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POLYTECHNIQUE MONTRÉAL

affiliée à l'Université de Montréal

Investigating the Concept of Integration in Construction Projects: Cases of Integrated Project Delivery and Design for Manufacturing and Assembly

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Thèse présentée en vue de l'obtention du diplôme de Philosophiæ Doctor

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Investigating the Concept of Integration in Construction Projects: Cases of Integrated Project Delivery and Design for Manufacturing and Assembly

présentée par **Sara MOMENNIA RANKOHI**
en vue de l'obtention du diplôme de Philosophiæ Doctor
a été dûment acceptée par le jury d'examen constitué de :

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DEDICATION

To my amazing husband, Hamid, and my beautiful daughter, Aurelia.

To my mother, father, and little brother, whose unconditional love and support bolstered me through the rocky parts of this incredible adventure.

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I would like to thank my supervisor at Polytechnique Montréal, Professor Mario Bourgault, who has provided me with his precious insight and kind support during my PhD degree. I am forever grateful for his constant support and encouragement, which enabled me to take on new challenges.

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I would like to thank my beautiful daughter, Aurelia, born in the middle of my PhD. I had to spend many hours of my days and nights studying and working, while caring for her. It was a very challenging journey and I could not have survived it without her beautiful smile shining bright on me. Aurelia, I am the luckiest person in the world because you are my daughter.

I would like to thank my mother, for her unconditional love, and support. Her constant care, love and attention helped me get through the hardest times of my life. No words of appreciation can do justice in return for what you have done for me, for as long as I can remember. Thank you, Mom. Thank you for always being there for me and constantly encouraging me every step of the way.

I would like to thank my father, for his valuable support and guidance throughout my life. He has always been the greatest mentor and role model for me. It is because of him that I chose to study engineering in the first place. Thank you Dad, for your love, support, and forever valuable inputs.

I would like to thank my brother who is always able to cheer me up even in the hardest times. Your energetic and joyful character is extremely powerful and does wonders that you do not know about.

Last but not least, I would like to thank my amazing husband without whom I could not achieve this. You stood by me all through this long, cumbersome journey and it means the world to me.

RÉSUMÉ

Cette thèse par articles vise à faire progresser les connaissances sur le concept d'intégration dans l'industrie de la construction, au moyen de concepts novateurs tels que la réalisation de projets intégrée (IPD) et la conception pour la fabrication et l'assemblage (DfMA). L'industrie de la construction connaît actuellement de profonds changements, passant des méthodes contractuelles transactionnelles traditionnelles à d'autres plus intégrées, durables et collaboratives telles que le préconisent ces deux approches. Les récentes crises mondiales, telles que les pandémies, le réchauffement climatique et les conflits politiques, contribuent à la transformation rapide du contexte industriel et social, également appelé la nouvelle normalité. Celle-ci tend à accélérer le rythme de changements dans le secteur de la construction, le poussant à adopter des approches qui éliminent les pertes et ajoutent plus de valeur aux projets de construction.

De nombreux chercheurs ont souligné l'impact substantiel des approches intégratives et collaboratives sur l'amélioration des performances des projets de construction ; cependant, leur mise en œuvre reste rare et peu documentée. Encore peu de praticiens et d'organisations semblent engagés à adopter ces stratégies d'intégration avancées. À cet égard, la recherche universitaire peut certainement jouer un rôle positif et faciliter leur compréhension et leur adoption par le milieu.

Pour notre part, nous avons d'abord choisi de décortiquer la réalisation de projets intégrée (IPD) comme mode de réalisation collaboratif. Nous avons tenté de comprendre (a) ce qu'est l'intégration dans le contexte de l'IPD et quels en sont les mécanismes d'intégration, (b) quelles sont les caractéristiques contractuelles, organisationnelles et opérationnelles de la IPD qui en permettent la mise en œuvre dans les projets de construction, et (c) comment la IPD peut relever les défis de la nouvelle normalité de l'industrie de la construction grâce à ses caractéristiques, et finalement, nous avons mené des études sur (d) l'interaction entre la IPD et les stratégies de conception intégrée telles que la conception pour la fabrication et l'assemblage (DfMA). Organisée sur la base de quatre articles de revues scientifiques (2 publiés, 1 sous presse et 1 en évaluation), cette thèse vise à répondre à ces questions et à contribuer à l'ensemble des connaissances, en menant diverses études conceptuelles et empiriques sur les deux concepts-clés que sont l'IPD et le DfMA.

Le premier article décortique le concept d'intégration à partir de la littérature sur l'IPD et identifie les stratégies de mise en œuvre pouvant contribuer positivement aux projets de construction. Toutes

les techniques d'intégration de l'IPD citées dans la littérature ont été extraites, et leurs dimensions (force, portée, durée et profondeur) et directions (verticale, horizontale et longitudinale) ont été discutées dans trois contextes : (i) les projets de construction sur site, réalisés de manière traditionnelle, (ii) les projets de construction sur site, réalisés par le biais de la IPD, et (iii) les projets de construction hors site, réalisés par le biais de l'IPD. Les résultats ont montré que l'application de la IPD dans les projets de construction hors site crée une intégration verticale, horizontale et longitudinale complète de la chaîne d'approvisionnement pendant le cycle de vie des projets, ce qui peut réduire la durée du projet.

Dans le deuxième article, une revue de la littérature est menée pour identifier les thèmes de recherche les plus récents sur l'IPD et les tendances futures. Les résultats montrent que les thèmes de recherche émergents les plus importants de la littérature sont identifiés comme suit : technologique et procédural sous le cluster opérationnel-cognitif ; juridique et commercial sous le cluster contractuel-réglementaire ; et culturel/comportemental et structurel sous le cluster organisationnel-structurel.

Dans le troisième article, les divers défis rencontrés par les projets de construction dans l'ère post-pandémie sont extraits de la littérature et classés en trois étapes : pré-construction, construction et post-construction. Ensuite, deux études de cas canadiennes sont menées pour recueillir des données et valider les résultats de l'examen. Plusieurs discussions de groupe et entretiens ont également été menés avec les parties prenantes des projets, au cours desquels les principes de la IPD ont été discutés, et les participants à l'étude ont été interrogés pour dresser la liste des principes susceptibles de relever les défis de la nouvelle réalité dans laquelle nous vivons. Dans les cas étudiés, les résultats ont montré que le nombre de principes liés à l'IPD utilisés a augmenté depuis le début de la pandémie. Les principes de IPD les plus appliqués sont liés aux aspects technologiques (intégration des technologies, plateformes numériques, technologies basées sur le cloud et le web) et relationnels de la IPD (alliance multipartite, gestion par grappes et partage des risques/récompenses).

Dans le quatrième article, une stratégie intégrée de conception et de construction, appelée conception pour la fabrication et l'assemblage (DfMA), est étudiée afin de comprendre comment l'interaction entre avec l'IPD peut améliorer l'intégration dans les projets de construction. Tout d'abord, une revue systématique de la littérature et plusieurs discussions de groupe sont menées

afin d'identifier les défis de l'application de la méthode DfMA dans les projets de construction et de les classer en 8 catégories : contractuel, technologique, procédural, culturel, commercial, géographique, financier et technique/cognitif. Les résultats montrent que la majorité des défis identifiés sont liés aux aspects contractuels et opérationnels des projets de construction et aux parties prenantes associées. Ensuite, un cadre de DfMA orienté construction (C-DfMA) est développé pour répondre aux défis identifiés, basé sur une interaction entre la DfMA, les modèles d'affaires intégrés, les modes de réalisation intégrée et les outils et technologies opérationnels basés sur le *Lean*. Les résultats montrent que l'impact synergique entre les stratégies intégrées et collaboratives telles que l'IPD, la DfMA et les techniques opérationnelles *Lean* peut créer un environnement approprié pour relever les défis actuels de l'industrie de la construction qui sont principalement dus à la fragmentation.

Les articles proposés dans cette thèse visent à fournir un éclairage théorique et empirique sur des concepts de grand intérêt pour l’industrie de la construction, et ce faisant, sensibiliser les acteurs du milieu à s’engager plus concrètement dans leur adoption.

Mots-clés : Réalisation de projets intégrée, IPD, Intégration, Construction, Gestion de projet, Conception pour la fabrication et l’assemblage, DfMA, Lean.

ABSTRACT

This dissertation by articles aims to advance knowledge on the concept of integration in the construction industry, through recently emerged concepts, such as integrated project delivery (IPD) and design for manufacturing and assembly (DfMA). The construction industry is experiencing a paradigm shift from traditional transactional contractual methods toward more integrated, sustainable, and collaborative approaches such as IPD and DfMA. Recent global crises, such as the pandemic, global warming, and political conflicts, have led us to live in a new context, also known as the new normal. This has accelerated the shift in the construction industry, pushing it to adopt approaches that eliminate waste and add more value to construction projects.

Many researchers have highlighted the substantial impact of integrative and collaborative approaches on improving construction projects performance; however, their implementation remains rare and poorly documented. Still few practitioners and organizations seem committed to adopting these advanced integration strategies. Accordingly, academic research can certainly play a positive role and facilitate their understanding and implementation by the industry practitioners.

In this context, first, we selected integrated project delivery (IPD) as the most recent collaborative delivery method and tried to understand (a) what integration in the context of IPD is and what the IPD integration mechanisms are, (b) what the contractual, organizational, and operational characteristics of IPD are which allow integration mechanisms to be implemented in construction projects, and (c) how IPD can address the new-normal challenges in the construction industry through its characteristics. Then, we selected design for manufacturing and assembly (DfMA) as a collaborative strategy that supports the implementation of IPD and conducted studies on (d) how the interplay between IPD and integrated design strategies such as design for manufacturing and assembly (DfMA) can improve the current status of construction projects. Based on three journal papers, that are published, this thesis aims to answer these questions and contribute the body of knowledge, by conducting various conceptual and empirical studies about IPD.

Accordingly, in the first article, the concept of “integration” in IPD literature is studied and implementation strategies that can positively contribute to construction projects are identified. All IPD integrating techniques cited in the literature were extracted, and their integration dimensions (strength, scope, duration, and depth) and directions (vertical, horizontal, and longitudinal) were

discussed in three contexts: (i) on-site construction projects, delivered traditionally, (ii) on-site construction projects, delivered through IPD, and (iii) off-site construction projects, delivered through IPD. The results showed that applying IPD in off-site construction projects creates complete vertical, horizontal, and longitudinal supply-chain integrations during the projects' life cycle, which can reduce the project duration. In the second article, a systematic literature review is conducted to identify the most recent IPD research themes and future trends. Results showed that the most prominent emerging research themes from the literature are identified as: technological and procedural under the operational-cognitive cluster; legal and commercial under the contractual-regulative cluster; and cultural/behavioral and structural under the organizational-structural cluster.

In the third article, various challenges encountered by construction projects after the pandemic era are extracted from the literature and classified into three stages: pre-construction, construction, and post-construction. Then, two Canadian case studies are conducted to collect data and validate the results of the review. Several focus group discussions and interviews were also conducted with projects stakeholders, in which IPD principles were discussed, and study participants were interviewed to list principles that could address the new-normal challenges. The results showed that the number of IPD principles that have been applied in case study projects has increased since the beginning of the pandemic. The IPD principles that are the most applied in the new-normal era relate to the technological (integrating technologies, digital platforms, cloud-based and web-based technologies) and relational aspects of IPD (multiparty alliance, cluster-based management, and shared risks/rewards.

In the Chapter 7, an integrated design and construction strategy, which is called design for manufacturing and assembly (DfMA), is investigated to understand how the interplay between integrated delivery and business models such as IPD and DfMA can enhance integration in construction projects. First, a systematic literature review and several focus group discussions are conducted, to identify challenges of applying DfMA method in construction projects, and categorize them into 8 categories: contractual, technological, procedural, cultural, commercial, geographical, financial, and technical/cognitive. The results show that the majority of identified challenges were related to the contractual and operational aspects of construction projects and the associated stakeholders. Next, a construction-oriented DfMA (C-DfMA) framework to address the identified challenges is developed, based on an interplay between DfMA, integrated business

models, relational and integrated delivery methods, and lean-based operational tools and technologies. The results show that the synergistic impact between integrated and collaborative strategies, such as IPD, DfMA, and lean-based operational techniques can create a suitable environment for addressing current construction industry challenges that are mostly due to fragmentation.

The articles proposed in this thesis aim to provide theoretical and empirical insight into the concepts of great interest to the construction industry, and in doing so, sensitize the practitioners in the field to engage more efficiently in their implementation.

Keywords: Integrated Project Delivery, IPD, Integration, Construction, Project management, Design for Manufacturing and Assembly, DfMA, Lean.

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LIST OF SYMBOLS AND ABBREVIATIONS

AEC	Architecture, Engineering, and Construction
AIA	American Institute of Architects
BIM	Building Information Modeling
CMR	Construction Manager at Risk
DB	Design-Build
DBB	Design-Bid-Build
DfM	Design-for-Manufacture
DfA	Design-for-Assembly
DfMA	Design-for-Manufacture-and-Assembly
DfMA	Design-for-Manufacturing-and-Assembly
GC	General Contractor
ID	Integrated Design
IPD	Integrated Project Delivery
GMP	Guaranteed Maximum Price
OSC	Off-site Construction
P3	Public-Private Partnerships
PPP	Public-Private Partnerships
PA	Project Alliancing
PP	Project Partnering
PDM	Project Delivery Method
QC	Quebec
US	United States

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CHAPTER 1 INTRODUCTION

1.1 Background

The construction industry has been experiencing long-term performance challenges regarding project time, cost, and quality (Ashcraft, 2014; Hanna, 2016; Lahdenperä, 2012; Thomsen et al., 2009). Statistics show that in developed countries, such as Canada, the construction sector is responsible for a considerable part of the environmental issues such as 39% of process-related greenhouse gas emissions, 50% of landfill wastes generation, and 39% of energy consumption (Leoto, 2019). Several studies have identified traditional, linear, fragmented, and non-integrated design and construction practices as the root causes of these issues (Hanna, 2016; Leoto, 2019), and have emphasized the positive impact of integrated project delivery methods in addressing these challenges and improving project performance metrics (Strickland et al., 2010; Kolbert et al., 2011; El Asmar et al., 2013; Azhar et al, 2014).

The successful delivery of projects in the construction industry has been a challenge for many years. Studies have shown that collaboration, high level of integration, interdisciplinary teams' interaction, and early involvement of project participants are vital for successful delivery of high-performance construction projects (Korkmaz et al., 2010; El Asmar et al., 2013; Ebrahimi, 2019). This has motivated many scholars to study the elements that affect the degree of integration in projects stakeholders' roles and relationships, inter-disciplinary teams' interactions, and organizational structures (Hall et al., 2021; Whyte et al., 2020). Project delivery methods, particularly those that focus on collaboration and integration, play a vital role in shaping project organization, team member interactions, participant roles, legal and commercial terms, and project performance metrics (Lahdenperä, 2012).

A project delivery method can be explained as a model which defines relationships between project participants, describes their responsibilities, specifies their time dedications to the overall delivery of a project, and controls financial distribution of project resources (Mesa et al., 2016). The construction literature reports that conventional delivery methods are associated with fragmentation and lack of integration. Lack of collaboration, effective communication, interaction, and information sharing among project stakeholders are key reasons for the poor performance of conventional delivery methods in the AEC industry (Ebrahimi, 2019; Mesa et al., 2016). This indicates the need for a fundamental change in the way projects are organized, executed, and delivered in the AEC industry. In this context, several scholars present relational contracting and collaborative project delivery methods as possible solutions (Hall et al., 2022; Fischer et al., 2017; Lahdenperä, 2012)

1.2 Integrated Project Delivery

Following the development of design-build (DB) methods in the United States (US), a collaborative delivery method, known as project alliancing (PA), was introduced, and successfully applied to several complex projects in Australia. PA later became the model based on which the integrated project delivery (IPD) model was developed in the United States (Kent and Becerik-Gerber, 2010; Noble et al., 2007). IPD, PA, and project partnering (PP), are the three main collaborative, also known as relational, forms of project delivery method (Lahdenperä, 2012). According to Lahdenperä (2012), while these three relational project delivery methods share common principles, they have distinct differences in their procedural practices, tools, and techniques. Studies show that the use of IPD is more common in North America than PA and PP (Lahdenperä, 2012; Hall et al., 2019; Ebrahimi, 2018). According to AIA (2007), IPD is defined as:

> “A project delivery approach that integrates people, systems, business structures and practices into a process that collaboratively harnesses the talents and insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction.” (AIA, 2007).

IPD with its collaborative nature has become very popular in recent years. In this method, project problems are resolved collaboratively, and decisions are taken jointly, which results in joint distribution of risks and rewards among all stakeholders.

1.3 Design-for-Manufacturing-and-Assembly

Design for manufacture and assembly (DfMA), is a methodology which, similarly 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 to facilitate manufacturing and assembly, boost productivity, improve quality assurance, and reduce projects' cost, time, and waste (Boothroyd et al. 2002; Bao et al., 2020; Montali et al. 2018; Lu et al., 2020; Bogue 2012). DfMA is well-developed in the manufacturing industry, however in the construction industry, it is an emerging design and production strategy, which is focused on using the design to control and improve product performance while enhancing production efficiency (Lu et al., 2020). As an emerging topic, the literature on DfMA in the construction industry is still limited (Gao et al., 2020; Ofori-Kuragu and Osei-Kye, 2021).

