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TOWARDS INTEGRATED IMPLEMENTATION OF IPD AND DFMA FOR CONSTRUCTION PROJECTS: A REVIEW

Sara Rankohi[1], Mario Bourgault[2], Ivanka Iordanova[3], & Carlo Carbone[4]

ABSTRACT

Integrated project delivery (IPD) and Design-for-Manufacturing-and-Assembly (DfMA) are emerging topics in the construction literature, which have attracted considerable attention in recent years. DfMA is known as a philosophy and a method whereby products' designs are optimized for downstream manufacturing and assembly. Similarly, IPD, is known as a philosophy and a method which enhance integration throughout the project life-cycle. Although literature identified the ability of both DfMA and IPD principles to enhance project performance metrics, little research has investigated their potential synergies. Keeping in view the opportunities accruable from this combination, this paper conducted a systematic literature review of papers that discuss minimum one of these two methods, and identified common principles or practices shared among IPD and DfMA. Finally, a framework is developed based on synergies between IPD, and DfMA in construction projects.

KEYWORDS

Integrated Project Delivery, DfMA, IPD, Design-for-Manufacturing-and-Assembly, Architecture and Construction, Lean, Literature Review.

INTRODUCTION

Conventional project delivery methods have performance issues due to their segmented structure (Fischer et al., 2017). Frustrations with conventional delivery methods and lower than expected end results, have led to the development of the Integrated Project Delivery (IPD) (Abdirad et al., 2019). IPD aims to address the problem of fragmentation in construction projects. In this contractual method, a new single purpose entity or limited liability company is created; consisting of the owner, the lead designer, the construction manager, and other key stakeholders in the design and construction of a project (Mesa et al., 2016; Yee at al. 2017; AIA, 2010). Design for manufacture and assembly (DfMA), is a methodology which, similar to IPD, seeks to resolve the problem of fragmentation in the industry by connecting design, manufacturing, and construction from early in the design process (Tan et al., 2020; Gao et al., 2020; Ng and Hall, 2019). This method aims

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for facilitating manufacturing and assembly, boosting productivity, improving quality assurance, and reducing projects' cost, time, and waste (Boothroyd et al. 2002; Bao et al., 2020; Montali et al. 2018; Lu et al., 2020; Bogue 2012).

As emerging topics in the construction management domain, we still know a little about IPD and DfMA. From a practical perspective, their adoption in the construction industry is still low and the awareness about them is still marginal (Yee et al, 2017; Bao et al., 2020). From a theoretical perspective, the conceptual aspect of IPD and DfMA practices are yet to be discovered (Mesa et al., 2019; Hall et al., 2019). Although IPD and DfMA represent two different domains of research and development, there are evidences that they have parallel principles and practices which seek to enhance integration in construction projects. The term "principle" here refers to a fundamental proposition that serves as the foundation for a system or a concept (Ng et al., 2019), while "practice" refers to shared behavioural routines which lead to the procedure of practical understanding (Hall et al. 2018). However, little research provide insights on identifying and describing these shared principles and practices in details.

In order to benefit from the full advantages of IPD and DfMA methods and understand the risks associated with implementing their synergy in construction projects, more research is crucial. The aim of this paper is to report on a systematic literature review that aimed at identifying common principles and practices of IPD and DfMA.

METHODOLOGY

This study employs a systematic review methodological approach. As shown in Figure 1, this methodological framework consists of two phases: (1) data collection: identify the search keywords, identify the search databases, and search, screen, and select the relevant articles; (2) data analysis: content analysis using VOSviewer, synthesize, and developing a framework.

