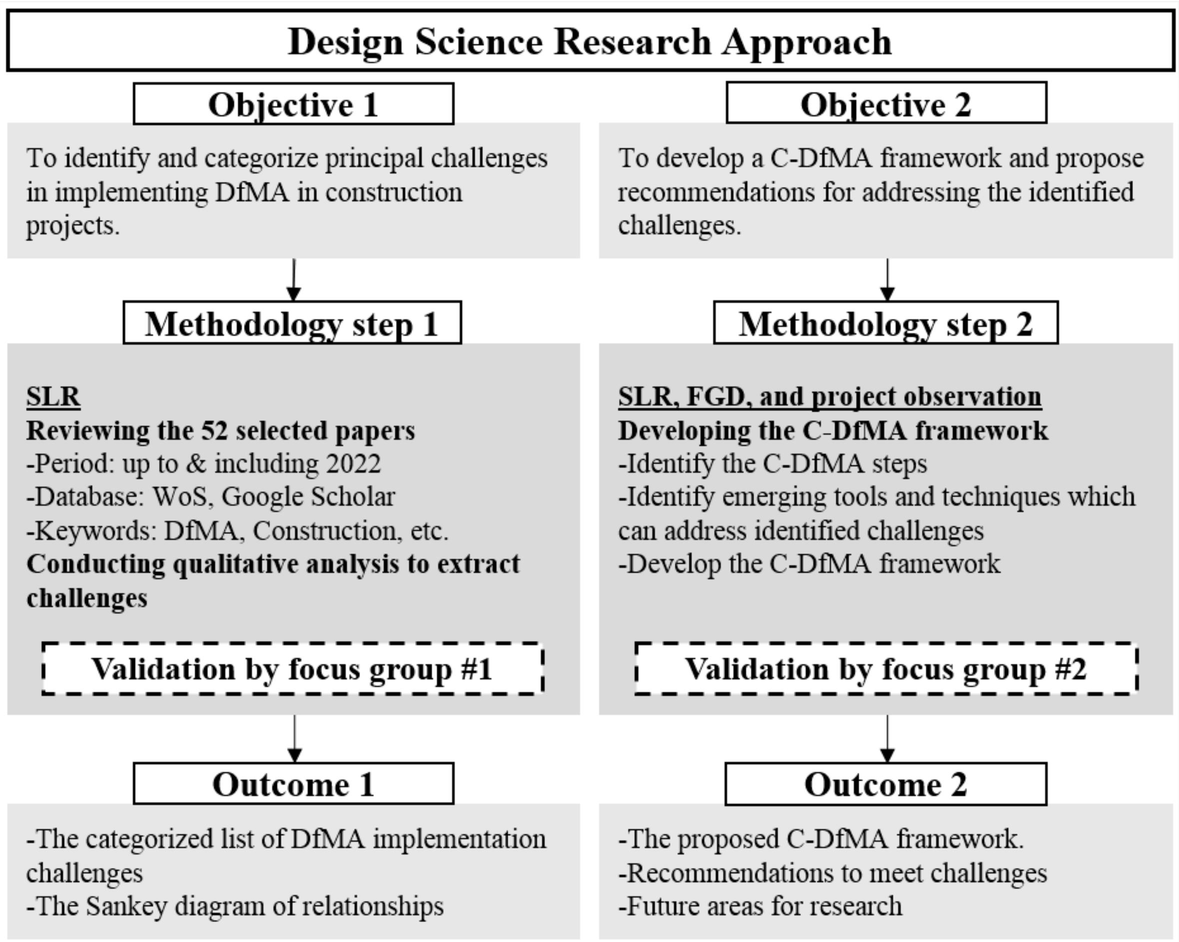

Figure 1. Stages of the DSR research approach for this study.

2.2. Step 2: Developing a Framework to Address the Challenges

The second step is to develop a conceptual framework to address the identified challenges. From the data collected through the systematic literature review and focus group #1 discussions, an initial conceptual, construction-oriented DfMA framework was developed and structured based on the most promising solutions identified in the literature. To verify and develop the initial framework, exploratory data were collected from two construction projects. These projects both involved off-site construction techniques, while having different contexts (project location, type, industry sector, etc.). The data for the framework verification were gathered through observations and discussions with the projects' stakeholders. Finally, the construction-oriented DfMA framework was discussed and validated during focus group #2 discussions with a separate panel of off-site construction industry experts. Similar to FGD #1, the FGD #2 process was non-linear, and several iterations were performed to validate optimal and feasible solutions.

3. Challenges to the Adoption of DfMA in Construction

To formulate the preliminary list of challenges, an SLR was conducted in two phases: (1) retrieve previous works from the academic database using pre-defined keywords; (2) filter the selected articles to include those that speak of factors that hinder the application of DfMA. Google Scholar, Scopus, and Web of Science were searched using the following keywords: "Design for Manufacture and Assembly" OR "Design for Manufacture" OR "Design for Assembly" OR "DfMA" AND "construction." To be thorough, we included DfMA-like construction concepts, such as design-for-excellence, fabrication-aware design, etc. Databases were searched for publications whose topics include at least one of 'design for manufacture and assembly', 'design for manufacture', 'design for assembly', 'DfMA', 'design for construction', and 'construction'. The search was limited to peer-reviewed published journal articles in English. A total of 232 hits resulted from an initial search for any one instance of the phrases. Next, inclusion and exclusion criteria were set. The inclusion criteria were as follows: (1) articles must be written in English and produced by peer-reviewed journals; (2) articles must discuss DfMA in the construction industry. The exclusion criteria were as follows: (1) lack of focus in the construction industry, and (2) only focus on DfMA generally. Using these criteria, we conducted the search in December 2022 and considered articles published by then and appearing in the database. After reading the title, keywords, and abstracts of the 232 articles, we retained 52 as being pertinent to the topic.