1.4 Problem Statement

Given that IPD and DfMA are emerging topics in the construction management domain, we still know little about them. From a practical point of view, the adoption of IPD and DfMA and awareness of industry participants about these integrative strategies, is still low (Mesa et al., 2016; Yee et al, 2017; Bao et al., 2020). From a theoretical point of view, conceptual aspects of these advanced integration strategies have yet to be studied (Ebrahimi, 2018; Bao et al., 2021). The term IPD is still institutionally-immature (Hall & Scott, 2019), and it will not see major industry adoption until its impact on integration is clearly contextualized with respect to construction projects. Proper implementations of IPD and DfMA require supportive environments as well as well-informed and skilled stakeholders (Ebrahimi, 2018). Adopting these strategies, without a full understanding of the required contractual, operational, and organizational contexts for their successful implementations, can result in projects failure (Mollaoglu-Korkmaz et al., 2014; Hall et al., 2019).

This thesis seeks to address this gap and help scholars and practitioners understand how construction projects can benefit from these advanced integration strategies. The results of this thesis can help industry practitioners apply the full potential of IPD and DfMA for delivering high-performance construction projects. My thesis consists of separate but interrelated studies, presented as four distinct chapters, which explore:

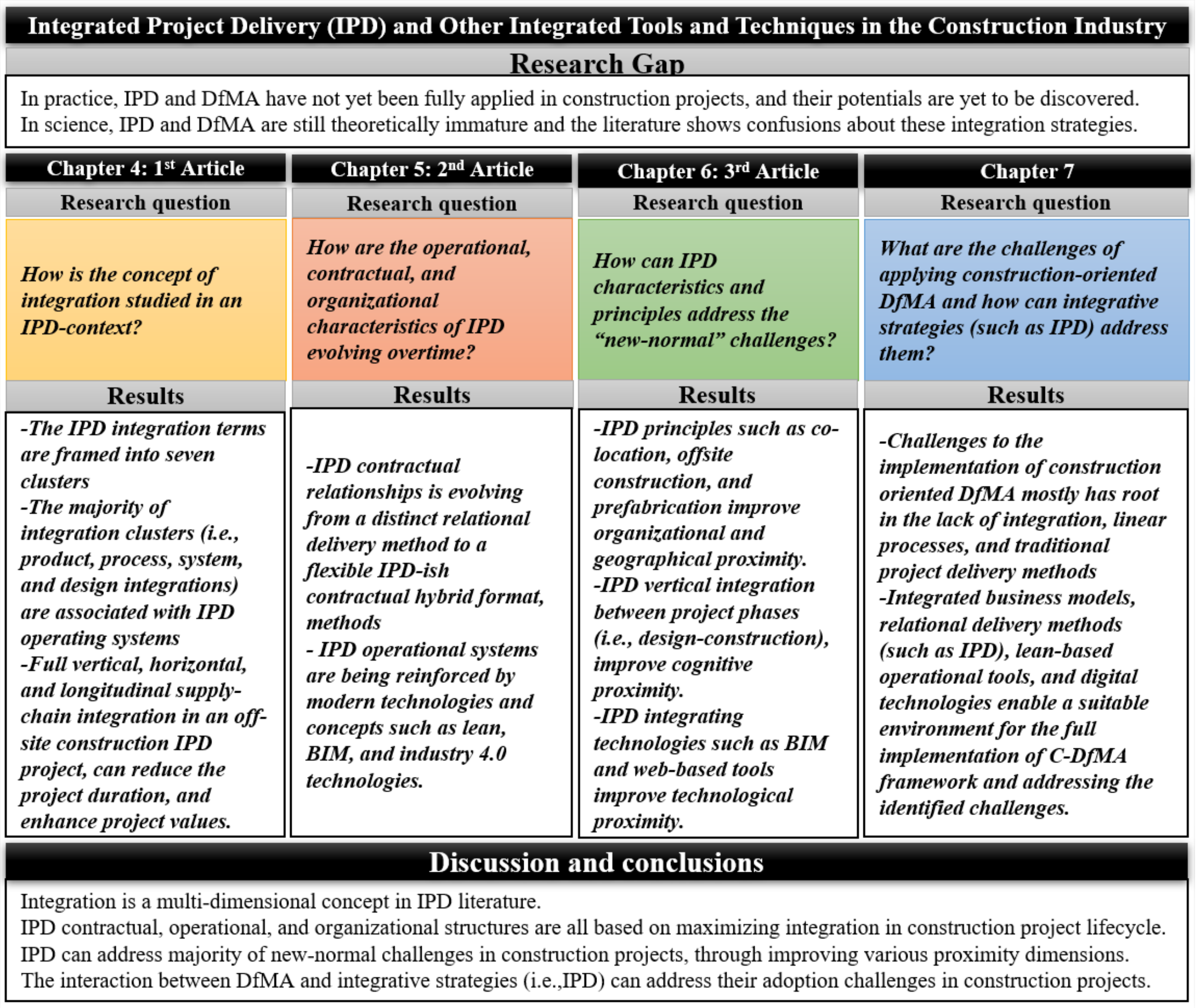
- The concept of integration in the scientific literature on IPD;
- The latest operational, contractual, and organizational themes and trends in IPD studies;

- The “new-normal” challenges in the construction industry and IPD solutions.
- The C-DfMA framework: an IPD-based construction-oriented DfMA deployment framework.

The research objectives for each of these studies will be explained in the following sections.

1.5 Thesis Structure

As shown in Figure 1.1, this thesis consists of nine chapters: the introduction, a literature review, research objectives and methodologies, four research chapters, a discussion, and a conclusion.



Integrated Project Delivery (IPD) and Other Integrated Tools and Techniques in the Construction Industry

Research Gap

In practice, IPD and DfMA have not yet been fully applied in construction projects, and their potentials are yet to be discovered.
In science, IPD and DfMA are still theoretically immature and the literature shows confusions about these integration strategies.

Chapter 4: 1st Article	**Chapter 5: 2nd Article**	**Chapter 6: 3rd Article**	**Chapter 7**
Research question	**Research question**	**Research question**	**Research question**
How is the concept of integration studied in an IPD-context?	***How are the operational, contractual, and organizational characteristics of IPD evolving overtime?***	***How can IPD characteristics and principles address the “new-normal” challenges?***	***What are the challenges of applying construction-oriented DfMA and how can integrative strategies (such as IPD) address them?***
Results	**Results**	**Results**	**Results**
-The IPD integration terms are framed into seven clusters -The majority of integration clusters (i.e., product, process, system, and design integrations) are associated with IPD operating systems -Full vertical, horizontal, and longitudinal supply-chain integration in an off-site construction IPD project, can reduce the project duration, and enhance project values.	***-IPD contractual relationships is evolving from a distinct relational delivery method to a flexible IPD-ish contractual hybrid format, methods - IPD operational systems are being reinforced by modern technologies and concepts such as lean, BIM, and industry 4.0 technologies.***	***-IPD principles such as co-location, offsite construction, and prefabrication improve organizational and geographical proximity. -IPD vertical integration between project phases (i.e., design-construction), improve cognitive proximity. -IPD integrating technologies such as BIM and web-based tools improve technological proximity.***	***-Challenges to the implementation of construction oriented DfMA mostly has root in the lack of integration, linear processes, and traditional project delivery methods -Integrated business models, relational delivery methods (such as IPD), lean-based operational tools, and digital technologies enable a suitable environment for the full implementation of C-DfMA framework and addressing the identified challenges.***

Discussion and conclusions

Integration is a multi-dimensional concept in IPD literature.
IPD contractual, operational, and organizational structures are all based on maximizing integration in construction project lifecycle.
IPD can address majority of new-normal challenges in construction projects, through improving various proximity dimensions.
The interaction between DfMA and integrative strategies (i.e.,IPD) can address their adoption challenges in construction projects.

Figure 1.1 Structure of this dissertation

Chapter 2 contains the literature review in two parts. In the first part, the literature review discusses IPD, its origin, and its main principles and characteristics. In the second part, the literature review focusses on other emerging tools and techniques, such as design for manufacture and assembly (DfMA), whose synergic impacts with IPD, create opportunities to enhance construction project outcomes.

Chapter 3 presents the purpose of this research and the objectives of each of the thesis studies.

Chapter 4 explores the concept of integration in an IPD-context. The findings were used to identify dimensions (strength, scope, duration, and depth) and directions (vertical, horizontal, and longitudinal) of integration in IPD literature.

Chapter 5 presents the latest trends in the operational, contractual, and organizational characteristics of IPD. The findings are used to develop an IPD integration framework and provide key technological, procedural, legal, commercial, cultural, and structural recommendations for improving the future success of IPD implementation.

Chapter 6 presents the new (post-pandemic) challenges in the various stages of the construction projects, their related proximity aspects (technological, organizational, geographical, and cognitive), and IPD principles that can address the identified challenges within their associated proximities. This chapter aims to explore the effectiveness of IPD principles on enhancing integration and the pathways to overcome the “new-normal” construction barriers.

Chapter 7 presents construction-oriented design for manufacturing and assembly strategies, identifies challenges to its broader adoption in the industry, and proposes a C-DfMA framework to enhance the implementation of construction-oriented DfMA strategies. The proposed framework is based on integrative contractual, operational, and organizational tools and techniques.

Chapter 8 provides the discussion. The findings from each of the substantive chapters are summarized and recommendations for enhancing future implementation of IPD are presented. This chapter also outlines the limitations of this study and provides suggestions for future research.

Chapter 9, as the concluding chapter, summarizes the thesis and provides a closing statement.

Appendix A, B, and C: Over the course of this research, several peer-reviewed conference papers were also published. Three of these were selected and are presented in the Appendix section.

CHAPTER 2 LITERATURE REVIEW

The successful delivery of projects in the construction industry has been a challenge for many years. Lack of integration, collaboration, effective communication, interaction, and information sharing among project stakeholders are key reasons for the poor performance in the construction industry (Ebrahimi, 2019; Mesa et al., 2016). Recent integration methods and strategies in the construction domain, such as integrated delivery methods and integrated design practices, aim to address these challenges and improve the overall performance. IPD is a project delivery approach that integrates people, systems, business structures and practices into a process that collaboratively apply insights of all participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction (AIA, 2007; Mesa et al., 2016). Design for manufacture and assembly (DfMA), is a methodology which, similarly 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 section will begin by presenting the terminology of main terms and concepts regarding delivery methods. This will be followed by a brief review of the Integrated Project Delivery (IPD) method, and its contractual, operational, and organizational principles. It worth noting that in Chapter 4 and Chapter 5, systematic literature reviews about IPD have been conducted. In addition, in Appendix B, the results of a systematic literature review about the mutual implementation of IPD and DfMA have been provided.

2.1 Terminology

Project delivery method: A framework for structuring project phases, determining project participants' roles and authority, their time engagement in the project, and controlling the financial distribution of resources (El Asmare et al., 2013).

Design-bid-build (DBB): A form of delivery method in which the owner contracts separately with the architect/engineer for the design and with the contractor for the construction of a facility (Mogerman et al., 2016).

Construction management (CM): A form of delivery method in which the owner contracts with a construction management professional (an individual or a company) who is engaged early in the design phase, acts as the owner's agent and advocates during the construction phase (Mogerman et al., 2016).

Design-build (DB): A form of delivery method in which the owner provides performance specifications for the project and then a single entity is awarded the contract to oversee the detailed design and construction of the facility (Mogerman et al. 2016). The DB method can be applied as: DB contractor-led, or DB architect-led.

Progressive design-build (PDB): A form of delivery method in which the design-builder and the owner work together to progressively develop a project's scope in accordance with the owner's needs and budget (Gransberg & Molenaar, 2019). PDB is described as an evolution of DB and CM/GC, which uses a qualifications-based selection and relies on real-time access to project information to make early decisions (DBIA, 2018; Alleman et al., 2019).

Integrated project delivery (IPD): A project delivery approach that integrates people, practices, systems, and business structures into a process that collaboratively harnesses the talents and insights of all project participants to optimize project results, increase value to the owner, reduce waste, and maximize efficiency through all phases of design, fabrication, and construction (AIA California Council 2007).

Design for manufacture and assembly (DfMA): an integrative design/manufacturing strategy, which considers the manufacturing and assembly principles from the early stages of design in order to maximize efficiency (Bakhshi et al., 2022).

Building Information Modeling (BIM): A process of information management and generation of digital representations of physical and functional characteristics of construction projects, which can be used by all project stakeholders throughout the entire lifecycle of a built asset (Thomsen et al., 2009; Eastman et al., 2011).

2.1 Project delivery methods

In the scientific literature, project delivery methods (PDMs) are defined from different perspectives. As stated by several researchers (El Asmar et al., 2013; Sanvido and Konchar, 1998; Moazzami et al., 2015), apart from the applied tools and processes, the majority of PDM definitions have two elements in common: (a) relationships of project stakeholders, and (b) timing of the stakeholders' engagement in the project. Therefore, a project delivery method can be explained as a model which defines relationships between project participants, describes their responsibilities, specifies their time dedications to the overall delivery of a project, and control the financial distribution of project resources.

Of all the existing project delivery methods, the three most popular methods are: Design-Bid-Build (DBB), Design-Build (DB), and Construction Management (CM) (Ebrahimi, 2019; El Asmar et al., 2013; Korkmaz et al., 2013; Moazzami et al., 2015). In DBB, the owner contracts separately with the design professionals for the design and with the contractor for the construction of a facility (Mogerman et al. 2016). In DB, the owner provides the performance specifications for the project and then a single entity will be awarded the contract to conduct detailed design and construction of the facility (Mogerman et al. 2016). In CM, the owner contracts with a construction management professional (an individual or a company) who is engaged early in the design phase and acts as the owner's agent and advocates during construction phase (Mogerman et al. 2016). According to the AIA (2007), in the DBB method, the general contractor or GC becomes involved after the full completion of the design phase. However, in DB the GC has an early involvement in the design phase, and usually the design packages are prepared by a single designer-contractor unit. In the CM method, usually the construction manager becomes involved early in the design process.

Studies show that conventional delivery methods are associated with fragmentation and lack of integration. Lack of collaboration, effective communication, interaction, and information sharing among project stakeholders are key reasons for the poor performance of conventional delivery methods in the AEC industry (Ebrahimi, 2019; Mesa et al., 2016). Existing segmented delivery methods and behavioral issues such as resistance to change, do not let the construction industry move towards the full implementation of emerging integrative tools and techniques (Forgues and Iordanova, 2010). This indicates the need for a fundamental change in the ways projects are organized, executed, and delivered in the AEC industry. In this context, several scholars present relational contracting and collaborative project delivery methods, such as IPD, as possible solutions (Hall et al., 2022; Fischer et al., 2017; Rankohi et al., 2022; Lahdenperä, 2012)

2.2 Relational delivery methods

In response to the existing challenges in the construction sector, such as fragmentation, in addition to the emerging collaboration requirements for servitization[1] of construction (Lahdenperä, 2012; Leiringer and Brochner, 2010), relational delivery methods are introduced to the construction industry. Relational delivery methods are collaborative forms of delivery agreements, which foster social integration and enhance long-term relationships between project stakeholders. The literature shows that the three most comprehensive and common approaches based on multi-party contracting practices are project alliancing (PA), project partnering (PP), and integrated project delivery (IPD), which are defined below:

PA is "*a method of delivering major capital assets where the owner and non-owner participants work together as an integrated, collaborative team […] and making unanimous, best-for-project decisions, managing all risks of project delivery jointly, and sharing the outcome of the project.*" (Lahdenperä, 2012).

PP is "*a single project application of a management approach used by two or more organizations to achieve specific business objectives and based on mutual objectives, an agreed method of problem resolution and an active search for continuous improvements*." (Lahdenperä, 2012). Eriksson (2010) described partnering as "Cooperative governance based on cooperative procedures in order to facilitate cooperation." According to Yeung et al. (2007) PA is characterized by soft components, such as trust, commitment, and cooperation, and hard components, such as formal agreements, liabilities, and gain/pain share. Public–Private Partnership (PPP or P3), is a well-known form of PP, which is widely used throughout the construction industry. It involves a contract

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[1] Servitization refers to the integration of additional support, services, and information to the supplier's principal product deliveries (Lahdenperä, 2012). This requires face-to-face interactions between organizations and their customers.

between a public agency and a private entity, commonly referred to as either the concessionaire or developer. PPP allows more private sector participation in public projects (Gransberg et al., 2022).

IPD is "*a project delivery method distinguished by a contractual agreement between the owner, design professional and builder, where risk and reward are shared, and stakeholder success is dependent on project success.*" (Cohen, 2010; Lahdenperä, 2012).