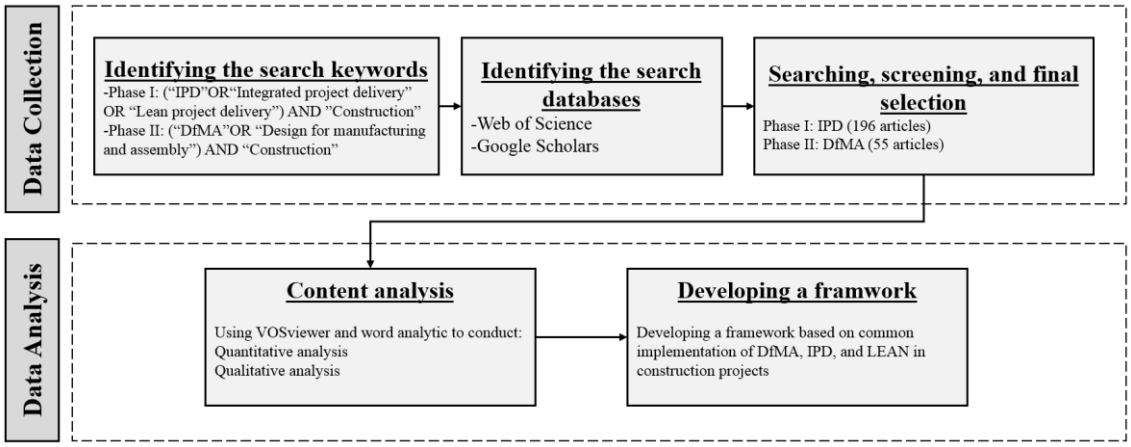

Figure 1: Flow diagram of research method.

The Web of Science and Google Scholar platforms were selected as search data bases from 2010 to February 2022 inclusively limited to English. As the most cited definition of IPD was proposed by AIA in 2010, we chose this time period to capture the most number of IPD relevant articles. For consistency, we covered the same search period for DfMA literature. As shown in Table 1, each keywords include controlled vocabulary and terms related to IPD and DfMA in the construction engineering domain.

Table 1: Search keywords.

IPD	DfMA
IPD	DfMA
LPD	Construction
Construction	Design for assembly
Lean Project Delivery	Design for manufacture
Integrated Project Delivery	Fabrication-aware-design
Integrated Design and Construction	Design for manufacture and assembly

The Lean construction community conducted significant research on IPD and DfMA. Therefore to grasp the true nature of the topic and assure the comprehensiveness of the review, in addition to electronic journal databases, conference databases related to Lean construction (i.e., proceeding database of the International Group for Lean Construction (IGLC)), are reviewed

The final selection and inclusion of relevant studies is done through: selection of articles by reviewing their titles and abstracts; primary screening the full texts to assure the relevance to the topic and the construction domain; and secondary screening of articles in circumstance of doubt about the relevance of a study. As shown in PRISMA diagram shown in Figure 2, a total of 196 papers for IPD and 55 papers for DfMA are included in this review. Among these articles, we have found a few papers (Lu et al., 2021; Langston & Zhang, 2021) which referred to the combined application DfMA and IPD in construction projects, but did not conduct further studies about it, as their principle research focus.

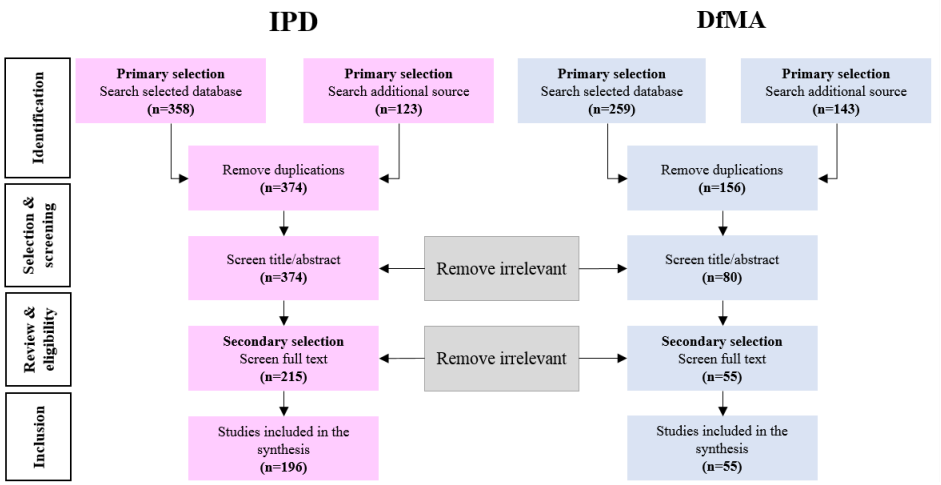

Figure 2: PRISMA diagram of the selected articles.

CONTENT ANALYSIS

RESEARCH TRENDS

The distribution of articles by the year of publication is depicted in Figure 3. As shown, there is an increasing interest toward IPD and DfMA research since 2010. In particular for the DfMA, in the year 2021, the number of publications doubled compared to the previous year. This shows a trend towards research about DfMA in the construction industry.