To extract the DfMA implementation challenges from the 52 selected articles, a qualitative content analysis, recommended by [31], was performed by developing the coding agenda, defining main categories, sub-categories, and coding rules for categories, and interpreting the results in an iterative manner. The initial content analysis and coding were conducted by the first author and reviewed and revised by the second and third authors. The review and analysis processes were iterated in team meetings until mutual agreements were reached. The final decisions were made based on choosing the approach that would best illustrate the results. Following the SLR, the following sections will present the results of our qualitative data analysis to identify construction-oriented DfMA challenges and their relationships to project phases/stakeholders.

3.1. Identified Challenges

Similar to any evolving research topic in the construction industry, several scholars have discussed particular challenges pertaining to the implementation of DfMA methods. Wuni et al. [32] discuss several challenges in applying design-for-excellence in industrialized construction, the most cited of which being "limited relevant knowledge and practical experience." Ref. [33] lists insufficient hands-on training for design professionals such as architects and engineers. They also explain that lack of sufficient knowledge and experience exposed design professionals to technical difficulties when implementing construction-oriented DfMA. In another study, professionals failed to apply appropriate DfMA tools and techniques in each phase of the project to address client needs efficiently, and were incapable of freezing design early to deliver the full benefits of construction-oriented DfMA in construction projects [25,34]. The second most-cited challenge identified by the literature relates to the lack of collaborative environments in the construction industry [25,32]. In fact, early involvement of project stakeholders in design, open communication, collaboration, and information sharing are pre-requisites for the proper implementation of construction-oriented DfMA [35]. Non-involvement of project stakeholders during the design stage in projects with traditional delivery methods was found to inhibit effective application of construction-oriented DfMA [36]. The third most-cited challenge concerns the lack of legislative frameworks of specified codes, guidelines, and standards for the implementation of construction-oriented DfMA methods [33–36]. The literature shows that limited industry guidelines, codes, and standards in various countries invoke a deficiency of systematic design metrics, and inhibit the development of construction-oriented DfMA best practices [37,38]. In this context, some scholars discussed inadequate tools and lack of affordable technologies as challenges to the adoption of DfMA in construction projects [25,39,40]. Due to the compounding effect of these constraints, project stakeholders do not have a common understanding of relevant DfMA principles in the industry [27]. Some scholars have identified "higher design costs" compared to the cost of traditional methods as a barrier to the proper implementation of construction-oriented DfMA methods in construction projects [5,41–43]. The extra cost is linked to additional organizational investment needs, namely, required specialized labor and technical skills [33,34], performance evaluation needs during the design and first-run prototypes [35], undeveloped market and limited competition among construction-oriented DfMA solutions [29,30], and complex code compliance requirements [3,4]. Unattractiveness to clients due to the deep-rooted poor image of post-war prefabricated buildings was also considered a significant challenge to the implementation of construction-oriented DfMA [22,27].

The primary list of DfMA implementation challenges is shown in Table 2. Moreover, to validate the results, the authors consulted the participants of focus group #1 about the identified challenges, and these confirmed that the aforementioned results are considered among the most pertinent in construction projects. In addition, as indicated in italics in Table 2, the consulted FGD #1 identified additional contractual challenges, such as traditional forms of contracts that create vertical, horizontal, and longitudinal fragmentations (i.e., design–bid–build), and operational/technological challenges, such as lack of capabilities to manage the module configuration processes, as being among the main challenges to be addressed. Accordingly, the focus group discussion results show that many challenges were associated with the contractual and operational aspects of construction projects related to issues such as risks and incentives, dispute resolution, insurance, liabilities and indemnification, and data sharing requirements. In light of the analysis of the selected articles and focus group #1 discussions, the authors identified 45 challenges to the implementation of DfMA in construction projects. As shown in Table 2, these challenges are classified into eight categories: contractual, technological, procedural, cultural, commercial, geographical, financial, and technical/cognitive. In particular, most of the identified challenges are related to the contractual, technical, and technological aspects of construction projects and their associated stakeholders. In this article, the impact or severity of the identified challenges are not investigated, which can be conducted in a complementary study.

Table 2. Challenges to the implementation of DfMA.