IPD was developed in the U.S., during the Sutter health project in 2004, while PA was first developed in the U.K. in 1992, to support oil exploration in the North Sea, and PP was first launched in 1988 by the U.S. Army Corps of Engineers, to provide an arrangement between the owners and contractors to reduce construction disputes (Lahdenperä, 2012). Among other relational delivery methods, IPD has gained more popularity recently. These three delivery methods have similar features such as early involvement of key participants, shared risk and reward, joint decision-making, and a collaborative multi-party agreement. Despite these similarities, these methods are different in terms of their degree of integration. Compared to PP and IPD, PA takes relational contracting to the extreme, while IPD has fallen between PA and PP as to overall project integration (Lahdenperä, 2012). IPD is described as a delivery method which imitates the PA method, while having a lean-based operational system. Compared to PA and IPD, PP is more conservative towards work scope, risks, and liabilities. In PP project manageable risks are carried by project parties, while in PA and IPD risks and uncertainties are equally shared. In fact, PP is a supplementary collaborative method, since the roles and liabilities of the parties remain the same as in the traditional delivery approaches (Lahdenperä, 2012; Young et al., 2017).

2.3 Integrated project delivery

Following the introduction of project alliancing by British Petroleum in the North Sea in the early 1990s, the mechanism of pain/gain sharing originated as an incentive for the team to establish joint collaboration and mutual decision-making processes for improving project outcomes (Alves and Lichtig, 2020; Lahdenperä, 2012). A few years later, these concepts were followed by a team of contractors in Florida, in the U.S., which established a company called "Integrated Project Delivery" to create a more collaborative environment in which stakeholders could smoothly interact, share risks and rewards, and deliver successful projects (Alves and Lichtig, 2020; Matthews and Howell, 2005). Following this, Lichtig (2004) developed the "Integrated form of

Agreement" (IFOA) to support Sutter Health's Lean Project Delivery initiative. This agreement was based on recognizing integrative concepts and collaborative decision making with lean design and construction methods (Alves and Lichtig, 2020). Lichtig developed this agreement to link project contracts with lean philosophies and concepts and converted them into functional principles and tools. The Lichtig's IFOA has evolved significantly since 2004 to meet the growing body of construction needs and reflect the updated experiences of the project supply chain participants (Alves and Lichtig, 2020). In fact, IPD standard contracts such as CCDC-30 in Canada and ConsensusDocs® 300 in the U.S. are based on the IFOA.

As stated by AIA (2007), in IPD method, a new single-purpose entity or limited liability company will be created that consists of the owner, the architect and engineer, the construction manager and other key project members in the design and construction of the project. This entity can enter into formal contracts with non-members, such as MEP engineers, contractors, sub-contractors, and suppliers for services, labor, equipment, and materials. To finance and obtain project funding, the entity signs a separate agreement with the owner. The IPD stakeholders' relationship is shown in Figure 2.1.

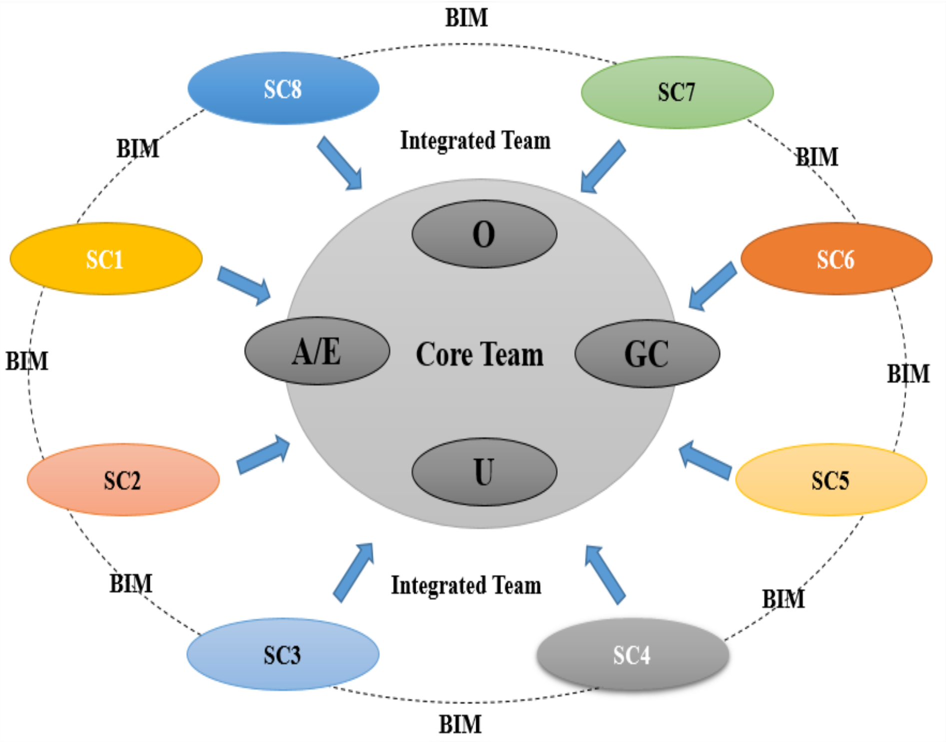

Figure 2.1 Integrated project delivery contractual relationship (adopted from Rumane, 2016)

IPD has been applied in various forms and models in the literature. The American Institute of Architecture (AIA) (2007) introduced IPD as a philosophy or "IPD principles" in addition to IPD as a "delivery method." Yee et al (2017), defined IPD as a continuum of integration from "Lean delivery", "IPD-ish", "Pure IPD", to the "Real IPD." They explain that these models are based on different levels of collaboration, among which, the highest collaborative level is referred to as "Real IPD" and the lowest level referred to as "Lean delivery." The paper further discusses that "Real IPD" requires a full level of collaboration and contractual commitment. Conversely, "Lean delivery" happens when IPD principles or philosophies are applied to traditional delivery methods (such as DBB, DB, and CM) and no contractual agreement is required in its structure (Yee et al, 2017). The term "IPD-ish" refers to the introduction of some of the IPD principles with limited risk-sharing into traditional forms of project delivery methods (Yee et al., 2017). An IPD-ish project becomes "Pure IPD" when project stakeholders sign a multi-party contract agreement to collaboratively deliver a project (Yee et al, 2017).

Even though in recent years the number of studies on integrated project delivery has increased, IPD is still a relatively new method and concept, and there is not much research conducted on this subject in the literature. From a theoretical point of view, the conceptual aspect of IPD and integrated practices have yet to be studied (Hall et al., 2019). From a practical point of view, the adoption of IPD in the construction industry and the awareness of industry participants about it, is still low (Yee et al., 2017).

2.3.1 Studies on IPD as a delivery method

Several studies discussed the significant benefits of IPD methods over traditional PDMs. In these studies, authors compared the IPD method with non-IPD delivery methods and concluded that IPD success is achieved as a result of the collaboration and open communication among project stakeholders. Gultekin et al. (2013) explained that IPD was developed to address the disintegration challenge faced by the construction industry. According to Fischer et al. (2017), in real IPD projects stakeholders: (a) sign a single multi-party agreement which connects them contractually; (b) join at early stages of the project to perform collective decision-makings; (c) share financial risks and rewards; (d) communicate openly, vividly, and clearly; and (e) own limited liability among themselves. This level of stakeholder involvement along with the IPD contractual arrangement, can create a framework for quality control, cost saving, coordinated efforts, and mutual interests (Paik et al., 2017; Zaghloul & Hartman, 2003). In fact, IPD strategies tie organizational success to project success which help owners achieve higher levels in their performance goals (Ebrahimi, 2018; Ashcraft, 2014; Fischer et al., 2017; Molenaar et al., 2010; Zhang et al., 2016).

Some studies indicate that this new delivery method is superior to traditional delivery methods in terms of project performance metrics, such as time, cost, and quality (Mesa et al., 2016; Ebrahimi, 2018; Hall et al., 2019). One of the first quantitative studies, which identified IPD benefits compared to traditional delivery methods, was performed by El Asmar et al., in 2013. They conducted case studies on thirty-five (12 IPD and 23 non-IPD) complex vertical construction projects, large healthcare and higher education research facilities in the U.S. Midwest and California. Based on these projects, they concluded that IPD outperforms DB and DBB delivery methods regarding quality, communications, change management, business, recycling, and schedule. In addition, El Asmar et al. found that the IPD method is the most suitable and applied method for these types of projects as it supports innovations in a multi-trade setting, which can justify the upfront investments required for IPD agreements. Hanna (2016) conducted a quantitative study on IPD project performance metrics from the perspectives of general contractors and construction managers. They compared IPD with more conventional delivery methods with respect to performance in communication, change management, and business performance areas. They developed a new term called project quarterback rating (PQR) which combines performance metrics to evaluate overall performance. The result of their study showed evidence of the overall superior performance of IPD and near-IPD compared with non-IPD projects.

Several researchers conducted case studies and investigated a specific characteristic of IPD as delivery method. Thomsen et al. (2009) investigated the IPD method from a legal perspective and explained that due to the application of BIM, which is a “collaboration software”, the IPD method is capable of answering major communication challenges that conventional and non-IPD delivery methods face, such as DBB, DB, and CM. in this context, Forgues et al., (2018) also indicated that the implementation of BIM has led to the development of IPD and innovative project procurement approaches, which can replace traditional segmented delivery methods by increasing collaboration and reducing project risks (Forgues et al., 2018).

Pishdad-Bozorgi et al. (2016a, 2016b) illustrated the benefits of IPD and its impacts on building trust between project parties. They developed a schematic of trust-building attributes and corresponded them to IPD traits. Lahdenperä (2012) indicated that IPD has mostly been used in North America for social infrastructure or "vertical" building construction projects, compared to "horizontal" projects, such as utility infrastructure and transportation projects (i.e., road, rail, and water projects) where the underlying risks are different. He related this to the associated risks and explained that in vertical buildings, risks, and uncertainties are mostly related to complex systems, their functionality, compatibility, and responses to the owner's requirements. In those situations, risks can be significantly minimized by intensified early collaborative planning, as can be seen in the IPD method. Jin et al., (2018) and Osmanetal et al., (2015) conducted studies on the application of the IPD method in off-site construction projects. They compared IPD versus conventional methods and indicated that IPD can significantly enhance collaboration throughout the fabrication, transportation, and construction of offsite projects.

In summary, many studies indicated that to achieve higher levels of construction performance, owners should be encouraged to consider the use of the IPD method, or some form of IPD-ish method in conjunction with other delivery methods, in the future development of all types of construction projects, from complex vertical buildings and capital facilities to transportation infrastructure projects (Jin et al., 2018; Osmanetal et al., 2015; Yee et al., 2017). Although these studies advocate the efficiency of IPD over traditional delivery approaches, in theory, IPD is still immature (Hall et al., 2019), and in practice, it has not been fully implemented yet, as most construction projects are being delivered through linear traditional delivery methods. More conceptual studies and practice-based research is needed to identify the specific integration mechanisms through which IPD can impact construction projects.

2.3.2 Studies on IPD as a philosophy (IPD principles)

According to AIA (2010), while IPD is recognized as a delivery method, it can also be considered as a set of principles that can be applied to various delivery methods. Yee et al. (2017) explained that the adoption of IPD principles or IPD philosophies in construction projects can be categorized based on their level of "integration" into two models: 1) lean delivery and 2) IPD-ish. These levels of IPD principles have no contractual agreement in their structures and they are both suitable to being merged into other delivery approaches.

According to Yee et al. (2017), IPD principles are divided into four main groups (contractual, behavioral, structural, and technological), as shown in Figure 2.2. The contractual principles can improve the contractual side of the agreement, while behavioral principles, such as mutual respect and trust, can also be applied in IPD-ish models. The structural principles, such as co-location of team members, and technological principles, such as the use of building information modeling (BIM), can significantly influence the level of integration in various delivery methods. The literature shows that there are a relatively low number of research studies conducted on the systematic execution of these principles in different construction projects (Zhang, 2018).

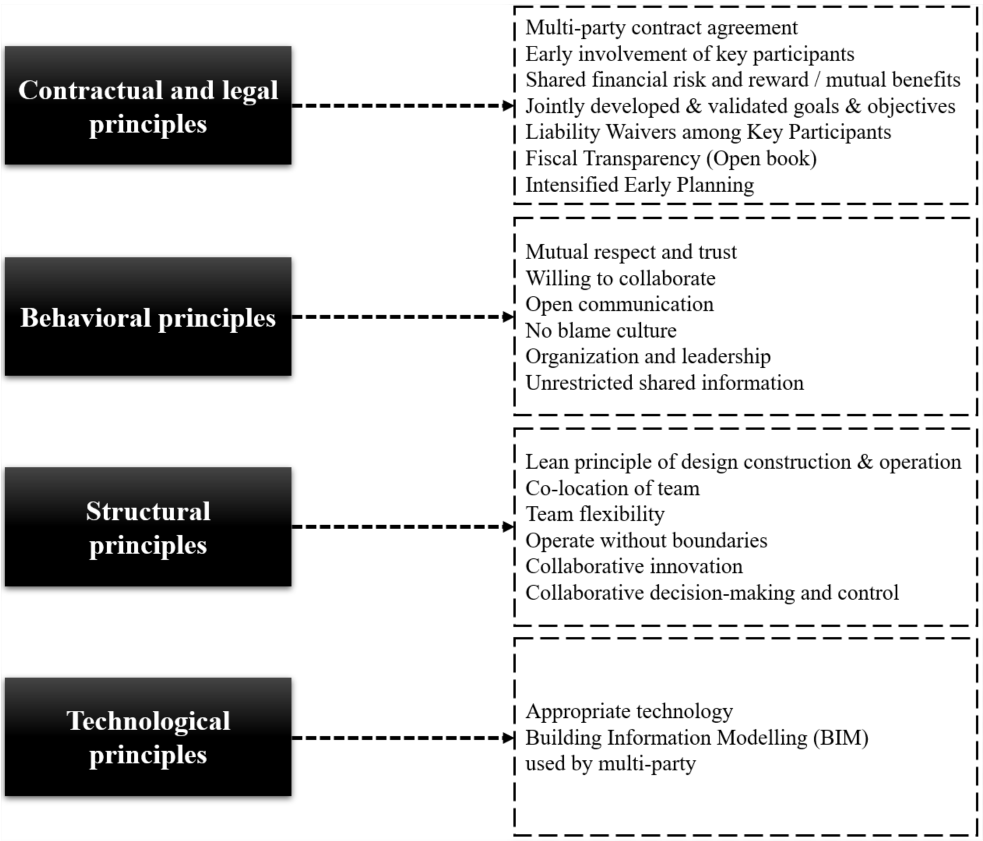

Figure 2.2: IPD principles (developed based on AIA, 2007 & Yee et al., 2017)

2.4 IPD in a Canadian Context

2.4.1 Canada

The literature shows that the extent of empirical research on the "project delivery method" topic, particularly on IPD, is relatively low in the Canadian construction industry compared to Europe and the U.S. (Ebrahimi and Dowlatabadi, 2018; Jobidon et al., 2021). According to Thomson Reuters' Practical Law website (2018), most of the widely used, standard forms of contracts for Canadian construction projects are published by the Canadian Construction Documents Committee (CCDC), Royal Architectural Institute of Canada (RAIC), and Canadian Construction Association (CCA). The CCDC, CCA, and RAIC published the CCDC-30 as a guide to integrated project delivery contracts for procurement authorities in 2018. The Canadian IPD principles are reflected in the CCDC-30 contract, although other jurisdictions, such as the U.K. and the U.S., apply other standardized models of IPD contracts, such as the NEC4 Alliance Contract, TAC-1 Term Alliance Contract or the AIA series (Jobidon et al., 2021).

The integrated project delivery alliance (IPDA), founded in 2015, is a not-for-profit Canadian organization that consists of universities and industry partners. The IPDA publishes reports, conducts research and development about IPD, and provides a forum for the exchange of related knowledge between industry experts. The most comprehensive recent report about IPD, published in 2022 (Poirier et al., 2022), was conducted collaboratively by École de technologie supérieure (ÉTS), University of British Colombia (UBC), IPDA, and several Canadian industry experts. In this report, three Canadian cases of real IPD projects were studied to identify the critical factors in the successful implementation of IPD. These case studies, which are among the first documented cases of IPD implementation in Canada, show the potential of applying IPD in a Canadian context, as a significantly superior method over traditional project delivery methods. The three projects, the Barrie-Simcoe emergency services campus in Ontario, the Canada Game Aquatic Center (CGAC) in British-Colombia, and the Thelma Chalifoux School and Soraya Hafez School in Alberta, were all publicly funded. The studies show that these projects generated value for their communities and taxpayers in a context that would not have been possible if a traditional approach had been used. This study concluded that more emphasis is required for the wide implementation of IPD in Canada, particularly for publicly-funded projects (Poirier et al., 2022).