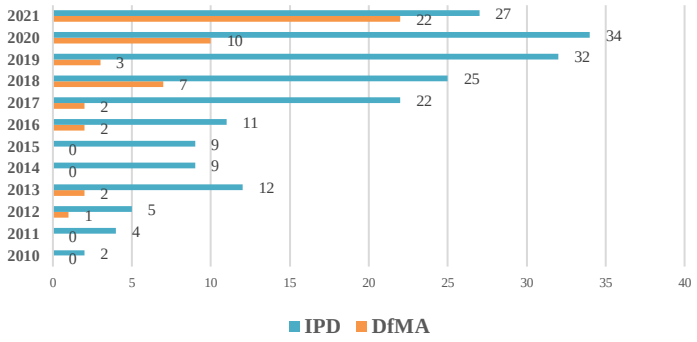

Figure 3: Distribution of articles by the year of publication.

The Sankey diagram in Figure 4 illustrates the IPD and DfMA research focus overtime, with respect to construction projects' phases. As shown, the volume of studies (width of blocks) has gradually increased over the past decade. Regarding research focus, IPD and DfMA studies focused more on the whole life-cycle of the project since 2015, while from 2010 to 2014 studies mostly focused on projects' design and construction stages.

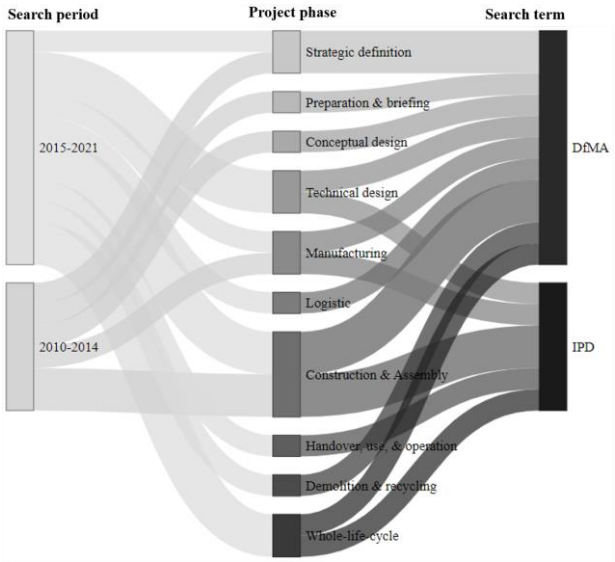

Figure 4: Sankey diagram of IPD & DfMA studies with respect to project phases.

WORD ANALYTIC

We used VOSviewer to conduct a word analytic and visualize the co-occurrence of keywords in IPD and DfMA literature. As shown in Figure 5, several keywords have co-occurred in both topics frequently; *Lean*, *BIM*, and *integration*, are discussed in this section.

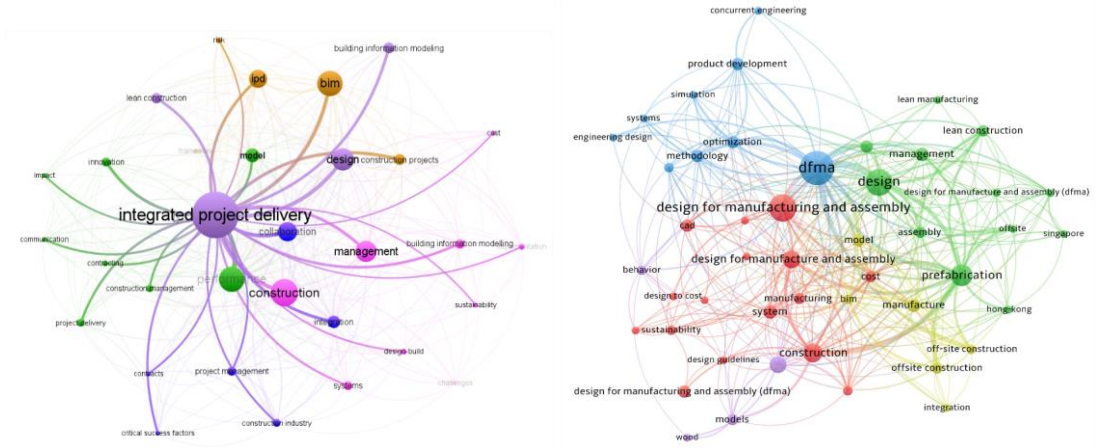

Figure 5: Co-occurrence of IPD (left) & DfMA (right) articles' keywords (VOSviewer).