Categories	Code	Challenges *(Italics Represent Additional Challenges Identified by the FGDs)*	Reference
Legal Contractual	L1	***Lack of prefab and IC consideration in tenders***	***FGD#1***
	L2	***BID overpricing and difficulty in cost estimation***	***FGD#1***
	L3	Lack of risk/reward sharing consideration in the contract	[6]
	L4	Lack of clarity in terms of guarantees and insurance	[5]
	L5	Lack of DfMA platforms which conform with the CCDC contracts	[16]
	L6	Lack of clear scope of work, confusions, and duplications	[36]
	L7	Lack of references to several manufacturers in the contract	[11]
	L8	Lack of vertical, and horizontal integration between stakeholders	[35]
	L9	***Lack of longitudinal integration, teams disband at project termination***	***FGD#1***
	L10	Lack of clear roles and responsibilities of stakeholders	[39]
	L11	Complex litigation and long negotiations between key stakeholders	[4]
	L12	***Lack of agility and flexibility in the contract***	***FGD#1***
Technological	T1	Management of interfaces with subsystems	[15]
	T2	Difficulty in identifying appropriate DfMA tools/techniques in each phase	[4]
	T3	Lack of coordination between phases and contractors	[44]
	T4	***Lack of capabilities to manage the module configuration process***	***FGD#1***
	T5	Lack of coordination and collaboration between stakeholders	[22]
Procedural	P1	Need to evaluate performance at every design stage	[43]
	P2	***Lack of innovation as product architecture is locked***	***FGD#1***
	P3	Management of assembly works and interface tolerances	[8]
	P4	Need for additional project planning and design efforts	[36]
	P5	Necessity of first-run prototypes	[35]
	P6	Management of customer expectation in design	[40]
Cultural	Cu1	Customer rejection due to poor image of industrialized construction	[35]
	Cu2	Early commitment requirements and communication among stakeholders	[1]
	Cu3	***High criticality of the know-how that must be shared with other stakeholders***	***FGD#1***
	Cu4	Conflicting cultures between engineering and design teams	[22]
	Cu5	***Lack of trust and collaboration between buyers and their suppliers***	***FGD#1***
Commercial	Co1	Few market options available	[18]
	Co2	Lack of competition among prefabricated and modular solutions	[22]
	Co3	***Increased organizational complexities and investment requirements***	***FGD#1***

Table 2. *Cont.*

Categories	Code	Challenges *(Italics Represent Additional Challenges Identified by the FGDs)*	Reference
Geographical	G1	Requires both trade and location-based division of procurement	[15]
	G2	Complex code compliance and inspection process	[21]
	G3	***Few local options available***	***FGD#1***
	G4	***Logistics and transportation management complexities***	***FGD#1***
	G5	Scarce availability of resources for component development	[29]
Economic Financial	F1	Higher capital costs and investment requirement	[23]
	F2	***Difficulty in financial management and lack of an efficient payment method***	***FGD#1***
	F3	Higher design costs than the traditional design methods	[30]
Technical Cognitive	Tc1	***Specialized labour requirements***	***FGD#1***
	Tc2	Definition of standard details and connections	[43]
	Tc3	Limited DfMA knowledge and experiences	[39]
	Tc4	Reduced performance in the first few installations due to learning curve	[5]
	Tc5	Inability to exercise early design freeze	[15]
	Tc6	Lack of awareness of DfMA benefits among owners/developers	[36]

3.2. Relationship with Project Phases and Stakeholders

The Sankey diagram shown in Figure 2 illustrates the relationship between the DfMA implementation challenges in construction projects, drawn from the 52 selected articles. The width of the arrows is proportional to the flow rate. This Sankey diagram of relationships can be used to understand which stakeholders contribute more significantly to the identified challenges, and at which stages of the construction projects these challenges occur most frequently. This can help researchers and practitioners investigate the root causes of barriers to the implementation of DfMA strategies in construction projects more quickly and direct them toward applying appropriate remedial actions to address these hindrance factors according to their associated stakeholders and project phases more efficiently.

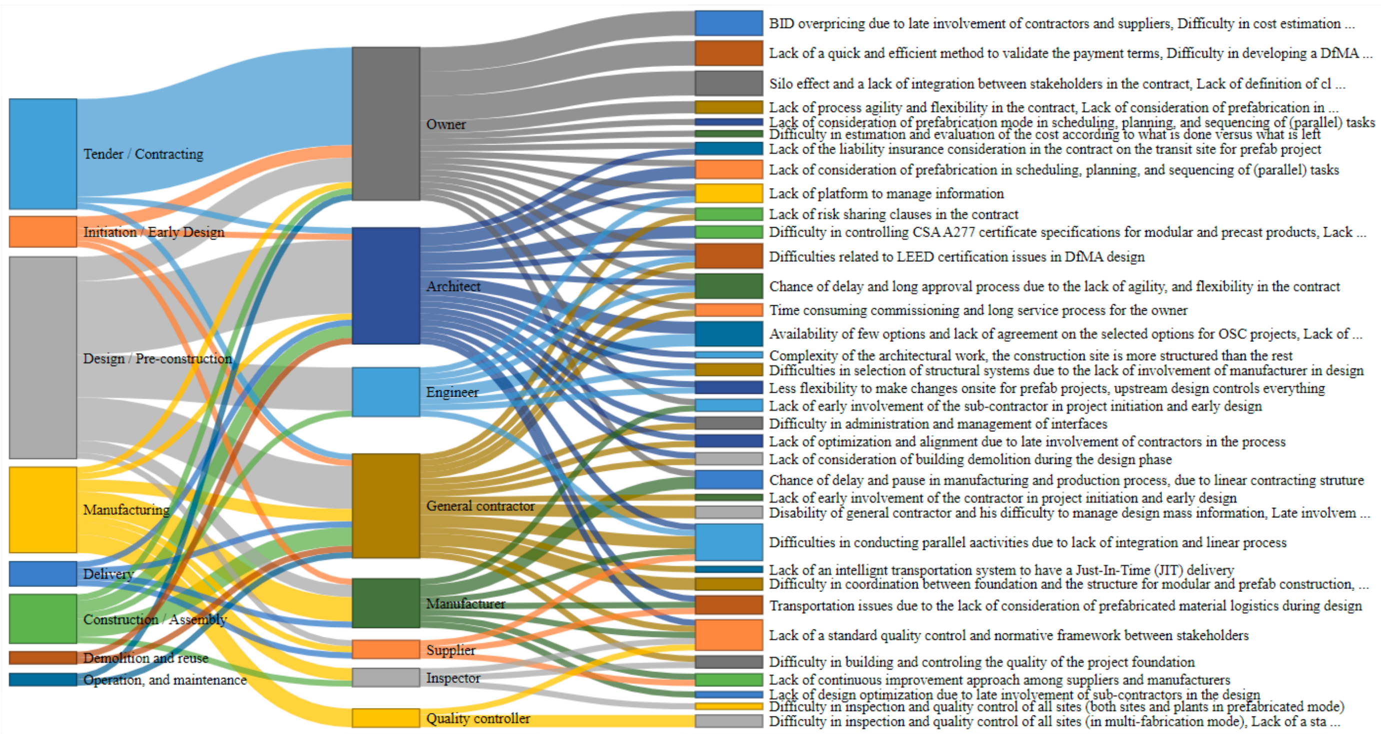

Figure 2. Relationship between challenges, stakeholders' roles, and project phases.