2.4.2 Québec

IPD is comparably a new delivery method in Québec. The *Société Québécoise des Infrastructures* (SQI) is responsible for managing the infrastructure projects in Québec. The SQI (2022) categorizes delivery methods into four groups: general contractor (entreprise générale), project manager (en gérance), turn-key (clés en main), and public-private-partnership (partenariat public-privé). This classification is relatively basic compared to the existing delivery methods in Canada. As part of the Quebec Construction (IQC 4.0) initiative toward construction digitalization, SQI implemented the "*pratiques intégrées BIM-PCI*" program with the intention of applying BIM and integrated design processes in all infrastructure projects in Québec (SQI, 2022). Although the SQI did not consider IPD as a delivery method in Québec, the BIM-PCI initiative has borrowed some principles from IPD. In addition, the SQI acknowledged the "*conception et construction par étapes*", also known as "*Conception-Construction Progressif (CC Progressif)*" or Progressive Design-Build, which follows similar principles to IPD, except for sharing project risks and rewards (Bourgault et al., 2021). According to the CEFRIO's report on "*Construction 2.0 l'efficacité par le numérique,*" conducted by Forgues et al. (2014), this digitalization and integration shift in Québec's construction industry started over the last decade. Compared to other provinces such as BC and Alberta, in practice, we still do not have any signed IPD projects in Quebec, nor is a standard template of agreement developed for this method in the province. In theory, only a few researchers have published about IPD in Québec, such as Jobidon et al., (2021) and Poirier et al., (2022). Still, more research and practice are required in this field to propel Québec's construction industry and fully implement the integrated project delivery method and principles.

2.5 Interaction between IPD and other collaborative tools and strategies

2.5.1 IPD and Lean

At its core, both IPD and lean promote simplicity, collaboration, and transparency (Alves and Lichtig, 2020). IPD operational processes have their root in lean processes. Literature shows that in IPD projects usually various lean-related concepts, principles, and tools/processes/systems (i.e., the Last Planner System (LPS®), and Target Value Design (TVD)) are being applied (Mesa et al., 2016; Alves and Lichtig, 2020; Rankohi et al., 2022). In fact, IPD applies many lean operating tools and processes. In this context, some scholars consider IPD similar (or even equivalent) to a Lean Project Delivery System (LPDS) (Ballard, 2008). In LPDS, information production, management, and dissemination follow visual lean management tenets to increase transparency and value (Alves, Lichtig and Rybkowski, 2017). The application of lean tools and the knowledge collected through co-location and working with multidisciplinary teams enhance organizational integration (Hall et al., 2020). According to the literature, lean behaviors, such as open communication, transparency, value identification, trust building, collaboration, learning and continuous improvement are essential to the success of IPD projects (Mesa et al., 2020). The lean-based IPD operating systems can help project participants to learn from past mistakes, prevent new ones, reduce wastes, enhance efficiencies, and continuously improve project performance (Darrington, Dunne and Lichtig, 2009; Alves, Lichtig and Rybkowski, 2017).

2.5.2 IPD and Design-for-Manufacturing-and-Assembly

IPD is an integrative and collaborative method that cannot be fully implemented in isolation. In this context, few scholars discussed the interaction between IPD and integrated design/construction strategies, such as lean-led design[2], evidence-based design[3], design for manufacture and assembly (DfMA), and other integrated design processes. In these collaborative design processes, all different types of specialists, such as architects, structural engineers, mechanical and electrical engineers get together, from the early definition stage of the project, to complete the procurement and design phases of the project (Azari & Kim, 2016; Forgues et al., 2018). The synergy between IPD and these integrated design strategies can reduce the gap between the clients' needs and project performance results.

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[2] Lean-led design is a collaborative design process which involves intense participation by all project stakeholders within an organization and design team. In this lean-based model, through an interactive process, the integrated design team delivers optimized design outcomes in a short amount of time (Forgues et al., 2018).

[3] Evidence-based design is a collaborative process of designing and constructing a structure or physical environment based on conducting scientific research and development to achieve the most optimized and valuable outcomes (Ulrich et al., 2009).

The literature shows that the lean construction community recently conducted research on the synergy between IPD and design for manufacture and assembly (DfMA). DfMA, an emerging concept in the construction industry, is an integrated strategy, which similarly 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; Poirier et al., 2020). Originated from the manufacturing industry (Bao et al., 2021), DfMA has been applied to many industry sectors, such as food and consumer products (Boothroyd, 1994), automotive (Suresh et al., 2016), and aerospace (Rajamani & Punna, 2020). Recently, the AEC have begun to adopt this emerging design thinking to add value for the clients and end users. It is regarded as a 'buddy system' of prefabricated and off-site construction, presents a new way to meet the market demand for mass, cost-effective, and high-quality production (Tan et al., 2020; Bao et al., 2021).

This method aims to improve off-site construction project performances by reducing waste and enhancing the quality of design, fabrication, and assembly. Both IPD and DfMA key principles are rooted in lean principles and practices, such as supply-chain-integration (SCI), just-in-time (JIT), pull-planning, early contractor involvement (ECI), standardization, waste reduction in cost, and labor, concurrent engineering (CE), client's commitment, as well as target value design (TVD) (Miron et al., 2015; Koskela et al., 2002; Gerth et al., 2013; Kim and Lee, 2010). According to the literature, some of the DfMA enablers are early collaboration, design standardization and simplification, and light material selection (Tan et al., 2020; Bao et al., 2021). Studies show that applying the DfMA approach, saves time and cost, and reduce wastes in construction projects (Marinelli, 2021).

Wuni et al. (2021) conducted a literature review to improve the implementation of DfMA in construction projects. Their study revealed four major issues with the proper implementation of DfMA in the construction industry, as limited knowledge and organizational readiness, unsupportive entrenched industry practices, increased organizational financial burden, and deficits in bespoke technical requirements and presented a set of recommendations to address them: (1) providing training programmes, (2) establishing a DfMA community of practice, (3) developing suitable ecosystem of DfMA codes, rules, guidelines, standards, and affordable technologies, (4) developing DfMA legislative framework to codify design policies, regulations, and best practices,

(5) upskilling designers awareness and capabilities, (6) developing systematic rules and evaluation metrics, (7) developing decision support systems to automate optimal design decisions, (8) develop methodologies to measure the lifecycle business value of DfMA methods, (9) applying integrated procurement methods and contracts to encourage design integration, and (10) developing a shared knowledge database to enhance the communication among project participants (Wuni et al., 2021).

Proper information integration and evaluation approaches for connecting the downstream and upstreaming activities are fundamental to the adoption of DfMA (Li et al., 2021; Bao et al., 2021). DfMA accentuates integrating downstream processes and enhances the design by evaluating manufacture and assembly, adopting the standardization principles, and promoting modularization and prefabrication (Li et al., 2021; Wuni et al., 2021). These are aligned with the impacts of IPD on construction projects, as an integrating project delivery method. Some previous studies have been conducted to enable an environment for proper implementation of DfMA. However, none of them focus on the contractual side of projects where DfMA can be applied (Li et al., 2021), more specifically, project delivery methods (such as IPD) which can facilitate the application of DfMA are yet to be studied.

The literature still lacks an enriched study on DfMA and IPD and their synergy, to offer a new model for designers and practitioners in the construction industry. The AEC industry will enjoy the full benefits of these innovative methods only when projects are well-structured and supply chains are well established to ensure the flow of information between all projects' phases and participants. Thus, more studies are required, and more developers, designers, manufacturers, contractors, and owners are encouraged to step into developing such value chain environments.

2.6 Critical review

IPD and DfMA are relatively newly introduced concepts in the construction industry, which are still under development. Studies show that the adoption of IPD in the construction industry and the awareness of industry participants about it, are still low (Ebrahimi, 2018; Hall et al., 2019; Gao et al., 2020). According to AIA (2011), of the 84% of AIA members who are aware of the IPD method and principles, less than half (40%) understood it, and only 13% were implementing it in practice. Still, after a decade, studies show that the awareness of industry practitioners about IPD is very low (Manata, 2021; Arar and Poirier, 2022). From a theoretical point of view, the majority of studies focused on conventional delivery methods and design approaches, such as DBB, and DB methods, and fewer studies have investigated IPD (Ebrahimi, 2018; Yee et al., 2017). The conceptual aspect of IPD and its characteristics have yet to be studied (Hall et al., 2019). The literature shows that scholars provided multiple definitions for IPD, which can sometimes be conflicting, confusing, and vague. For instance, the majority of IPD definitions state that IPD “integrates” people, processes, and systems. However, the integration mechanisms, through which IPD integrates various elements of a construction project, are not well-defined. From another perspective, there is still not much research conducted on the impact of IPD integrating mechanisms in various project contexts (i.e., on-site vs. off-site construction projects).

Although IPD has shown great success in delivering construction projects, still it does not fit well into certain types of projects as stated before. As seen in the literature, few studies have been conducted on IPD-ish projects, in which some IPD principles have been applied within different delivery methods. According to these studies, signing an IPD contract is not always feasible, particularly for projects in which the projects’ contextual specifications do not support IPD as a distinct delivery method (Abdulaal et al., 2017; Zhang et al., 2018). In fact, for owners who cannot use IPD contracts, an IPD-ish approach could be an alternative solution (Yee at al., 2017; Abdulaal et al., 2017; Zhang et al., 2018). Conversely, according to KPMG (2013), IPD is not a ‘one-size-fits-all’ model, and it can only be adopted at different levels of integration based on certain conditions including the projects context and participants’ characteristics. However, the literature shows a lack of studies in this regard. Similarly, 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 (Wuni et al., 2021; Wasim et al., 2020).

To understand how IPD and DfMA can be implemented in different contexts, more studies are required to investigate the principles underlying these concepts. Therefore, it is essential to characterize the concept of integration in IPD projects, and then identify the latest IPD contractual, operational, and organizational characteristics, in order to achieve IPD’s full potential in delivering various construction projects. Once a thorough understanding of these topics has been achieved, synergic studies about the interplay between IPD with DfMA in the construction sector will be required, to facilitate their mutual implementation and address challenges which impede the successful delivery of construction projects.

2.7 Conclusion

In summary, despite all the rhetoric about IPD and DfMA, their implementations are still low, and their theoretical foundations are still under construction. There is a need for a more nuanced approach to investigate IPD and DfMA characteristics, principles, and specifications. Both IPD and DfMA have common principles (Rankohi et al., 2022). 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. In order to benefit their full implementation in construction projects, more studies need to be conducted to address the following challenges:

Lack of industry knowledge and maturity: lack of individual and organizational knowledge about both IPD and DfMA, ranges from understanding of technical specification, project participant integration requirement, software tools and technologies to production workflows, analysis and optimization.

Lack of demand: aligned with lack of knowledge, lack of demand is a key challenge in the construction industry that hinders widespread adoption of IPD and DfMA principles. The owners (such as governmental organizations) are the main bodies who can ask for these, however in reality, demand is coming from downstream project participants (such as general contractors, architect, and professionals) who have little to no influence on making decisions early on in the project.

Project organizations and structures: the application of IPD and DfMA principles urges the necessity of sharing and the handoff of information between project participants with high level of integration. In this regard, project organizations and contracts need to be supportive of this level of integration to provide a suitable structure and platform for downstream processes and information being shared with upstream decision-making units to support the mutual application of IPD and DfMA.

Asymmetry of effort and benefits: the applications of both IPD and DfMA in construction projects require high levels of efforts which are in line with contractual and organizational requirements for their proper usages. the challenge lies in the asymmetry of benefits across the supply chain with regards to upstream efforts deployed to develop implementation models that will benefit downstream uses. Project incentives such as fee structures need to be adapted in the context of projects where IPD and DfMA are deployed.

CHAPTER 3 RESEARCH OBJECTIVES AND METHODOLOGY

The goal of this research is to increase the general knowledge and understanding about two recent integrated and collaborative approaches in the construction industry, IPD and DfMA. First, this study aims to investigate the concept of integration in the context of IPD and identify its impact on construction projects. Furthermore, this research aims to understand the characteristics of IPD, and identify how construction projects can benefit from these characteristics. Next, it aims to identify post-pandemic challenges in the construction industry and explore how can IPD characteristics address these challenges. As IPD cannot be implemented in silos and must be accompanied with other collaborative design and construction strategies to be fully efficient, the final chapter of this thesis aims to investigate DfMA and explore how interaction between DfMA and integrated methods (such as IPD) can address existing challenges in the construction industry.

3.1 Research objectives

The specific objectives of each of the four Chapters presented in this thesis are as follows:

Chapter 4 (Article 1):

- To characterize how the concept of integration is studied in IPD literature and identify various integration mechanisms/strategies in IPD projects.

Chapter 5 (Article 2):

- To identify the latest operational, contractual, and organizational characteristics of IPD, and understand how these characteristics are evolved over time.

Chapter 6 (Article 3):

- To identify the post-pandemic "new-normal" challenges in construction projects.
- To explore how the IPD operational, contractual, and organizational characteristics can address some of these challenges.

Chapter 7:

- To identify the principal challenges of applying DfMA in construction projects.
- To develop an integrative construction-oriented DfMA framework (C-DfMA framework) based its synergy with IPD and propose recommendations for tackling identified challenges

3.2 Research methodologies

Due to the nature of this thesis, various methodologies including quantitative and qualitative approaches, have been applied in this study to capture a comprehensive understanding of the construction industry towards IPD and DfMA. Several methods, including systematic literature reviews, semi-structured interviews, focus group discussions, and case studies were employed to achieve the objectives of the four studies presented in this thesis. Figure 3.1 portrays which methods were used in each study. A detailed description of the data collection techniques and analysis methods used for each study is provided in the corresponding chapters.

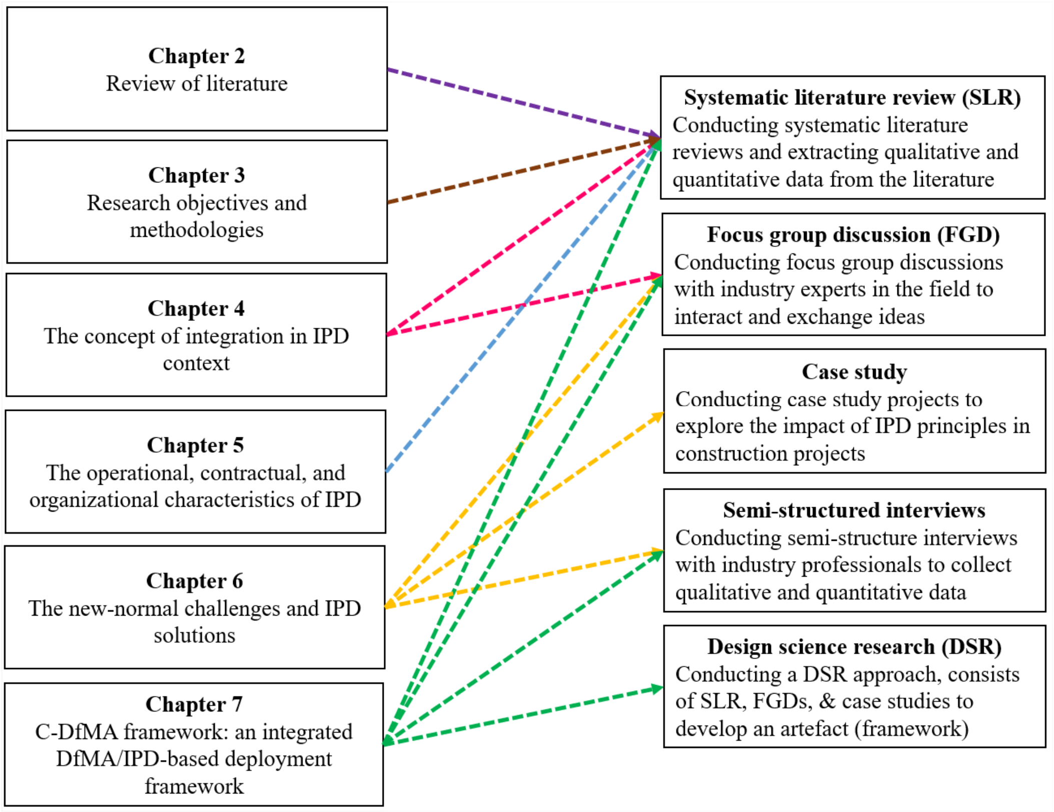

Figure 3.1 Various research methods that have been applied in this dissertation

3.3 Conclusion

In summary, the goal of this article-based thesis is to provide more insight into two recent integrated and collaborative approaches in the construction industry, IPD and DfMA. The research is conducted in separate journal articles and specific objectives of each of the four studies are presented in Section 3.1. As presented in Section 3.2, due to the paper-based nature of this thesis, various methodologies including systematic literature review, case-studies, and focus group discussions, have been applied in this thesis to capture a comprehensive and thorough understanding of the construction industry towards IPD and DfMA.

CHAPTER 4 ARTICLE 1: THE CONCEPT OF INTEGRATION IN AN IPD CONTEXT: A GROUNDED THEORY REVIEW

Chapter Information: An article based on this chapter has been published since 20 September 2022, as per the following reference:

Rankohi, S., Bourgault, M., Iordanova, I., (2022), The Concept of Integration in an IPD Context: A Systematic Theory Review. *Journal of Engineering, Construction and Architectural Management*, Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/ECAM-2022-01-15.