Lean Construction

The keyword "Lean" has co-occurred frequently in both IPD and DfMA literature. It matches the procedural and cultural principles of both concepts. Lean Construction is a method of planning and optimizing the supply chain to minimize the waste of time, materials, and labour and maximize value (Koskela et al., 2002). Lean principles originated from car manufacturing and the Toyota production system (reference) and then adapted to the particular characteristics of construction projects, such as uniqueness, complexity, and 'one-off' project-based production processes. Lean construction principles are currently more diverse and focused on waste elimination, user-satisfaction, value-addition, and improved communications (Lu et al., 2021).

Literature shows that IPD and DfMA key principles are rooted in Lean principles and practices such as supply-chain-integration (SCI), just-in-time (JIT), automation (Jidoka), pull-planning, early contractor involvement (ECI), standardisation, waste reduction in cost, and labour, concurrent engineering (CE), client's commitment, target value design (Miron et al. 2015; Koskela et al 2002; Gerth et al. 2013; Kim and Lee 2010).

A few scholars investigated similarities and differences between Lean and these two approaches. Mesa et al. (2019) conducted a comparative analysis of IPD and Lean project delivery (LPD) methods through analysing of organizations, contractual relationships, and operational systems in projects. They found that the core difference between IPD and LPD is related to their operational system. Both approaches are similar in terms of encouraging the application of integrated organizations, relational contracting, and integrated delivery process. DfMA and Lean principles are also interrelated and mutually supportive in construction literature (Gerth et al.,2013). For instance, DfMA supports Lean construction practices by helping designers optimize design, reduce waste, and eliminate non-value adding activities in the project supply-chain, through minimizing the number of parts, and maximizing ease of handling and assembly. Ng and Hall (2019), conducted a review of Lean and DfMA literature, and concluded that the three Lean concepts of: JIT, quality improvement, and concurrent engineering (CE), are the most influencing factors in the adoption of DfMA.

Scholars conducted various studies on the mutual impact of these concepts on each other. Some report DfMA facilitate Lean process (Gbadamosi et al., 2018), while others report Lean enhances DfMA philosophy (Banks et al., 2018; Ramaji et al., 2017). Regarding IPD, some studies apply IPD and LPD perceptions interchangeably (Do et al., 2015), while some studies indicate that Lean Construction is a set of techniques which supports IPD (Mesa et al., 2019). In summary, while IPD, DfMA, and Lean principles are

conceptually different with different focuses and scopes, they can bring common benefits and values to the construction industry, such as maximizing value, reducing construction cost and efforts, and improving construction productivity (Ogunbiyi et al., 2014).

Based on the review, we have identified all principles and practices of IPD, DfMA, and Lean cited in the literature. The Sankey diagram in Figure 6, illustrates the relationship between these principle (left column) and practices (right column), and how they are associated with the studied concepts (middle column). As shown, integration is the most cited principle, which relates to all three concepts. Also, several practices such as maximizing value, reducing costs, and eliminating wastes are shared between IPD, DfMA, and Lean.