As shown, the biggest volume of challenges occurred in the design, manufacturing, and contracting phases; however, DfMA challenges can arise in all other phases. This could be because all types of construction involve design and manufacturing processes. The owners, architects, and general contractors are the most-cited stakeholders in DfMA-related studies. This may be because these stakeholders can directly cause or affect these challenges. For instance, major owners (i.e., governmental organizations, public agencies, policy-makers, etc.) make decisions to select and modify project delivery methods and contracting strategies for their projects; thus, they can address or contribute to several challenges that occur in the various phases of projects (i.e., contracting, design, construction, etc.).

4. Construction-Oriented DfMA Framework

This section presents the results of our qualitative data analysis to develop a conceptual framework for implementing DfMA in construction projects. Following the systematic literature review and focus group #1 discussion, we developed the initial framework based on the steps provided by the RIBA Plan of Work 2020 [11]. In the next stage, we verified the initial construction-oriented DfMA framework, and RIBA steps with two off-site construction projects, which will be described in this section. Both case study projects involve modular and off-site construction techniques, but they were conducted using different delivery methods and business models. The research strategy relies on piloting, observation, interpretation, and data collection. The data were collected through observation and direct discussions with representatives of the different stakeholders involved in the projects.

Project A, a multi-residential facility in Gibson, British Columbia, Canada. The project consists of a four-story multi-residential building with a total area of 9930.4 square meters (101,230 square feet), including 54 residential units, ten commercial spaces on the ground floor, two levels of underground parking, additional storage spaces, a swimming pool, and a gym. It was a fast-track project that started in December 2021 and terminated in May 2022. It had a very tight schedule, despite the shortage of labor, material, and supply chain interruptions due to the impact of the global pandemic on the construction industry. The owner awarded this project to a general contractor (GC) under the design–build (DB) delivery method. The project was situated in a remote location, and material delivery was only feasible by boat and ferry. In this context, finding local labor, suppliers, and arranging the delivery of materials was extremely challenging. Consequently, the GC sub-contracted parts of the project under traditional forms of delivery method, such as design–bid–build. To apply and verify the framework on this project, first, the general DfMA concept and challenges were explained to the project participants, and then the various sequential steps of the framework were assessed during the project life cycle. The implementation of the construction-oriented DfMA framework was found to be challenging in this project, as the project delivery method and business model were not supportive of the construction-oriented DfMA framework. Due to the traditional nature of project delivery methods and business models, there was a lack of integration between organizational structures of project stakeholders, and from the planning to delivery stages, project teams were not motivated to collaborate. In addition, there was no central information sharing platform accessible to all project stakeholders, and each team worked with its own systems. Even though the implementation of the DfMA framework was difficult due to the project's specifications, its application allowed project teams to fast-track the project. The integrated design process minimized the number of detected clashes, and fewer fabrication errors occurred. The integrated teams quickly adapted to the design alternatives based on locally available materials. Finally, although the project was completed on schedule, there was cost overrun. Several change orders occurred during the project that caused the project's final cost to exceed the estimated budget.

Project B, a structural steel industrial facility in Ohio, United States. The 32,516 square meter (350,000 square foot) electric resistance welded (ERW) pipe facility is designed to produce hollow structural sections and standard pipes. The construction began in November 2021 and terminated in the summer of 2022. For the construction of this facility, custom joist girders were designed to be built entirely from HSS materials supplied by a steel manufacturer in Ohio. The non-load-bearing prefabricated wall panels were manufactured in Canada and delivered to the U.S. site, where erection of the modular panels was fast-tracked using multiple cranes and erector crews to meet the tight schedule under difficult conditions. In addition to the shortage of labor, water accumulation on the job site made the site assembly very challenging. This project used a hybrid contracting model that combined a design–build method and integrated project delivery principles, which are also known as a type of IPD model. As with case A, to verify the construction-oriented DfMA framework on this project, first the general DfMA concept and challenges were explained to the project participants, and then the initial framework's sequential steps were assessed for each project phase. Compared to case A, the implementation of the framework was less challenging, as the project delivery method and business model were supportive of the framework. The IPD-type project delivery method provided incentives for stakeholders to collaborate during all phases of the project. For instance, the shared risks and rewards and joint decision-making principles fostered a collaborative project environment. The project business model was based on a semi-vertical integration model, in which integrated hierarchical firms kept control of some in-house material production processes. A digital information sharing and tracking central system was used by various departments, which enabled users to access the project progress information in real time. This facilitated the implementation of the framework and enabled the project stakeholders to follow the framework steps efficiently. The application of the construction-oriented DfMA framework improved project performance metrics from the project's initiation phase to close-out and execution. The design was optimized, the fabrication and assembly time was reduced, the materials were delivered just-in-time, and site safety improved significantly. Ultimately, the project was completed ahead of the original schedule, and compared to project A, fewer change orders occurred during the project.