Abstract

Purpose: Recent construction literature has been focusing more on integrative contracting approaches such as integrated project delivery (IPD). However, conceptual studies on integration in IPD literature are scattered and fragmented, that is, most of the studies only focused on the segmented dimension of integration. A systemic understanding of the concepts of integration in IPD project-based context is still lacking. To fill this gap, this paper analyzes two aspects of integration (*dimensions* and *directions*) in IPD literature and explores their extents in construction projects.

Method: Systematic theory review and focus group discussion approaches were employed to perform a thorough conceptual review of the literature, frame the research into the theory, and increase the fundamental understanding of the concept of integration in IPD literature.

Findings: In this study, IPD integrating techniques were identified and their integration dimensions and directions were discussed. Results show that integration in the project-based environment of IPD is a multidimensional construct. Based on organizational, contractual, and operational characteristics of IPD projects, twenty-four integration-related terms were identified and framed into seven clusters. The integration directions over project life-cycle were demonstrated in three contexts: (i) an on-site construction project, delivered traditionally, (ii) an on-site construction project, delivered with IPD, and (iii) an off-site construction project, delivered with IPD.

Originality/Value: This paper gathers the segments of integration into a comprehensive overview, which can help researchers and practitioners explore elements of IPD project success more precisely. A theoretical framework of integration clusters is developed, based on IPD literature. The impact of IPD on on-site versus off-site construction is illustrated from an integration direction perspective. Finally, future areas of studies for researchers and practitioners about the concept of integration in an IPD context are discussed. This paper provides a point of departure for future theoretical and empirical explorations.

Keywords: *Integration; Integrated Project Delivery; IPD; Contracts; Construction*

4.1 Introduction

Integrated project delivery (IPD) was first developed in United-States, during the Sutter Health project in 2004 (Darrington and Lichtig, 2010). IPD is defined as a collaborative process that "integrates" project stakeholders, system structures, and construction practices (Tee et al., 2019; Chountalas & Tepaskoualos, 2019). Integration is a term frequently used in IPD literature, but it is rarely defined. The construction literature shows that studies on the concept of "integration" in project delivery methods have been started since 1960s (Fergusson and Teicholz, 1996; Mesa et al., 2016). While these studies go back to more than sixty years ago, a comprehensive conceptual study that could enable both a detailed and systemic understanding of integration in IPD project-based supply chains is still lacking (Eriksson, 2015). Most studies only focus on a segmented dimension of integration (i.e., team integration or information integration). Several authors have stressed the pivotal role of IPD in enhancing synergies for the successful delivery of construction projects (Tee et al., 2019; Hall et al., 2020). However, they each have different interpretations of integration (McDermott and Khalfan, 2006).

The literature shows that the period of theorization of IPD is still ongoing, and yet, there is insufficient theoretical attention as to the implications of IPD as a project delivery method to improve integration and provide integrated solutions (Hall and Scott, 2019; Whyte, 2019). IPD will not see major industry adoption until its impact on integration is clearly contextualized with respect to construction projects. Therefore, a comprehensive study is required to build a foundation to develop IPD theories and improve its current applications in practice. By grouping the segments of integration into a broader, more all-encompassing tableau, it will be easier for researchers and practitioners to explore the elements that contribute to or hinder an IPD project's success (Uihlein, 2015). This paper conducted a conceptual review study based on the Systematic Theory review method (Wolfswinkel et al., 2013). The focus on general integration found in construction literature is shifted to an IPD context and aims to increase the fundamental understanding of the integration aspects of IPD projects. To address this goal, we will answer how integration is studied and clusterized in IPD literature.

4.2 Background

In this section, a general review was first conducted to explore the concept of integration in the construction literature, with focus on *dimensions* and *directions* of integration. This helped to develop a theoretical framework and comprehensive view of the broad range of inconsistencies and define specifications. Next, the integration tools and techniques found in IPD literature, were analyzed from three fundamental aspects: *organizational, contractual,* and *operational*. We selected these aspects because they outline fundamental characteristics of IPD projects (Thomsen, Darrington, Dunne, and Lichtig, 2009). More details will be discussed in the following sections.

4.3 Integration in the construction literature

Integration has been defined in various ways. One such definition was by Baiden and Price (2011) who defined integration as the merging of different organizations, functions, or disciplines into a single cohesive and mutually supporting unit, with an alignment of processes, objectives, and cultures. Prior studies on integration in construction projects see integration under various classifications. Several studies discussed strategies of integration (i.e., full and partial) in construction projects (Arashpour et al., 2018; Demirkesen & Ozorhon, 2017; Chountalas & Tepaskoualos, 2019; Monteiro et al., 2014). Arashpour et al. (2018) identified five groups of strategies: full integration, skill chain, upstream, down-stream, and direct integration. They described these strategies as suitable for optimal process integration architectures in off-site construction. The most applied strategy is direct integration, in which all resources can cover processes carried out by over-utilized resources, and the most comprehensive strategy is full integration, in which multi-skilled resources operate across the entire production network (Arashpour et al., 2018). As for digital integration in the construction supply-chain, several scholars have studied various facets (Abdirad, 2022; Hamledari & Fischer, 2021; Elghaish et al., 2020). Hamledari and Fischer (2021) conducted studies on the block-chain application for financial management of construction projects. Their research emphasized the digital integration between physical and virtual financial supply chains in construction projects.

4.3.1 Dimensions of integration

Strength of integration: refers to the degree of integration (Frohlich and Westbrook, 2001; Fabbe-Costes and Jahre, 2007; Eriksson, 2015) and defines the level or extent to which integrative activities in construction projects are undertaken (Flynn et al., 2010). The extent of integration can be measured based on integrative practices, patterns, and attitudes (Van der Vaart and Van Donk, 2008). According to Leuschner et al. (2013), the strength of integration depends on the extent of *informational, operational,* and *relational* integration.

Scope of integration: differentiates integrative activities and technologies based on the type of stakeholder, *internal* or *external* (Leuschner et al., 2013; Eriksson, 2015; Liu et al., 2020; Flynn et al., 2010). Internal refers to departments and functional roles (e.g., estimation, engineering, R&D, purchasing, etc.), which function within the principal company as parts of an integrated process to facilitate decision-making and enhance collaboration (Flynn et al., 2010). External refers to the importance of reinforcing the connection with other organizations by establishing trust-based, interactive relationships with upstream clients and suppliers (Leuschner et al., 2013).

Duration of integration: refers to the period during which integrative events and activities take place during the project life cycle. Due to the project-based nature of the construction industry, this period is mostly *short-term*, although in few studies *long-term* integration (longitudinal) is discussed to reinforce the integration (Flynn et al., 2010; Koolwijk et al., 2018).

Depth of integration: refers to the actors who perform the integrative activities. The actors can be top and/or middle managers, specialists, and engineers, and/or production personnel at the shop floor. According to Barnes et al. (2007), interaction among individuals at various hierarchical levels and having different functional roles expedites integration. The depth of integration can be categorized in top-down, bottom-up, and top-only/bottom-only integration levels (Barnes et al., 2007; Eriksson, 2015; Sjödin et al., 2016). The depth is affected by how many people at different hierarchical levels and internal disciplines are involved in the integrative activities across the partner organizations (Eriksson, 2015).

4.3.2 Directions of integration

Vertical integration: is based on linking the different components of a system. In vertical integration, business units, application devices, people, information, knowledge, and services are integrated within an enterprise, to coordinate, collaborate, and cooperate (Hall et al., 2018; Barutha et al., 2021; Sanchez et al., 2020). According to Oesterreich and Teuteberg (2016), vertical integration results in a cross-functional collaboration and creates a smart manufacturing environment, in which systems, processes and data integration flows within the company's borders.

Horizontal integration: is based on connecting two or more systems together. It occurs when two or more companies collaborate to achieve individual or mutual goals (Franz et al., 2017; Fergusson and Teicholz, 1996; Sanchez et al., 2020). Oesterreich & Teuteberg (2016) stated that horizontal integration is when IT systems, processes, people, and data through value networks, flow between different companies. This allows customers, suppliers and other external partners to collaborate more closely with value chain partners across company borders.

Longitudinal integration: refers to the flow of knowledge and information over time. In construction projects, the two major time horizons are: within-project and project-to-project (Bygballe and Swärd, 2019; Fergusson and Teicholz, 1996). The within-project horizon refers to the flow of knowledge and information from a project life cycle's start to end. The project-to-project time horizon discusses the flow of information from prior to current projects, or from current to future projects (Fergusson and Teicholz, 1996).

4.4 Integration in an IPD context

IPD, as is known today, was first crafted by Sutter Health, as a new delivery method arrangement with new rules, regulations, and common principles to form integrated relationships between stakeholders and develop an effective way to deliver new projects (Lichtig, 2006; Darrington et al., 2009; Cheng et al., 2016; Hall and Scott, 2019). In 2004, Sutter Health, which is one of the leading healthcare providers in northern California (Lichtig, 2005), decided to find a solution for addressing the problems facing healthcare construction in United-States, through developing a new contracting model based on lean project delivery (Lichtig, 2005). To achieve this goal, attorney Will Lichtig drafted an integrated form of agreement (IFOA) for Sutter Heath project which binds together the owner, design professionals, and general contractor within one design and construction contract (Lichtig, 2006). This created the IPD foundation to make a virtual project-based "company" whose employees take on roles based on the project requirements rather than their employers' needs (Thomsen, Darrington, Dunne, and Lichtig, 2009). Following the efficient application of IPD on several successful utility projects, Matthews and Howell (2005), conducted a case study to document the benefits of this approach in which they used the term "integrated project delivery" for the first time (Matthews and Howell, 2005; Cheng et al., 2016; Hall and Scott, 2019). According to Lahdenpera (2012), the successful accomplishment of Sutter Health project below the estimated cost and schedule, initiated the current era of IPD.

IPD significantly emphasizes on integration, as a project delivery method which integrates people, systems, business structures, and practices into a collaborative process to harness stakeholders' talents, reduce wastes, and optimize efficiency throughout the project (Hall and Scott, 2019). IPD integration stems from three foundations: organizational structures, contractual frameworks, and operating systems and processes (Thomsen, Darrington, Dunne, and Lichtig, 2009).

4.4.1 Organizational structures

IPD integrates project structures by converting vertical silos into integrated high-quality teams. It emphasizes on the early engagement of stakeholders, and consists of integrated organizational teams which collaborate with design professionals. Integrated activities, such as joint decision-making and problem-solving practices which involve all stakeholders, create a collaborative project culture and develop a unified team (Thomsen, Darrington, Dunne, and Lichtig, 2009).

4.4.2 Contractual frameworks

IPD is based on an integrative contractual framework which calls for collective risk management. According to a pain/gain sharing contractual agreement, stakeholders goals and objectives are aligned with project objectives, and all team members mutually share (cost overruns) risks and (cost saving) rewards. This encourages stakeholders to work mutually towards a common goal of ensuring project overall success (Thomsen, Darrington, Dunne, and Lichtig, 2009; Cheng et al., 2016).

4.4.3 Operating systems and processes

IPD replaces the traditional delivery methods with a lean operating systems, based on using lean tools and technologies which foster integration, and effective interaction among project participants (Alves and Lichtig, 2020). IPD implements lean processes and mechanisms, such as last planner system (LPS) and target value design (TVD), in order to reduce wastes and add value to the project. The lean operating systems help project stakeholders to address failures, meet project targets, learn from their mistakes, prevent similar errors, and continuously improve the processes (Alves and Lichtig, 2020; Cheng et al., 2016; Darrington, Dunne and Lichtig, 2009; Lichtig, 2005). IPD processes (i.e., integrated goals and objectives, building information modeling, integrated project management, collaborative decision-makings, and applying last planner system in the planning process), emphasize on improving integration and collaboration between stakeholders (Thomsen, Darrington, Dunne, and Lichtig, 2009).

4.5 Research methodology

To frame this research topic within the broader theory and increase the fundamental understanding of the concept of integration in IPD projects, a thorough conceptual analysis was performed, using the Systematic Grounded Theory review approach proposed by Wolfswinkel et al. (2013). Systematic grounded theory is a conceptual methodology that helps to develop theory that is grounded in systematically collected data about a research phenomenon (Nguyen & Akhavian, 2019). It allows the key concepts to surface from the literature during the analytical process of substantive inquiry, instead of deductively deriving key concepts in advance. Wolfswinkel et al. (2013) discussed the full benefits of meticulously applying systematic literature review to extract the full theoretical value from a well-chosen set of published studies. The systematic grounded theory literature review method has five stages. As shown in Table 1, these five stages must be used in an iterative fashion.

Table 4.1 Systematic literature review method

Stage	Task	Description
1. Define	Defining the inclusion/exclusion criteria to determine appropriate databases	-English language papers -Books and peer-reviewed published journal and conference papers -Published from 1990's to 2022 -Focused on the construction sector
2. Search	Defining search keywords, and searching the selected databases.	-Search terms: "Integrated Project Delivery", "Lean project delivery", "Integrated Form of Agreement", "IFOA", "IPD"
3. Select	Selecting the appropriate articles and refining the sample.	-Search and conduct the primary and secondary screenings, and collect retained studies
4. Analyze	Analyzing the articles, coding, categorizing, and developing theories/conceptual frameworks based on identified concepts.	-Code and critically analyze retained studies to discuss integration dimensions and directions of IPD integrating practices
5. Present	Presenting the results, revealing, validating, representing, and structuring developed concepts	-Discuss the identified integration clusters in a focus group discussion, validate the results, demonstrate their impact on on-site versus off-site construction project life-cycles, and provide future study directions

Stage 1**:** the search was conducted on well-known construction engineering electronic databases over a 30-year period from 1990 to 2021 inclusively and limited to the English language. To capture the most relevant articles and track how the concept of integration has evolved over time, we chose 1990-2021, as several in-depth conceptual studies about integration in the construction industry date back to the 90's (Ferguesson, 1996; Koskela, 1999). The Web of Science (WoS), Scopus, and Google Scholar (GS) were selected as search databases. To assure the comprehensiveness of the review about IPD, in addition to electronic journal databases, the conference proceeding databases of the International Group for Lean Construction (IGLC) and the Lean Construction Journal (LCJ) were searched.

Stages 2: Search keywords included controlled vocabulary and terms related to IPD in the construction engineering domain including: "Integrated Project Delivery", "IPD", "Integrated Form of Agreement", "IFOA", "Lean Project Delivery", "LPD", "Integrated Delivery", and "Integrated Design and Construction." The integrated form of agreement (IFOA), was the first agreement which was drafted for Sutter Health IPD project in 2005, thus some scholars use IFOA to refer to IPD. On another note, there is a confusion about IPD and LPD approaches in the literature. The LPD system emerged in 2000 based on lean manufacturing theoretical and practical investigations, and IPD was introduced as a relational contracting method to support this lean construction movement for generating more values and reducing wastes in projects (Ballard, 2008). According to Mesa et al. (2019) the core of both innovative approaches is based on the use of integrated project organizations, relational contracting, and integrated process, however their operational systems are different. In order to capture all IPD-focused publications, we considered IFOA, LPD, and all their related terms in our search keywords.

Stage 3**:** The final selection and inclusion of relevant studies is done through (a) selection of articles by reviewing their titles and abstracts; (b) primary screening the full texts to assure the relevance; and (c) secondary screening of articles in circumstance of doubt about the relevance of a study. As of April 2022, 4856 studies have been identified. First, duplications and articles including white and grey papers, Calendars, Editors Notes (EN), Subject Index (SI), Content of Volume (CV), and irrelevant studies were excluded (4856–4395=461 articles). In the primary screening stage, the title and abstract of the retrieved studies were screened, and 144 articles which did not focus on the construction domain, were excluded (461–144=317 articles). In the secondary screening stage, the full text of 317 included articles are evaluated, and 81 articles which briefly discussed IPD but did not have a principle focus on IPD applications in construction projects (i.e., Ma et al., (2018) and Chen et al., (2018)), are excluded (317–81=236 articles). Eventually, 236 studies satisfy the inclusion and exclusion criteria, as shown in Figure 1.