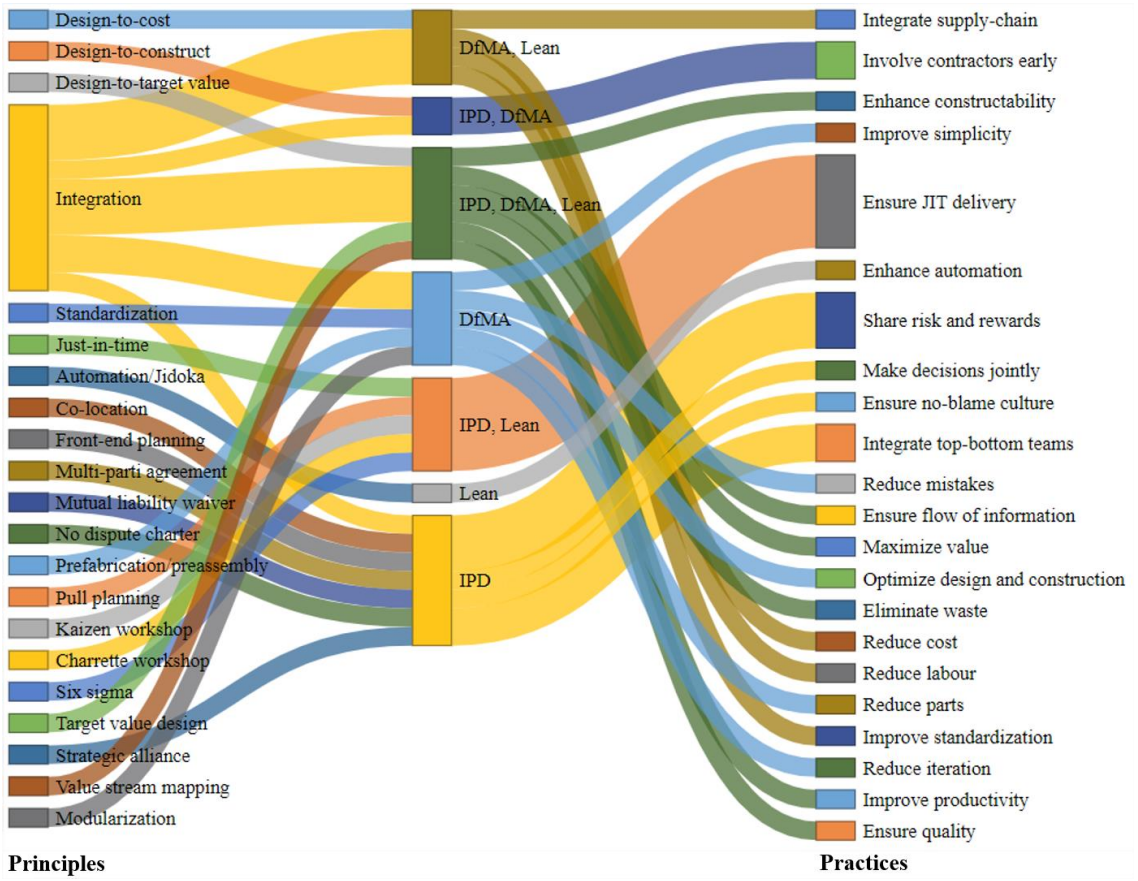

Figure 6: Sankey diagram of relationship between IPD, DfMA, and LEAN.

BIM

The term "building information modelling" or "BIM" has occurred frequently in both IPD and DfMA literatures. BIM is associated with the technological aspects of both concepts. A building information model is the digital representation of a building with its components characterized by parametric objects (Yin et al., 2019). Several studies identified that there is a trend toward the integration of DfMA, and IPD with technologies like BIM (Gerth et al. 2013; Lu et al., 2019; Bogus et al. 2006). There is a growing attention to the connection between IPD, BIM, and Lean construction in the literature, particularly for their application on large and complex projects (Langston et al., 2021). In both IPD and DfMA approaches, a high level of communication, collaboration and real-time data transfer among different stakeholders is required (Ng and Hall, 2019; Gerth et al. 2013), which can be addressed through various dimensions of BIM (2D, 3D, 4D, nD).

BIM can provide designers, engineers, suppliers, and contractors a seamless collaboration environment, as the digital model provides a platform to exchange ideas and share knowledge (Lu et al., 2021; Chen et al., 2017; Zhong et al., 2017). BIM facilitates the implementation of DfMA through acting as a design analysis tool for improving manufacturing and assembly processes. This platform can be used in IPD projects to verify whether DfMA principles are applied correctly to optimize the design for fabrication and construction (Lu et al., 2021).

Integration

The term "integration" also co-occurred frequently in both IPD and DfMA literature. This is due to the fact that both IPD and DfMA emphasize enhancing integration throughout the project life-cycle. Figure 7, provides a summary of IPD, DfMA, and LEAN individual and joint principles cited in the literature, which can improve integration from four perspectives: informational, organizational, geographical, and cognitive (Dallasega et al., 2018). As shown in grey, various digital tools and technologies can contribute to informational integration, and enable project participants to share knowledge while integrating project information.