The verified framework in studied projects is shown in Figure 3. The framework is divided into seven stages based on the RIBA Plan of Work 2020. The fifth stage of the RIBA was divided into two sub-stages: (5.1) manufacturing and (5.2) construction/assembly/closure to specify tasks that are required for those sub-stages. As shown in the framework, during each phase a strategic plan must be followed to facilitate the implementation of construction-oriented DfMA. For instance, during the initiation phase, project objectives, including the requirements for construction-oriented DfMA must be defined, and a project execution plan must be designed to ensure objectives can be achieved in accordance with the client's objectives.

To fully implement the construction-oriented DfMA method, a high level of integration is required. This highlights the importance of selecting an optimal project delivery method, business model, and operational tools/techniques that enhance collaboration among project participants and improve supply chain integration. During the verification stage of the two studied projects, it was found that the construction-oriented DfMA steps could only be implemented efficiently in projects that were delivered through relational and integrated delivery methods and business models. For instance, in project A, with several traditionally sub-contracted scopes, the joint planning and design tasks were not feasible.

The operational processes in the framework are "lean", meaning that they emphasize maximizing value, minimizing waste, creating an efficient workflow production system, and no redundancy [45] throughout the project life cycle. Applying lean principles and practices improves value-based design, supply chain integration, just-in-time delivery, and construction automation in various phases of the project. The operational tools and techniques are based on the application of BIM and intelligent technologies, which support the flow of information throughout the project, including Artificial Intelligence (AI), Internet of Things (IoT), reality capture (RC) technologies, and smart logistics tracking applications. For construction-oriented DfMA, BIM acts as (a) a process enabler, (b) an implementation tool, and (c) an information source/model [3,24,37,46]. The BIM-based digital platform assists with visualization (3D-BIM), schedule optimization (4D-BIM), cost management (5D-BIM), sustainability (6D-BIM), facility management (7D-BIM), occupational health and safety (8D-BIM), maintenance (9D-BIM), and recycling (10D-BIM) [47,48]. Real-time sharing of the site information enables just-in-time deliveries of factory produced sub-assemblies and efficient planning of the crane logistics [46]. Consequently, several quality control activities are considered in the framework, in which multi-discipline design models, manufactured parts, and assembled structures are checked for errors, collisions, and omissions as well as for quality assurance metrics.

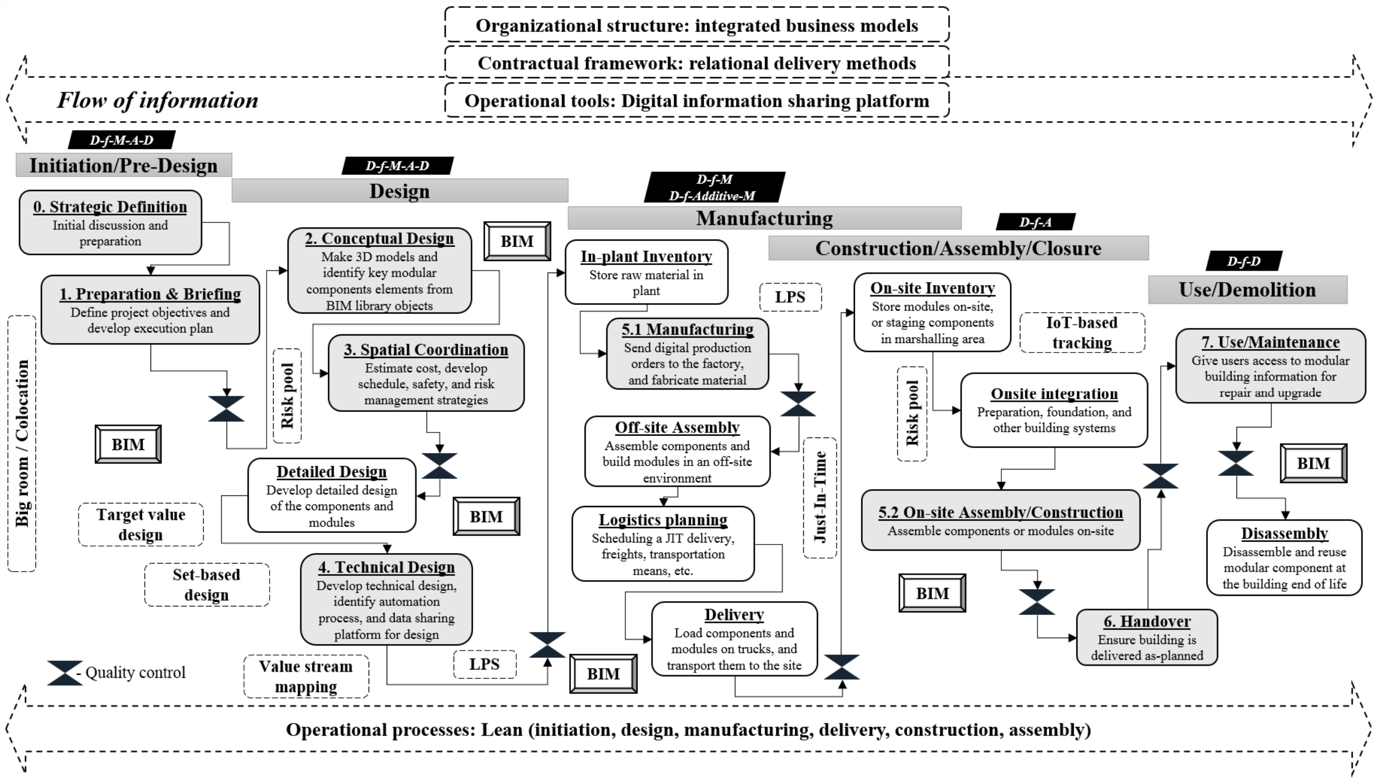

Figure 3. Flowchart of construction-oriented DfMA framework.