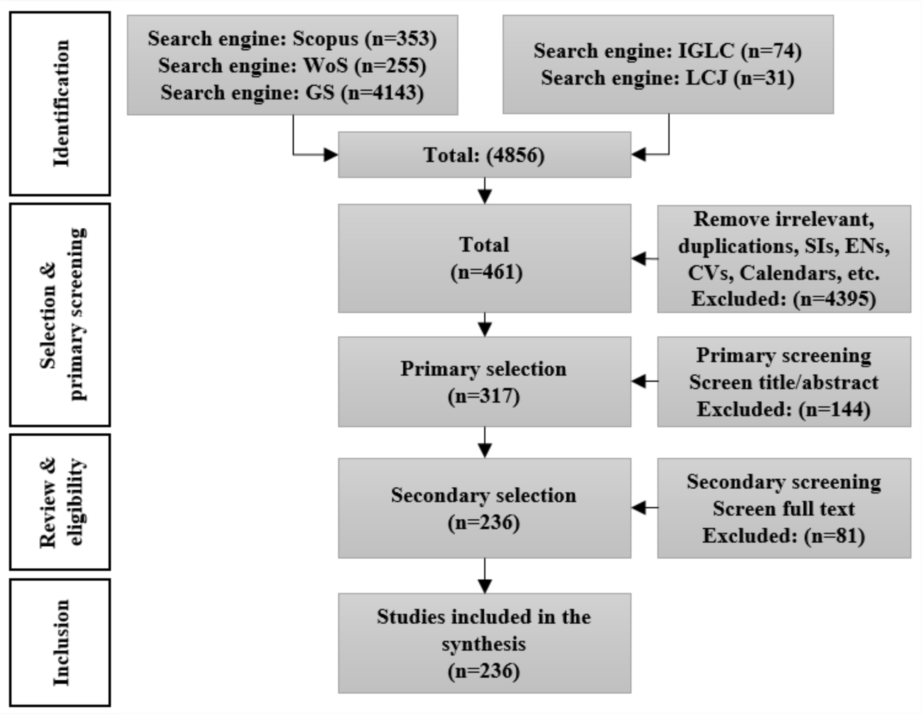

Figure 4.1 The flow diagram for the systematic review

Stages 4: Since integration is a concept, studies might not necessarily mention it in the title, keywords, abstract, or even content. Therefore, we selected a content-analysis based review method, which is widely applied in the construction research domain. A qualitative content analysis, recommended by Oesterreich and Teuteberg (2016), was performed by formulating the research question; developing the coding agenda; defining main categories, sub-categories, and coding rules for categories; and interpreting the results in an iterative manner. To theorize from the empirical data on integration in a grounded way, we iteratively coded collected data, and compared emergent findings from the literature (Whyte & Nussbaum, 2020). The initial content analysis was conducted by the first author, reviewed and revised by the second and third authors. The review and analysis processes were iterated in team meetings until mutual agreements were achieved, and final decisions were made based on the best approach to illustrate the review results.

Stage 5**:** We continuously sought to discuss, modify, refine, and relate our emergent categories and understandings to IPD literature, as we moved from descriptive analyses to more theoretical conceptualizations of integration. In the final stage, based on the results, we developed an integration framework, and adopted the focus group discussions (FGD) method to validate it. 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 (Liu et al. 2017). This method has been widely adopted for qualitative research and is recommended to be used for studies in which different perspectives of diverse stakeholders about a topic are required (Sun et al., 2020; Hasan et al. 2019; Ma et al. 2020; Wang et al. 2020). According to Sun et al., (2020) each focus group consists of 5 to 25 experienced experts in the area of study. The results and theoretical findings are presented in the following content analysis section.

4.6 Content Analysis

To analyze the data set, the first author conducted open coding to identify the most prominent “integration” terms and themes arising from IPD literature (Whyte & Nussbaum, 2020). Then, the activities related to various levels of integration were identified. These were associated with various components of an IPD project (e.g., project stakeholders, phases, etc.). To realize the data’s theoretical potential, we related the themes emerging from the IPD literature, returning to and recoding our data as we contrasted our emergent findings with existing insights. Links are discussed (with each other and with peers in the research community) to extend the understanding of integration. This section lists IPD integration techniques and their levels of integration; then, all integration terms are identified and defined; finally, the directions of integration (vertical, horizontal, longitudinal) are discussed based on the IPD literature.

4.7 IPD Integration Terms

Some 236 articles from the IPD literature were reviewed and 24 integration terms were identified as: *actor integration* (Eriksson, 2015), *change integration* (Demirkesen and Ozorhon, 2017), *circular integration* (Hossain et al., 2020), *concurrent engineering integration* (Avnet and Weigel, 2010; Cheng et al., 2016), *contractual integration* (Ahmad et al., 2010), *crypto asset-enabled integration* (Hamledari and Fischer, 2021), *design integration* (Forgues and Koskela, 2009), *digital integration* (Kang et al. 2012; Papadonikolaki, 2018; Abdirad, 2022), *financial supply chain integration* (Hamledari and Fischer, 2021), *information integration* (Ng et al., 2021; Davies and Mackenzie, 2014; Isikdag, 2012), *knowledge integration* (Demirkesen and Ozorhon, 2017), *meta system integration* (Whyte and Davies, 2021), *operational integration* (Leuschner et al., 2013), *organizational integration* (Baiden and Price, 2011; Cheng et al., 2016; Tee et al., 2019), *relational integration* (Leuschner et al., 2013), *physical supply chain integration* (Hamledari and Fischer, 2021), *process integration* (Ng et al., 2021), *product integration* (Zerjav et al., 2018; Whyte et al., 2016), *relational integration* (Eriksson, 2015), *service and application integration* (Davies and Mackenzie, 2014), *system integration* (Whyte et al., 2016), *staff integration* (Demirkesen and Ozorhon, 2017), *supply chain integration* (Eriksson, 2015), and *team integration* (Bartlett et al., 2007). The definition of these terms are provided in Table 1, Appendix A. The identified terms are later categorized in various integration clusters, as discussed in section 5.1.

4.8 Dimensions of Integration in IPD

IPD integration techniques enhance collaboration and facilitate the coordination of horizontal-axis activities within an integrated team (Barutha et al., 2021). Figure 2, shows IPD organizational, contractual, and operational tools and techniques, based on the strength and duration of their integration impacts. The results of the review show that some of the IPD tools and techniques meet all the elements of integration *"dimensions"*, such as integrating technologies (Ng et al., 2021), no dispute charter, co-location, and risk-reward sharing (Demirkesen and Ozorhon, 2017), and pre-fabrication and modular construction techniques (Xu et al., 2021). These techniques are often inseparable part of every IPD projects, and have bigger impacts on the project's overall performance. For instance, BIM is an integrating technology that is applied in many IPD projects. Numerous studies identified BIM as a process, product, knowledge, and supply-chain integrator in construction projects (Khosrowshahi and Arayici, 2012; Cheng et al., 2016; Jobidon et al., 2021). It provides integration from an informational perspective (across a project's short-term or long-term life cycle), operational (over the project's phases), and relational (between the project's internal and external stakeholders, at various hierarchical levels). Generally speaking, IPD integrating tools and digitization techniques such as building material digital passports, improve circular integration and promote technological proximity in construction projects. Integrating technologies facilitate on-site services, and provide digital collaborative platforms that improve the visualization of the physical and functional representations of as-built construction (Jobidon et al., 2021). Thus meeting all dimensions of integration in IPD projects. As for techniques that meet less integration dimensions, they may have longer-term longitudinal impacts on IPD project goals, such as "strategic alliancing," which provides relational integration between project stakeholders and organizations over a long period of time, sometimes beyond the project duration.

As shown, the majority of IPD tools and techniques provide strong integration during the projects' life-cycle (short-term). Due to the project-based nature of IPD, most of contractual tools, techniques, and their related mechanisms have a short-time integration impact, while a few of them (such as strategic alliancing) provide a long-term impact. IPD organizational techniques are all based on high level of integration between project participants, while IPD operational tools and techniques can have both short-term strong integration impact (such as lean techniques) and long-term medium/low integration impact (such as lesson learned documentations). Compare to these techniques, some of the emerging digital tools and technologies that have been applied in IPD projects recently, are providing lower integration over a shorter period of time (such as block-chain based technologies for projects financial management). As shown, IPD contractual and organizational specifications include higher order concepts which provide more long-term integration impacts, whereas operational specifications are more short term tools which focus on addressing project-based needs.

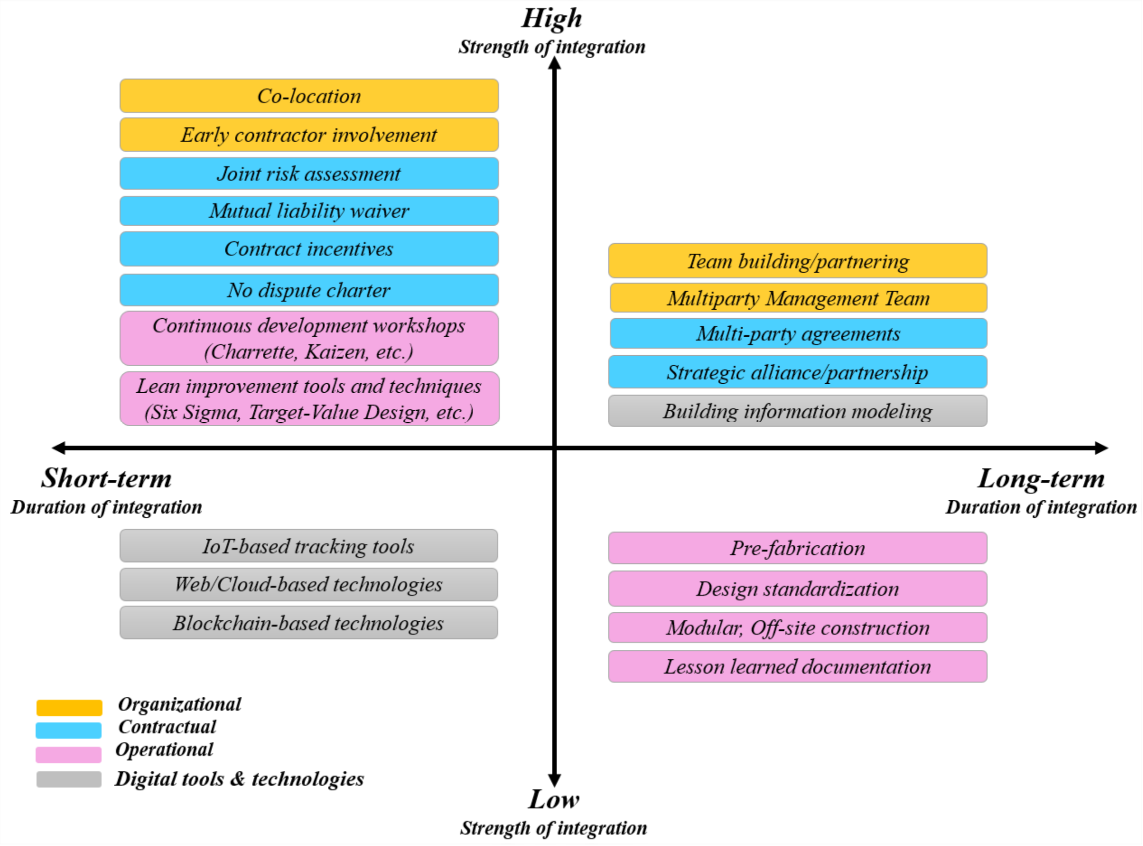

Figure 4.2 The strength and duration of integration for IPD tools and techniques

A full list of IPD tools and techniques, identified in the IPD literature, and their levels of integration based on the dimensions (strength, scope, duration, and depth) provided by Eriksson (2015), is shown in Table 2, Appendix A.

4.9 Directions of Integration in IPD

The results of the literature review show that 65% of IPD articles implicitly or explicitly referred to various directional integrations, of which 60% focused on vertical integration, 30% on horizontal integration, and only 10% discussed longitudinal integration. As shown in Figure 3, from vertical integration perspective most studies explored design-construction integration in on-site projects, while few researchers studied design-manufacturing-construction integration in off-site construction projects.

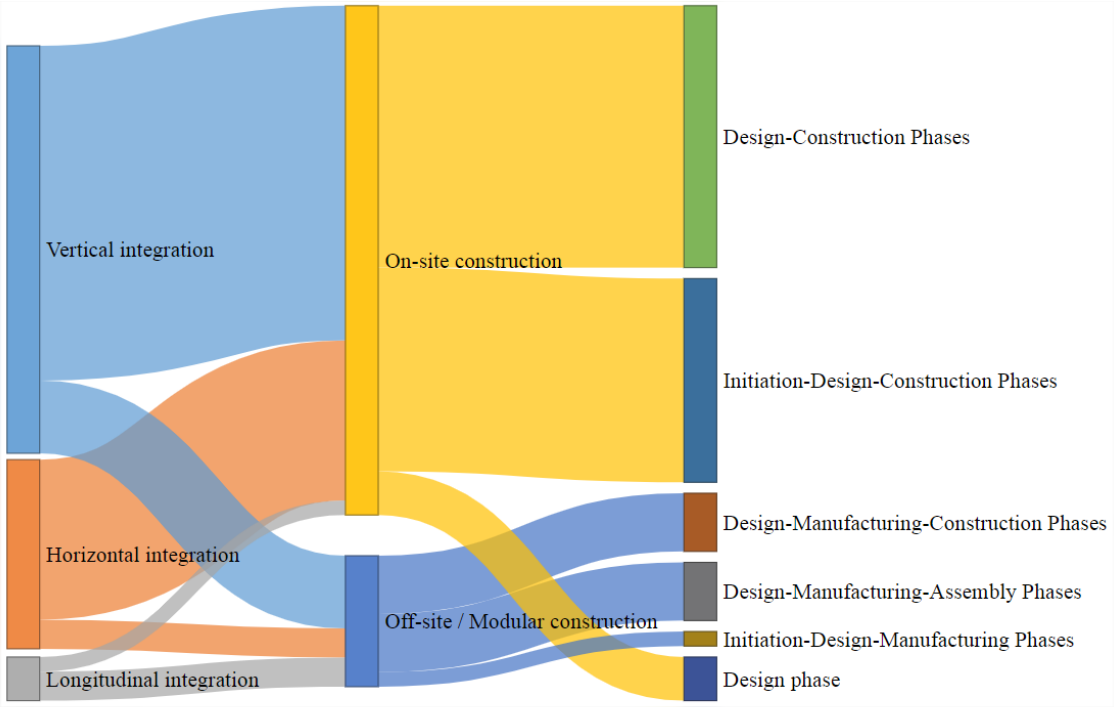

Figure 4.3 Relationships between directions of integration, construction methods, and project phases in IPD literature

From horizontal integration perspective, off-site/modular construction projects got more attention from scholars. This can be related to the efficiency of modular/prefabricated construction techniques in reducing projects' cost and duration, which ultimately results in repeated projects and more chance of longitudinal integration between supply-chain actors over time. Regarding the contract stakeholders, most IPD studies explored owner-contractor-architect-engineering team integration. Scholars which conducted case-studies on on-site construction projects, mostly discussed vertical integration between design professionals (architects/engineers) and construction trades (general contractors, site-supervisors, etc.), while studies on OSC projects, mainly discussed the horizontal and longitudinal integrations between design professionals and suppliers/manufacturing teams.

4.10 Results and Discussion

4.10.1 Integration Clusters in IPD Projects

The integration terms identified in IPD literature show that different researchers use dissimilar terms when referring to similar integration concepts. For instance, organization, relational, team, actor, and staff integration all described flow of information between various "people" in IPD projects, either in inter/intra-project or organizational levels. Thus, the twenty-four integration terms were categorized into seven clusters based on the flow of information throughout the elements of IPD projects. As shown in Figure 4, each cluster contains integration terms that refer to similar concepts using different wordings.

Knowledge integration (Demirkesen & Ozorhon, 2017) cluster contains knowledge, data, and information integration terms. This cluster refers to a free flow of information throughout all phases, actors, processes, and products in construction projects. Most IPD studies focused on knowledge integration between design and construction phases and discussed how early contractor involvement enhances this integration, while a few studies discussed supply-chain knowledge integration over the project life-cycle. In parallel, the literature shows that there is a systematic shift from analogue to digital forms of knowledge integration in IPD projects, and this shift has led to the emergence of innovative generations of integrative practices (e.g., blockchain-based crypto assets for financial supply-chain integration (Hamledari & Fischer, 2021). With innovative digital integrative practices, IPD projects deliver not only a physical product and its associated services, but also its digital information (Whyte, 2019). Several studies on knowledge integration also emphasize the application of building information modeling (BIM) and cloud digital collaboration for IPD projects. These studies spotlight the shifting loci of knowledge integration in practice, where custom agendas urge industry practitioners to shift the focus of integration from their permanent practice at an organizational-level to temporary workflows at the project-level (Abdirad, 2022).

Organization integration (Tee et al., 2019; Baiden & Price, 2011) cluster contains organizational, team, and staff integration terms. This cluster refers to a free flow of information between various stakeholders in a typical construction project. IPD literature which studied organizational integration focused on team identities, incentive alignment, and co-location (Tee et al., 2019). Bygballe and Swärd (2019) focused on the day-to-day practices of people within project organizations and stated that organizational *truces* need to be implemented to enhance coordination and integration. Given the short-term nature of construction projects, they said these temporary truces might be replaced by more permanent settlements between organizational actors (Bygballe & Swärd, 2019). Organizational integration-focused IPD literature promoted collaborative working environments with long-term benefits for construction projects (Baiden, 2006). While this contributes to the success of construction projects (Forgues & Koskela, 2009), several studies focused on barriers such as adversarial attitudes of project parties, competing cultures of team members, team discontinuities, and ineffective responses to changes, which impede full organizational integration in IPD projects.

Design integration (Kang et al., 2012; Papadonikolaki, 2018; Abdirad, 2022) cluster contains architectural and engineering design integration terms. This cluster refers to the free flow of information between various designing (architectural and engineering) functions in a typical construction project. In IPD literature, these terms are associated with design integration, such as integrated design (ID), integrated design process (IDP), design for manufacturing and assembly (DfMA), and target value design (TVD). ID, IDP, and DfMA are collaborative design processes with multidisciplinary teams that focus on environmental and economic goals to optimize the design, manufacturing, construction, and operation of a project over its entire life cycle (Wu et al., 2019). TVD is a management approach in which the design and construction processes are merged to maximize customer value while reducing project wastes (Chountalas & Tepaskoualos, 2019).