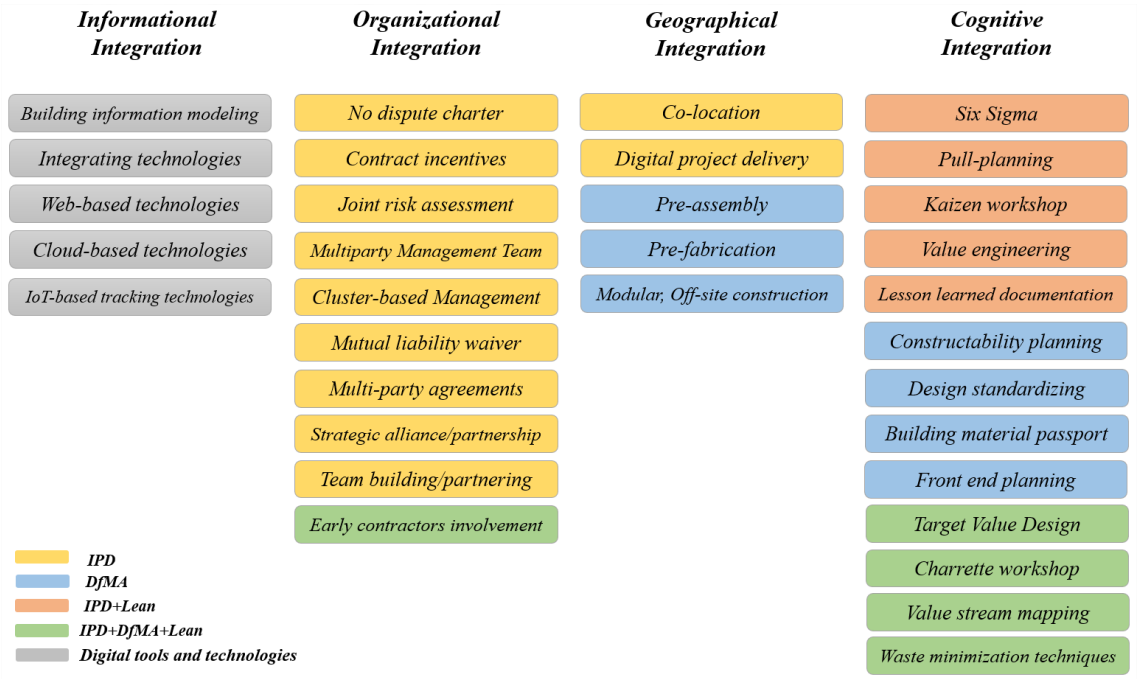

Figure 7: Various modes of integration based on IPD, DfMA, and Lean principles.

DISCUSSION

Based on the results of the literature review on synchronicities between DfMA, IPD and Lean a conceptual framework is proposed in this section (see figure 8). This framework outlines (I think this is better) future developments of these concepts, and helps improve their application in construction projects. The combination of these principles enhances supply-chain-integration and ensures stakeholders' collaboration for improving productivity from the initial design phases to the construction-closeout phases. The central part of the framework illustrates the implementation of DfMA concepts in different stages of a typical construction project. For instance, in the manufacturing and delivery phases, design-for-(additive)-manufacturing (Df(A)M), design-for-assembly

(DfA, for off-site construction projects), and design-for-logistics (DfL) criteria must be respected. Table 2, provides a full list of DfMA abbreviations with their complete name and description (Arnette et al., 2014). As shown, the core of the proposed framework is supported by Lean procedures, IPD contracting method, and an information sharing platform.

The Lean strategies in the platform emphasize on maximizing value, minimizing waste, creating an efficient workflow production system, and no redundancy (Langston & Zhang 2021) throughout the project life-cycle. Applying Lean principles and practices, improve value-based design, supply-chain-integration, just-in-time delivery, and construction automation in various phases of the project.

The contractual relationships are based on the IPD method, which emphasizes team integration, a no-blame collaborative culture, and shared risks and rewards. As shown in the framework, several standard forms of IPD contracting are available in North America, among which, CCDC30 (in Canada) and AIA C-191 and ConsensusDocs 300 (in USA) are the most cited contracting guidelines.

The technological platform, is based on applications which support the flow of information in various stages of a project, including BIM, Internet of Things (IoT), reality capture (RC) technologies, and smart logistics tracking applications. The digital platform assists with visualization (3D-BIM), schedule optimization (4D-BIM), cost management (5D-BIM), sustainability (6D-BIM), facility management (7D-BIM), health and safety (8D-BIM), maintenance (9D-BIM), and recycling (10D-BIM) (Lu et al., 2021).