As illustrated, the combination of DfMA, lean, BIM, collaborative delivery methods, and integrated business models along with the application of I4.0 technologies enables efficient knowledge sharing, communication, and productivity monitoring throughout the project, and supports a streamlined alignment of tools and techniques with people and processes as the basis for a new integration strategy. The proposed conceptual framework helps reduce supply chain disruptions, elucidate synergies, and outlines future opportunities for the mutual application of these emerging integrated strategies in off-site construction projects. Following the verification of the framework in the studied projects, the framework was validated in the discussion with focus group #2, as explained in the methodology section.

5. Results and Discussion

The results of this study indicate that most of the identified challenges to the full implementation of DfMA in the construction industry are related to the lack of integration and fragmented nature of construction projects, in which a free flow of information is blocked by various impediments. This is in accordance with previous studies that aimed to enhance the implementation of DfMA strategies in construction projects [23,27,34]. According to the studies conducted by [9–11], a lack of integration in construction projects can be related to applying unsupportive organizational structures, contractual frameworks, and operational systems. Conversely, integrated business models, relational project delivery methods, and collaborative operational systems can improve collaboration [32,46] and thus enhance the implementation of collaborative strategies such as construction-oriented DfMA [46,47]. Organizational structure defines the team structure, which is formed by the project's key stakeholders and refers to the timing of stakeholders' collaborative engagement in the project. A contractual framework refers to the regulative guidelines that align the stakeholders' goals and objectives with the overall project's objectives through framing compensation structures and addressing risk allocations among project participants. Finally, the operational systems and processes refer to the application of tools, technologies, and implementation of mechanisms, which ensure effective interaction, collaboration, and communication among project participants [45]. To improve integration and address the barriers to the full implementation of DfMA in fragmented environment of construction projects, we categorized the identified challenges based on our literature review, focus group discussions, and case study results in three classes: organizational structures, contractual frameworks, and operational systems. As shown in Table 3, the results indicate that many of the challenges relate to the operational and contractual aspects of projects, while fewer challenges are related to the organizational structures of project firms. In this section, we discuss emerging business models, project delivery methods, and operational tools and techniques that can ease the adoption of construction-oriented DfMA by promoting the required collaborative working environment.

Table 3. Categories with which DfMA challenges are associated.

Classes	Challenge Codes
Organizational structure	L8, L9, P6, Cu2, Cu4, Cu5, Co1, Co2, Co3, G1, G3, and G4
Contractual framework	L1, L2, L3, L4, L5, L6, L7, L10, L11, L12, Cu1, G2, G3, G4, G5, and F2
Operational systems	T1, T2, T3, T4, T5, P1, P2, P3, P4, P5, Cu3, F1, F2, F3, Tc1, Tc2, Tc3, Tc4, Tc5, and Tc6

5.1. Organizational Structures

Organizational structures are influenced by both business models and project delivery methods, which are different yet related concepts [12,45]. A business model is defined at the organization level and is used to classify different organizations. It describes how firms are structured to grow, prosper, and survive by capturing and creating additional value over time [4,12]. In contrast, a project delivery method is defined at the project level and is used to classify project participants' roles and responsibilities. It describes how stakeholders are organized to create and capture value on a one-time basis, and then scatter once the project is completed [12]. Big project-based firms and organizations can have multiple delivery methods that can be deployed within their business model and broader organizational strategy [12]. Although the use of relational project delivery methods (such as IPD) improves horizontal and vertical integration, it still does not change the prevailing business model orientation of project-based organizations, which leads project teams to disband and tacit knowledge to be lost at the termination of each project [21,22]. Deploying a relational delivery method under proper business models can result in repetitive project teams [18,22], which can resolve challenges related to longitudinal fragmentation, sustainability, and circularity. This is aligned with the goal of the construction-oriented DfMA method to add value and diminish waste in construction projects.

The results of this study show that business models that are characterized by integration and longitudinal continuity can enhance the implementation of construction-oriented DfMA in construction projects. In this context, three suitable emerging integrated business models are discussed below:

Vertical integration: In this model, firms are structured as integrated hierarchical firms that control production architecture and processes in-house by developing their own off-site factories [21,49–51]. Nothing is outsourced in this model, and the construction-oriented DfMA strategy can be coordinated throughout the initiation, design, manufacturing, delivery, assembly, and construction within the same integrated firm. High capital costs are required in this model, which is mostly applicable to modular housing projects with repeatable and flexible modules. The Swedish company BoKlok is a successful example of this model [18].

Digital systems integration: In this model, firms leverage an integrated cloud-based product configurator to achieve mass customization and support optimal decision-making. Usually, a BIM-based product platform is applied to streamline the flow of information between different stakeholders and support integrated design-to-production workflows in the context of industrialized construction [44,48,52,53]. These firms do not own the manufacturing technology, but through industry 4.0 supply chain principles, they can manufacture parts through peripheral supply chain partner suppliers [12,42,54–56]. Compared to vertical integration, this model requires more time to develop new products. Project Frog is an example of this model [18,57,58].

Spinoff factories: In this model, an existing project-based business shifts toward industrialized construction through new spinoff factories or new business lines. In this approach, there is a continuous need to update and train the existing supply chain about new factory capabilities [18,22,59]. DPR Construction and their spinoff factory Digital Building Components are examples of this model [18,60].