System integration (Whyte et al., 2016) cluster contains systems, meta-systems, and service and application integration terms. This cluster refers to the free flow of information between various components of a meta-system, its underlying systems/subsystems, and the service or application that each system provides to the down-stream client. IPD literature shows that the concepts, which originated from the industrial revolution, influenced system integration studies in construction and motivated scholars to shift from studying centralized systems to developing more decentralized sub-systems with similar functionalities. Thus, these decentralized sub-systems can provide more value-based service and applications to clients. Integration of these decentralized sub-systems can be achieved through digitalized knowledge integration techniques, which relates with the knowledge integration cluster.

Product integration (Zerjav et al., 2018; Whyte et al., 2016) cluster contains product, and change integration terms. This cluster refers to a free flow of information between various products in a construction project supply-chain. The main product in a construction project is what is being built. Hence, the flow of as-built change information throughout the project life-cycle is included in the product integration cluster. IPD literature shows an increased emphasis on new product integration due to companies investing in design and processes integration. Studies reveal that concurrently designing a product and integrating the production process results in increased quality and reduced costs (Rodrigues et al., 2021; Su et al., 2021). Another product integration related topic in IPD literature is Product-Lifecycle-Management (PLM). PLM deals with the integration of information produced throughout all the life-cycle phases of a company's product (Oesterreich & Teuteberg, 2016), which is a form of vertical integration.

Process integration (Ng et al., 2021) cluster contains process, operational, digital, and contractual integration terms. This cluster refers to a free flow of information between various processes in a construction project supply-chain. Process integration can be physical or virtual via digital means. In this regard, recent IPD literature showed a trend towards digital integration. In addition, process integration can be achieved through contractual clauses and regulations, which is the case for IPD projects. The literature showed that combining BIM, early contractor involvement (ECI), and digital fabrication in IPD projects, facilitated process integration throughout the project life-cycle (Ng et al., 2021; Whyte, 2019). Process integration refers to properly organizing the sequence of activities and developing a logical order between processes. This enhances automation in delivery of IPD projects by (1) centralizing information, (2) systematizing production methods, (3) automating the generation of project outputs upon predefined inputs, (4) standardizing classification formats for product date, and (5) defining frameworks for adequate usage of project resources (Monteiro et al., 2014). According to Mesa et al. (2020), integrated processes in conjunction with organizational and product integration improves value creation in the project life cycle.

Supply-chain integration (Mesa et al., 2020; Eriksson, 2015) cluster contains circular, physical, and financial supply-chain integration related terms. This cluster draws on the notion of supply chain integration across IPD project life-cycle, in which supply-chain management practices are performed both physically and digitally. Recent IPD literature focused on the application of smart and artificial intelligence technologies to manage the financial aspect of supply-chain management practices in construction projects. Supply chain integration (SCI) is one of the most studied integration-related topics in the construction literature (Eldamnhoury & Hanna, 2020). It is the degree of strategic collaboration between a focal company and its supply chain partners to manage intra-and inter-organizational processes (Eriksson, 2015). According to Hall et al. (2018), supply chain integration is a strategy to align goals and integrate resources within the boundaries of a company to deliver a highly value-added project or product.

Once the integration terms were categorized in seven clusters, a focus group discussion was conducted to validate the integration framework. A group of industry experts were selected and series of discussions were conducted for the following objectives: (1) validate the integration clusters extracted from the literature, (2) identify which IPD fundamental characteristics (organizational structure, contractual framework, and operating systems) these clusters belong to, and (3) discuss the impact IPD integration practices on on-site and off-site construction projects. Our focus group consisted of 12 participants. The discussion was led by a facilitator who encouraged participants to interact and contribute constructively. In the beginning of the focus group discussion, the goal of the study was explained. During the discussion, participants were provided with the results of systematic literature review and content analysis, and at the end, the literature review and focus group discussion results were compared to validate the results.

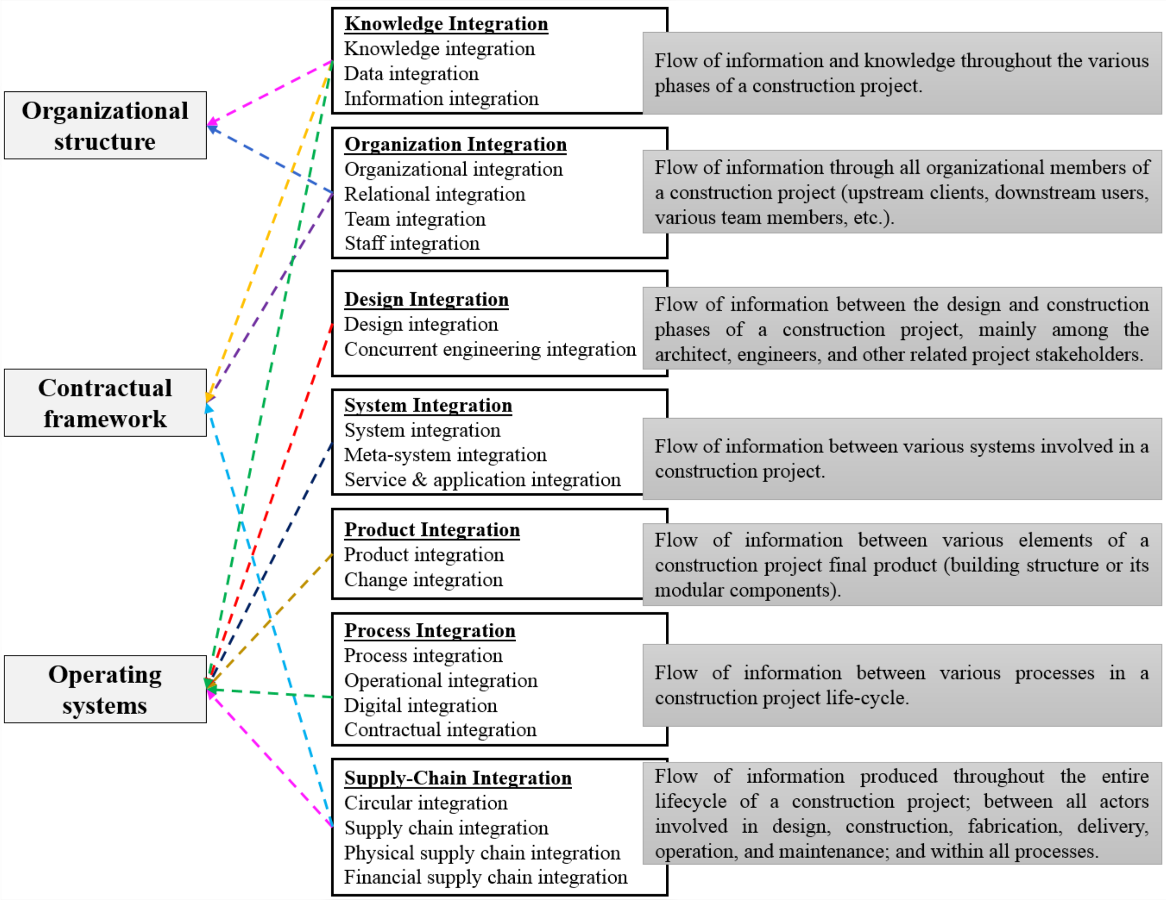

Figure 4.4 Integration clusters in IPD literature

As shown in Figure 4.4, the results of literature review and focus group discussions show that, the majority of integration clusters (i.e., product, process, system, and design integrations) are associated with IPD operating systems. In fact, operating systems apply various tools and techniques to integrate the projects supply-chains. On the other hand, IPD contractual framework and organizational structures are mostly associated with high-level integration clusters within the projects such as knowledge, organizational, and supply-chain integration clusters.

4.10.2 Integration Directions for On-site versus Off-site Construction

Studies discussed (El Asmar et al., 2016; Jobidon et al., 2021; Jin et al., 2018) or provided evidence (Xu et al., 2021; Ng et al., 2021; Li et al., 2017) that IPD can overcome the fragmentation issues related to traditional delivery methods and boost supply-chain performance in construction projects by enhancing integration. While supply chain integration can happen in a variety of directions (i.e.

vertical, horizontal, longitudinal), most IPD studies focused on vertical and horizontal integration, in which information continuously flows between various phases and stakeholders of the project. Several studies discuss how the early involvement of contractors improves vertical and horizontal integration in the design and construction phases (Arashpour et al., 2018; Osman et al., 2017), while a few studies discussed longitudinal integration of projects' supply-chain. This could be due to the project-based nature of the construction industry, in which project teams scatter once the project is completed, and integration from project-to-project usually does not occur.

Based on the results of the literature review and focus group discussions, we developed the diagram illustrated in Figure 5. As shown in Figure 5 (a), vertical and horizontal SCI do not occur in traditionally delivered construction projects. In this case, project phases are fragmented, and information silos block the free flow of knowledge throughout the project. In an on-site construction project which is delivered through IPD, Figure 5 (b), the level of integration is improved from vertical and horizontal perspectives, and the construction phase can commence even while the design phase is in progress. This results in accelerating project completion, saving time, and adding value to the end product. In the case of an off-site construction project, illustrated in Figure 5 (c), which is delivered through an IPD contracting method, vertical and horizontal SCI happens throughout the project, from initiation to termination. As shown, site preparation, fabrication, off-site construction, and on-site assembly can all happen in parallel, while the design phase is still in progress. In addition to vertical and horizontal integration, off-site construction projects provide a suitable environment for fostering the longitudinal supply-chain integration. The synergy between offsite construction and prefabrication techniques with IPD principles such as co-location and strategic alliancing, enhance all proximity scopes (technological, organizational, geographical, and cognitive) proposed by Dallasega et al. (2018). This synergetic impact, can address supply-chain interruption challenges, improves projects longitudinal integration, and usually enhances all scopes of proximity (technological, organizational, geographical, and cognitive) proposed by Dallasega et al. (2018). This level of vertical, horizontal, and longitudinal integration which occurs in OSC projects as a result of implementing IPD, can significantly reduce projects' time and cost, compare to on-site construction projects which are delivered through traditional delivery methods.

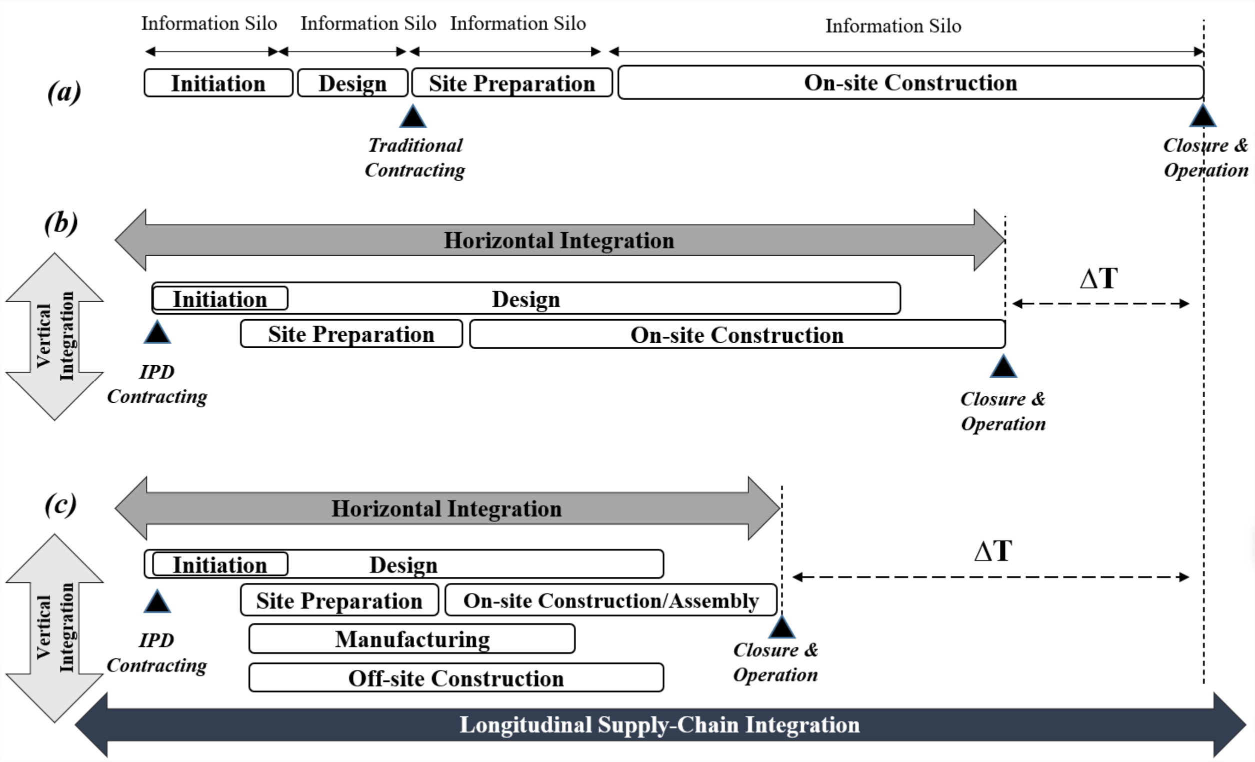

Figure 4.5 (a) Traditional contracting, on-site construction; (b) IPD contracting, on-site construction; (c) IPD contracting, off-site construction

Fully vertical and horizontal SCI saves time and cuts costs and can only be achieved when knowledge flows freely across all phases of the project. IPD and lean-based project delivery systems enabling flow of information throughout the project life-cycle from the project definition, initiation, design, all the way to the construction and maintenance, while generating value and reducing wastes (Ballard, 2008). According to Hall et al. (2018) vertical SCI can reveal the full potential of modular construction. However, empirical studies on this topic are lacking in current IPD literature. In terms of SCI for prefabricated and off-site construction projects, vertical and horizontal information integration makes it possible to coordinate downstream fabrication-related information with upstream design and decision-making processes, so that in addition to meeting the technical and technological requirements, the design meets the projects' target value goals, such as cost, quality, and project life-cycle performances metrics (Ng et al., 2021). In addition to vertical and horizontal integration, the longitudinal integrating practices can provide better real-time supplier visibilities (Whyte, 2019) and enhance project performance by going beyond projects' typical life-cycle. In modular and prefabricated off-site construction projects, repeated collaboration between the same contractor, designer, and fabricator teams over time, results in reducing design alteration, increasing modules standardization, facilitating mass production, and speeding up construction process. Therefore, longitudinal integration over time and from projects to projects, enhances project performance metrics. IPD literature still shows a lack of interest in promoting longitudinal integration studies for OSC projects. One reason could be the current contractual structure of IPD, which is not necessarily suitable for OSC projects. In this context, regulatory bodies and governmental organizations can adjust IPD contractual criteria and impose rules and regulation to promote the application of IPD for off-site construction projects and emphasize on longitudinal integration practices across projects' organizations, processes, and modular products.

4.11 Conclusion

The review showed that the literature offers a scattered and partial understanding of integration in IPD studies, due to the episodic focus on individual projects, particular areas of interest, or the initial adoption of IPD integrating practice in construction projects. The challenge for the construction industry is to align with an unprecedented variation of segmented studies on integration agendas across IPD projects that is found in recent literature. In this study, we drew on the notion of integration in the construction industry, on ideas of integration *dimensions* (based on Eriksson, 2015) and integration *directions* (based on Fergusson & Teicholz, 1996) across IPD project life cycles, to frame our analyses in relation to recent debates on IPD-integrating practices.

4.11.1 Contributions of the review

Through a systematic review of the literature and focus group discussions, this paper: (a) identified all IPD integrating techniques cited in the literature, and explored their integration dimensions (strength, scope, duration, and depth); (b) classified IPD integration-related terms in an integration framework, into seven clusters and their associated organizational, contractual, and operational characteristics which exist across IPD project life-cycles as: knowledge, organization, design, system, product, process, and supply-chain integration clusters; (c) illustrated integration directions (vertical, horizontal, and longitudinal) in three contexts: (i) on-site construction projects, delivered traditionally, (ii) on-site construction projects, delivered through IPD, and (iii) off-site construction projects, delivered through IPD; and finally (d) identified the gaps and future areas of study about the concept of integration in IPD projects. The systematic review results show that applying IPD in an off-site construction project life-cycle, can potentially create a full supply-chain vertical integration, which can result in reducing the project duration, and enhancing project values. This demonstration provides more depth to previous studies, which promoted the application of IPD for OSC, and focused on SCI practices during project life-cycle (Jin et al., 2018; Hall et al., 2018; Xu et al., 2021; Ng et al., 2021; Hall et al., 2020). In summary, this study helps researchers and practitioners to effectively use what is known so far about the concept of integration in IPD literature and understand research limitations. It also provides a point of departure for future theoretical and empirical explorations.

4.11.2 Research limitations

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

Identifying additional IPD integration terms and practices;

Further developing and validating the IPD integration clusters within bigger focus groups discussions; and

Testing and applying the IPD integration framework in case study projects (off-site and on-site projects).