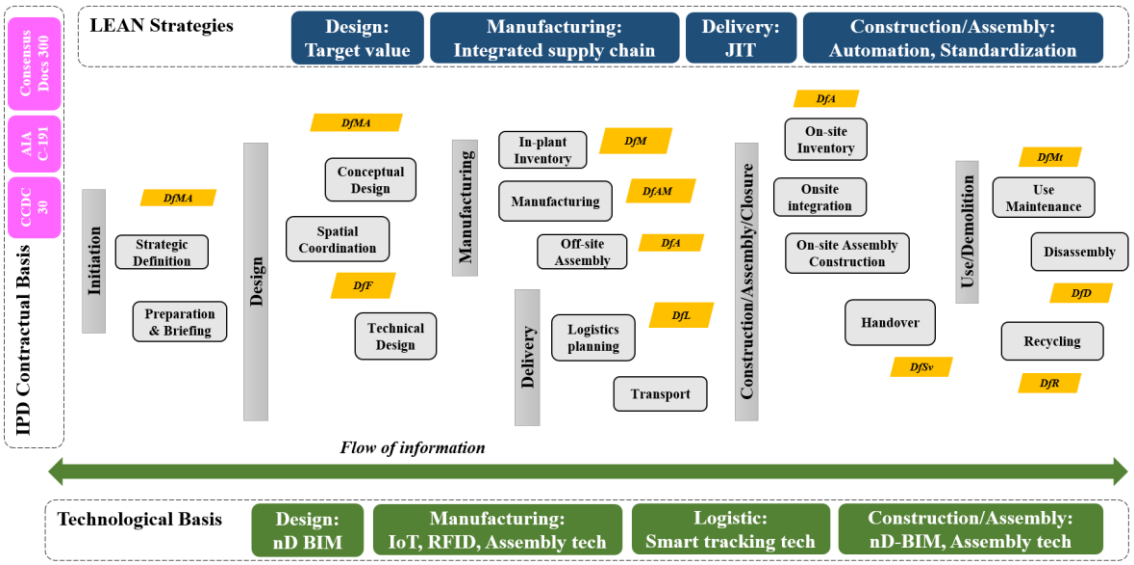

Figure 8: The proposed conceptual framework.

The combination of DfMA, IPD, and Lean along with the application of digital platforms, enable an efficient knowledge sharing, communication, and productivity monitoring throughout the project, and support a streamlined alignment of tools and techniques with people and processes as the basis for a new integration strategy. The proposed conceptual framework helps elucidate synergies and outlines future opportunities for the mutual application of DfMA, BIM, and Lean strategies in IPD construction projects.

Table 2: DfMA abbreviations, full names, and their descriptions.

Abbreviation	Full name	Description
DfMA	Manufacturing Assembly	Design products that can be fabricated efficiently
DfF	Flexibility	Create products and fabrication lines that are flexible to meet customers changing requirements
DfM	Manufacturing	Focus on the manufacturing stage of production
DfAM	Additive Manufacturing	Focus on the additive manufacturing of products
DfA	Assembly	Focus on the assembly stage of production
DfL	Logistics	Focus on designing products that can be shipped effectively
DFSv	Serviceability	Create products which can be repaired upon failure, by the consumer, company, or third-party
DFMt	Maintainability	Create products which can be maintained, and its life can be extended with proper maintenance
DfD	Demolition	Focus on disassembly of parts, components, or materials
DfR	Recycling	Focus on recycling of materials

CONCLUSION

In summary, the results of this review show that IPD and DfMA are expected to be increasingly adopted in the construction industry. The implementation of IPD methods, Lean principles, and information technology platforms such as BIM, can facilitate a smooth adoption of DfMA principles in construction projects. This study contributes to the existing body of knowledge by synthesizing IPD and DfMA similarities, and identifying common principles and practices, practices, to define potential synergies for increasing efficiencies in the design and construction of buildings. The results show that both IPD and DfMA have common Lean principles. They both aim to enhance integration across various stages of the project and both stress the importance of digital information sharing platforms for their successful implementation. Furthermore, this paper proposed a DfMA framework based on a synergy between IPD, Lean, and BIM. The proposed framework can improve future developments of DfMA method, when the implementation of BIM-based digital platforms, IPD, and Lean practices become routine in the construction industry.

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