These new business models characterize re-organization attempts to deliver construction projects in a more collaborative and integrated way through vertical, horizontal, or longitudinal continuity across the supply chain of projects [61–64]. The achieved integrated supply chain facilitates the proper implementation of the construction-oriented DfMA framework in construction projects.

5.2. Contractual Frameworks

Project delivery methods frame contractual guidelines within projects, which define the roles and responsibilities of project stakeholders. In traditional forms of delivery methods (i.e., design–bid–build), project phases are fragmented, and stakeholders mostly compete instead of collaborating. In traditional delivery methods, information models are stuck in phase-based silos, project participants are not motivated to share them beyond the phases to which they are related [22,65], and this leads to construction projects encountering vertical, horizontal, and longitudinal fragmentations. This is why proper implementation of construction-oriented DfMA is not possible in traditional delivery methods. This challenge can be addressed using supply chain integration practices, which structure information, processes, people, and firms for the purpose of collaboration and integration within the supply chain [24,66,67]. In this context, relational project delivery methods that emphasize integration can be applied. For instance, integrated project delivery is a formal approach to integration through signing multi-party contracts and sharing the associated risks and rewards of the project [68,69]. Similar to DfMA, integrated project delivery (IPD) is known as both a philosophy and a method that enhances integration throughout the project life cycle [21–23]. In projects in which IPD acts as a philosophy, also known as IPD-ish projects, collaboration is not contractually required, and IPD principles are applied in the projects without the formal signature of the contracts. In real IPD projects, collaboration is required by a multi-party contract, and IPD acts as a delivery method [20]. While DfMA focuses on product/process integration, it needs to be accompanied by a contractual framework such as IPD, which focuses on people integration.

5.3. Operational Systems and Processes

To efficiently apply construction-oriented DfMA strategies in construction projects, BIM, lean, and I4.0 operational systems and processes are required. BIM-based platforms can streamline the flow of information between different stakeholders and support integrated design-to-production workflows throughout the project life cycle [70–73]. BIM improves communication and collaboration among project participants by connecting DfMA downstream activities (i.e., supplying, procurement, manufacturing, delivery, assembly, and installation) to upstream activities (i.e., initiation, briefing, appraisals, and conceptual design) [74]. Lean operational systems focus on the definition of production systems that can deliver the project from initiation/design through to construction [75]. In fact, some emerging concepts in the construction industry, such as IPD and integrated business models, use lean as a foundation [21]. Similar to DfMA, lean is also borrowed from the manufacturing industry. Lean-related concepts, tools, principles, processes, and systems such as Last Planner System (LPS), A3s problem solving, Target Value Design (TVD), Choosing By Advantages (CBA), and Pull Planning are all based on adding value and diminishing waste in projects. In the construction-oriented DfMA framework, the lean operational processes are concrete, observable, specific, and act as part of the framework. On the other hand, Industry 4.0 (I4.0) technologies are tools that are required for the implementation of these lean processes. I4.0 technologies enable proximity and integration for construction supply chains [11,47,76]. These technologies improve collaboration between all project participants. Unlike the manufacturing industry, in the construction industry, products (buildings) carry both product-level (i.e., prefabricated modules design dimensions, engineering features, plant production processes, etc.) and project-level (i.e., site planning, as-built elements, on-site activities, etc.) information [77]. Therefore, an information-sharing platform for implementing the construction-oriented DfMA framework should support both product- and project-level information management. Emerging I4.0 tools and technologies can be useful in deploying the construction-oriented DfMA framework. For instance, cloud-based real-time data sharing platforms can help in monitoring project progress and daily operations regarding health, safety, quality, and environmental impact. Tracking technologies, such as IoT-based applications, can help to control the structural performance of the building elements [15,46,78]. To further enhance the implementation of the construction-oriented DfMA framework in prefabricated projects, the I4.0-based information-sharing platforms could support various degrees of mass customization [79–81].

6. Conclusions

This study presented a comprehensive review of the challenges, constraints, and problems of implementing construction-oriented DfMA. From the literature review and focus group discussions, forty-five challenges were identified and categorized into eight categories: contractual, technological, procedural, cultural, commercial, geographical, financial, and technical/cognitive. The majority of the identified challenges relate to the contractual and operational aspects of construction projects and the associated stakeholders.

Based on the results of the review and project observations, we developed a construction-oriented DfMA framework to address the identified challenges. We discussed opportunities for enhancing the implementation of construction-oriented DfMA through applying emerging organizational structures, contractual frameworks, and operational tools and techniques in the construction industry. The results show that integrated business models, relational delivery methods, lean-based operational tools, and digital technologies enable a suitable environment for implementing construction-oriented DfMA strategies and addressing the identified challenges.

6.1. Implications for Research and Practice

The research conducted in this paper contributes to the body of DfMA-related knowledge and has several implications for accelerating the application of DfMA in the construction sector.

For researchers: a comprehensive list of challenges to the implementation of DfMA in the construction industry is provided in this study, and the relationships between these challenges and project phases/stakeholders are investigated. For proper implementation of DfMA strategies, a high level of integration is required in construction projects. Thus, more studies on the synergetic combination of DfMA with emerging integrated contracting strategies (such as IPD), new technologies (IoT, 3D printing, nD BIM, digital cloud-based platforms, etc.), and emerging business models (spin-off company, virtually integrated, etc.) are required.

For governments and policy-makers: continuous support to construction companies that are interested in using DfMA principles in their projects is recommended. Policy-makers can collaborate with practitioners and researchers to develop guidelines, provide standards, and prepare training to industry practitioners to improve the application of DfMA strategies in construction projects.

For practitioners: commitments and mutual collaboration between industry practitioners and local manufacturers, engineers, architects, general contractors, sub-contractors, and project managers are required to foster an environment propitious to the application of DfMA guidelines and strategies in construction projects. Practitioners can use the proposed DfMA framework as a guide to plan their project-based solutions to build trust with future project partners. In fact, the implementation of the construction-oriented DfMA framework can enhance longitudinal integration in construction projects. Ultimately, this research should support the broader adoption of DfMA in construction projects.

6.2. Future Areas of Study

This study revealed that construction-oriented DfMA cannot be implemented efficiently in isolation. Further study on the application of the construction-oriented DfMA framework proposed in this research, combined with newly developed business models (spin-off company, virtually integrated, etc.), delivery methods (integrated project delivery, progressive design–build method, etc.), and tools and technologies (IoT, 3D printing, nD BIM, cloud platforms, etc.) is required. Based on the results, we identified the following directions for future research:

6.2.1. Organizational Structures

Integrated trust-based organizational structures: More studies are recommended on the impact of the proposed construction-oriented DfMA framework on long-term trust-building activities.

6.2.2. Contractual Frameworks

Integrated project delivery: The results of this study show that relational delivery methods can enhance the application of integrated design and manufacturing strategies such as DfMA in construction projects. However, there is a lack of empirical studies in this regard. Additionally, several standard forms of IPD contracting are available in North America (i.e., CCDC30 in Canada and AIA C-191 and ConsensusDocs 300 in the U.S.). Further study is needed on the synergic impact of IPD and construction-oriented DfMA to enhance off-site construction projects, in particular, to develop an optimal IPD contractual guideline for reinforcing this synergic impact.

6.2.3. Operational Systems and Processes

There is an increasing need for a collaborative and integrative operational environment for the successful implementation of DfMA in construction projects [5,33]. Thus, more studies on collaborative information-sharing systems on multiple levels (project, organization, and industry) are required. In this context, the following directions for future studies are recommended:

- BIM-based intelligent technologies: There is little empirical research in the literature on construction-oriented DfMA technological adaptation in the construction sector. Initial research on this topic focused on the combination of BIM and cloud-based technologies with construction-oriented DfMA [46,52,70]. Applying DfMA strategies based on BIM and other digital technologies results in the digitization of building models throughout the manufacturing and assembly processes [3,28]. The combination of BIM and intelligent technologies can increase the innovative and collaborative applications of construction-oriented DfMA at both the object and integrated collaborative environment levels [11], and facilitate the improvement of evaluation and decision-making for choices or alternatives [52]. More in-depth research and multiple case studies for the application of BIM, AI, data analytics, block-chain, and IoT technologies are required to improve construction-oriented DfMA adaptation in the industry.

- Smart flexible supply chain: Recently, the construction industry has encountered severe uncertainties (i.e., the COVID-19 crisis, war, etc.). In this context, supply chain flexibility becomes vital [82–87]. More studies on developing smart, dynamic, agile, integrated, and practice-oriented supply chains are required to improve construction-oriented DfMA implementation strategies.
- Generative design: Studies indicate that the integration of construction-oriented DfMA with BIM-based generative design can enhance automation and optimize the design for prefabricated and off-site construction projects [26,33,47]. In fact, the combination of construction-oriented DfMA with BIM-based generative design provides a promising path to automation and AI-based BIM applications for modular construction.
- Design for additive manufacturing (DfAM) and 3D printing: Due to increasing labor costs and the worldwide aging-population crisis, robotics and additive manufacturing (also known as 3D printing) are essential tools for the future of the construction industry [87,88]. However, current industry practices are not prepared for the full-scale application of DfAM techniques. The integration of construction-oriented DfMA and BIM with robotics and additive manufacturing strategies (3D printing), can increase the level of automation and productivity even with current labour issues. More studies on exploiting the capability of 3D-printing techniques for manufacturing pre-assembled structures with a focus on construction-oriented DfAM are required [89,90].
- Design for circularity in construction: With natural resources becoming scarce and demands for reuse and recycling increasing, the construction industry is shifting toward a more sustainable and circular approach. However, few studies address construction-oriented design-for-deconstruction or disassembly techniques, which is a gap that is worth exploring. In this context, more work on the synergy between construction-oriented DfMA and emerging IoT-based tracking technologies for recycling material and developing smart decision-making tools for stakeholders is recommended [18].
- Digital fabrication (DFAB): DFAB is an emerging technical and computational approach for the architecture and construction industry [24,28]. To manage DFAB, integrated design and construction processes such as lean construction management and DfMA practices are required [24,80,90]. According to [24], significant synergies exist between Lean, DfMA and DFAB, and they have several shared practices such as "design to target value" and "concurrent engineering". However, large research gaps between DfMA and DFAB studies show that more research is required on integrating them with lean management techniques, BIM, and machine learning (ML) algorithms to increase operational efficiency, construction automation, and sustainable design and construction practices [24,28,91].

6.3. Limitations of the Study

This research contains certain limitations that provide opportunities for future improvements, including the following:

- Prioritizing the identified DfMA implementation challenges, defining their impacts, and identifying their severities.
- Identifying additional construction-oriented DfMA implementation strategies.
- Further developing and validating the construction-oriented DfMA framework within bigger focus group discussions.
- Testing and applying the construction-oriented DfMA framework to other case study projects in different contexts (publicly funded, infrastructure, and complex projects).

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