4.11.3 Future works

The study results and their applications provide opportunities for future work by the construction researchers and industry practitioners, as recommended below:

4.11.3.1 Future areas of research

4.11.3.1.1 Organization structures

Longitudinal integration over time: the literature seems to favor vertical and horizontal organizational integration studies in IPD projects. However, scholars should balance these efforts by studying longitudinal integration, particularly for the impact of IPD on enhancing circular economy in off-site and prefabricated construction projects.

Disrupted digital integration routines: recent IPD literature showed a trend towards digital integration. However, disparate digital agendas across projects disrupt digital integration routines. In order to address issues related to disparate digital agendas and improve digital integration in IPD projects, studies that go beyond project boundaries and influence project portfolios and organizational structures are required (Abdirad, 2022).

4.11.3.1.2 Contractual frameworks

More appealing contractual framework: The current segmented environment of the construction industry along with the ingrained passive mindset of the industry practitioners reduce the chance of implementing the IPD method. More studies are required on enhancing integration through applying IPD contractual characteristics, while developing business models to sustain in the market.

4.11.3.1.3 Operating systems and processes

Challenges of digitalization: we predict more digital IPD operating systems and processes in the future. While innovative digital integration practices (such as blockchain) have gained momentum as seen in recent IPD studies, their associated challenges and limitations (i.e., cyber-security concerns, intellectual property rights, etc.) need further investigation.

Change management and digital platforms: the continuing process of change in IPD projects, creates an increasing volume, complexity, and convergence of heterogeneous sets of digital information across projects boundaries (Whyte, 2019). Thus, more studies are required on the role of knowledge integration and digital platforms in managing disruptive change in IPD projects.

Product and process integration: even though several scholars have demonstrated the importance of process integration in delivering successful prefabricated projects (Arashpour et al., 2018; Jin et al., 2018), the literature shows a lack of case studies in this regard. In addition, studies on product integration is essential for prefabricated projects. More studies on the physical and digital integration of modular products can improve off-site construction quality and affect the level of adoption of IPD for off-site construction projects.

4.11.3.2 Future areas of practice

4.11.3.2.1 Organization structures

Shifting loci of knowledge integration towards decentralization: studies on the application of BIM and cloud digital collaboration in IPD projects, spotlight the shifting loci of knowledge integration in practice, where industry practitioners are urged to shift from centralized knowledge units, to decentralized decision-making hubs. This change of focus can be recognized when knowledge integration structures shift from permanent practices at an organizational-level to temporary workflows at the project-level (Abdirad, 2022).

4.11.3.2.2 Contractual frameworks

IPD contractual integration structure: regulatory organizations and governmental agencies can generate standards to improve IPD contractual criteria, to further adapt it to current industry practices, such as OSC and prefabrication. Also, contractual studies are required to address issues related to digitalization, the massive production of digital information, intellectual property rights, and knowledge integration across all constellations of practice in IPD projects.

4.11.3.2.3 Operating systems and processes

IPD integrative practices for OSC: the literature shows that only a few studies focused on the implementation of IPD in off-site construction projects. Considering that both IPD and OSC methods insist on increasing the level of integration in construction projects, more empirical studies are required to investigate their combined applications in practice.

Digital integration tools for OSC: recent digital integration practices (i.e., the application of blockchain-based crypto assets for financial supply-chain integration (Hamledari & Fischer, 2021) are mostly implemented on on-site construction projects. Considering the importance of these digital techniques for improving prefabrication, testing their applications on supply-chain-integration and supply-chain visibility of OSC projects are recommended.

CHAPTER 5 ARTICLE 2: THE LATEST OPERATIONAL, CONTRACTUAL, AND ORGANIZATIONAL TRENDS IN IPD LITERATURE: REVIEW AND FUTURE DIRECTIONS

Chapter Information: An article based on this chapter has been published since 14 June 2022, as per the following reference:

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Abstract

Purpose: Integrated project delivery (IPD) has attracted considerable attention in recent years, however only a few review studies captured the dynamic and evolving nature of this topic. The purpose of this study is to review the most recent IPD publications, in order to shed light on future research.

Method: Using a systematic review methodology, the study aims to synthesize the current IPD literature, and frame the latest research and development in this domain. A systematic review is conducted to identify the current state-of-the-art of IPD research and the latest research themes and trends in this domain. A bibliometric analysis is performed to explain characteristics of screened articles, and through a thematic content analysis the latest themes and trends are recognized.

Findings: In this study, based on IPD characteristics (operational-cognitive, contractual-regulative, and organizational-structural), research themes (technological, procedural, legal, commercial, cultural, and structural), sub-themes, and their associated trends are identified. The latest emerging trends are mostly related to the contractual characteristics of IPD, and are focused on the combination of IPD with new business models and developing contractual guidelines for promoting IPD applications in off-site and on-site construction projects.

Originality: This research contributes to the body of knowledge by synthesizing the state of the art of IPD in construction literature and exposing the latest research trends in this area. A theoretical

framework of integration in an IPD context is developed, based on the literature. Finally, future areas of studies are discussed.

Keywords: Integrated project delivery, IPD, Systematic review, Construction

5.1 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 been led to the development of the Integrated Project Delivery (IPD). IPD is an emerging form of collaborative delivery method (Hall and Bananomi, 2021), in which, a new single purpose entity or limited-liability company is created to enhance efficiency and innovation in projects and promote greater collaboration and trust among the project stakeholders; consisting the owner, the lead designers, the construction managers, and other key project members in the design and construction of a project (Darrington et al., 2009; Darrington and Lichtig, 2010; Cheng et al., 2012; Hall and Bananomi, 2021). As an emerging topic in the construction management domain, we still know a little about IPD. From a practical point of view, the adoption of IPD in the construction industry and awareness of industry participants about it, is still low (Yee et al., 2017). From a theoretical point of view, the conceptual aspect of IPD and integrated practices are yet to be studied (Hall et al., 2019). Literature shows various definitions exist for IPD; several researchers consider it as a standalone delivery methods (El Asmar et al., 2013; Elghaish et al., 2020); while others define it as a philosophy which can be applied within various types of delivery methods (AIA, 2010; Yee et al, 2017).

5.2 Previous work

Studies on integrated project delivery related topics have been started since 1960s, when the concept of integration in project delivery method gained attention by scholars (Hall et al., 2021; Cheng et al., 2016; Mesa et al., 2016).

While studies on integration for construction delivery methods go back to more than sixty years ago, IPD, as is known today, was first crafted by Sutter Health, as a new delivery method arrangement with new laws, regulations, and agreed-upon principles to form integrated relationships between stakeholders and develop an effective way to deliver its new projects

(Lichtig, 2006; Darrington et al., 2009; Cheng et al., 2012; Hall and Scott, 2019). Sutter Health is one of the leading healthcare providers in northern California (Lichtig, 2005). In 2004, Sutter Health decided to find a solution for addressing the problems facing healthcare construction in United-States, through developing a new contracting model which supports lean project delivery (Lichtig, 2005). To achieve this goal, attorney Will Lichtig drafted an integrated form of agreement (IFOA) for Sutter Heath project which binds together the owner, design professionals, and general contractor within one design and construction contract (Lichtig, 2006). According to Sakal (2005), this first version of an IFOA encompassed a financial incentive strategy that borrows from the Australian Project Alliancing model. Based on this plan, stakeholders used alternative dispute resolutions and mutually waived damage liabilities (Darrington and Lichtig, 2010; Cohen, 2010). This created the IPD foundation to make a virtual project-based "company" whose employees take on roles based on the project requirements rather than their employers' needs (Thomsen, Darrington, Dunne, and Lichtig, 2009). Following the efficient application of IPD on several successful utility projects, Matthews and Howell (2005), conducted a case study to document the benefits of this approach in which the authors used the term "integrated project delivery" for the first time (Hall and Scott, 2019). The Sutter Health project was accomplished with a great success; the project was completed below the estimated cost and stakeholders indicated higher feelings of respect, trust, and satisfaction compared to their other experiences. According to Lahdenpera (2012), this initiated the current era of IPD.

Studies show that the period of theorization is still continuing and IPD is still institutionally immature (Hall et al., 2020; Fischer et al., 2017). Yet, a standard definition of IPD which has been accepted by the industry and academia as a whole, does not exist (Hall and Scott, 2019). Various definitions exist and widely-different approaches and levels of sophistication show that the term 'IPD' is applied to different contractual arrangements and team organization (Hall and Scott, 2019). The American Institute of Architects (AIA) in 2007 provided a definition of IPD, under which, other project delivery methods could be counted as IPD. For example DB, in which the design and construction phases are under single integrated contract, could have been considered as an IPD. In 2010, AIA provided a revised definition for IPD to address this confusion, and described IPD as a delivery method which is distinguished by a contractual agreement. As definitions evolved over time, IPD became more explicitly distinct form of a delivery method. Recent definitions, described

IPD as more than just a project delivery method, and defined it as a set of philosophies which can improve other delivery methods. Yee et al. (2017), defined IPD as a continuum of integration levels from “Lean delivery”, to “IPD-ish”, “Pure IPD”, and “Real IPD.” These models are based on different levels of integration, among which, the highest integrative level is referred to as “Real IPD” which requires a full level of collaborations and contractual commitments. The term “IPD-ish” refers to the application of IPD principles with some limited risk-sharing activities within traditional delivery methods (Sive, 2009; Yee et al., 2017).

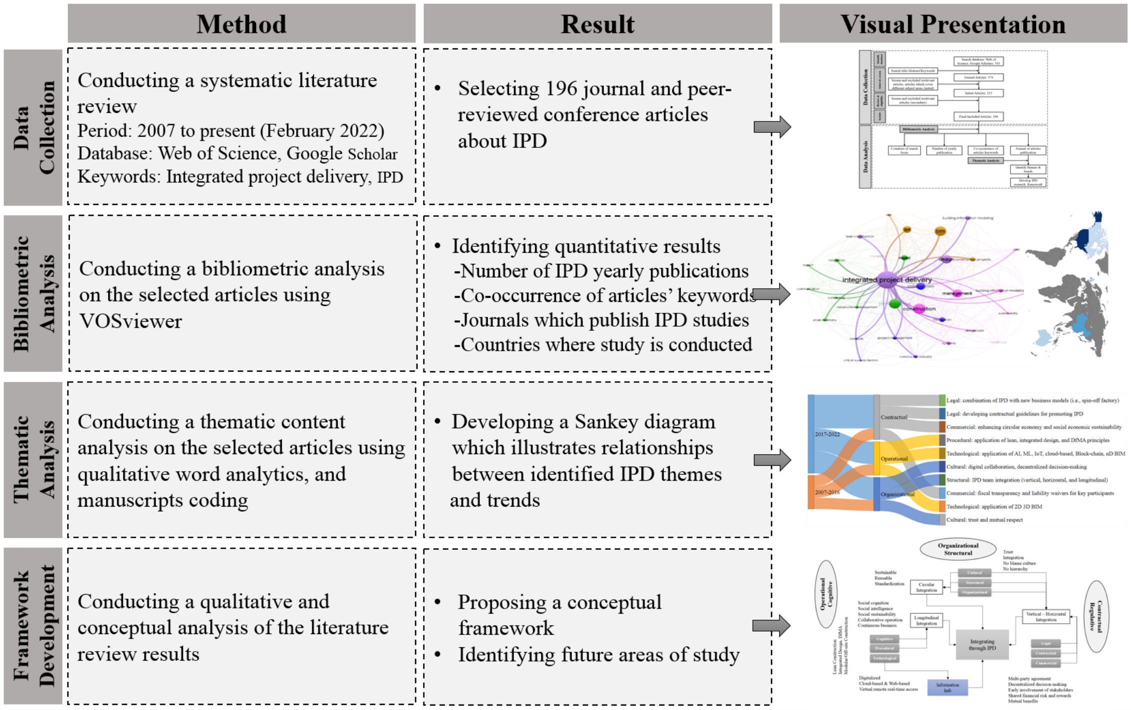
The rapid increase in the volume of IPD literature in recent years, creates a critical challenge in terms of identifying the latest research direction, themes, and trends. Although IPD is an emerging topic and the majority of studies about IPD are published after 2018 (63%), to the best of authors’ knowledge, no comprehensive systematic review is conducted on this topic which covers the articles published since 2018. A few literature reviews covered similar topics (Table 1), often with a specific frame of reference such as IPD improves teams’ collaboration efforts and enhance projects’ performance metrics. They are typically qualitative and still lacked a full review of the latest emerging trends in the construction domain. In addition, the reviewed papers are selective and some of the related IPD and Lean data-bases are not covered. On another note, in the published review studies, IPD themes and principles are categorized differently and sometimes in contrast with each other. This can be to some degree connected to the geographical distribution of the authors. IPD research is most prominently promoted in North America (Engebo et al., 2020), but the majority of IPD reviews are conducted by Asian and European scholars. Therefore to review the IPD themes and principles, re-categorize them if required, and identify the latest IPD trends, it is essential to conduct a comprehensive literature review, which covers the most recent studies. In this context, this study has the following objectives: 1) identify the state-of-the-art of IPD in the construction literature, and 2) identify the latest research themes and trends.

Table 5.1 Literature review papers about IPD

Authors	Year	Search period	No. of articles	Methodology	
				Quantitative	Qualitative
Kahvandi et al.	2017	2001-2016	152	✓	✓
Yee et al.	2017	2007-2016	Unknown		✓
Engebo et al.	2020	1987-2017	28		✓
Viana et al.	2020	2001-2018	74		✓
This study	**2022**	**2002-2022**	**204**	✓	✓

5.3 Research methodology

This research employs a systematic review methodological approach (Mostafa et al., 2016; Xia et al., 2018). As shown in Figure 1, the methodological framework consists of: (1) data collection; (2) bibliometric analysis; (3) thematic content analysis; and (4) framework development based on the results. The synthesis is organized based on the abovementioned framework.



	Method	Result	Visual Presentation
Data Collection	Conducting a systematic literature review Period: 2007 to present (February 2022) Database: Web of Science, Google Scholar Keywords: Integrated project delivery, IPD	• Selecting 196 journal and peer-reviewed conference articles about IPD	
Bibliometric Analysis	Conducting a bibliometric analysis on the selected articles using VOSviewer	• Identifying quantitative results -Number of IPD yearly publications -Co-occurrence of articles' keywords -Journals which publish IPD studies -Countries where study is conducted	
Thematic Analysis	Conducting a thematic content analysis on the selected articles using qualitative word analytics, and manuscripts coding	• Developing a Sankey diagram which illustrates relationships between identified IPD themes and trends	
Framework Development	Conducting a qualitative and conceptual analysis of the literature review results	• Proposing a conceptual framework • Identifying future areas of study	

Figure 5.1 Overview of research framework

The Web of science and Google scholars were selected as search data bases from 2002 to April 2022 inclusively with a limit to English language. We have selected this time period to cover all IPD-related studies that have been conducted in the past two decades. To assure the comprehensiveness of the review, in addition to electronic journal databases, the conference proceeding database of the International Group for Lean Construction (IGLC) and the Lean Construction Journal are searched. Search keywords include controlled vocabulary and terms related to integrated project delivery in the construction engineering domain. The search query used was: (“Integrated Project Delivery” OR “IPD” OR “Integrated Form of Agreement” OR “IFOA” OR “Lean Project Delivery” OR “Integrated Delivery” OR “Integrated Design and Construction”) AND “Construction.” The final selection and inclusion of relevant studies is done through (a) selection of articles by reviewing their titles and abstracts; (b) primary screening the full texts to assure the relevance; and (c) secondary screening of articles in circumstance of doubt about the relevance of a study.

As of April 2022, 589 studies have been identified. First, the title and abstract of the retrieved studies are screened, which exclude 261 articles including Calendars, Editors Notes, Subject Index, Content of Volume, and irrelevant studies (589–281=328 articles). In the second stage, initial screening, the full text of 328 included articles are evaluated, and 113 duplicated articles or studies with principle focus on the application of IPD in different domains other than the construction industry, are excluded (328–113=215 articles). In the third stage, secondary screening, the full text of 215 included articles are re-evaluated, and 11 studies that do not have a principle focus on IPD, are excluded (215–11=204 articles). Eventually, 204 studies satisfy the inclusion and exclusion criteria, as shown in Figure 2. The data extraction from the selected articles, is performed by all the authors in an iterative process. The bibliometric analysis is conducted to define the characteristics of selected studies, such as the overall number of studies, year of publication, and countries where studies are conducted. The thematic content analysis provides an overview of the breadth of the literature. To extract the emerging themes, a qualitative content analysis, recommended by Oesterreich and Teuteberg (2016), was performed by formulating the research question; developing the coding agenda; defining main categories, sub-categories, and coding rules for categories; and interpreting the results in an iterative manner. The emerging themes from the literature are compiled into tables and charts, which allow easy comparison of studies. The initial thematic analysis is conducted by the first author, reviewed and revised by the second and third authors. The review and analysis processes are iterated in team meetings until mutual agreements are achieved, and final decisions are made based on the best approach to illustrate the review results.

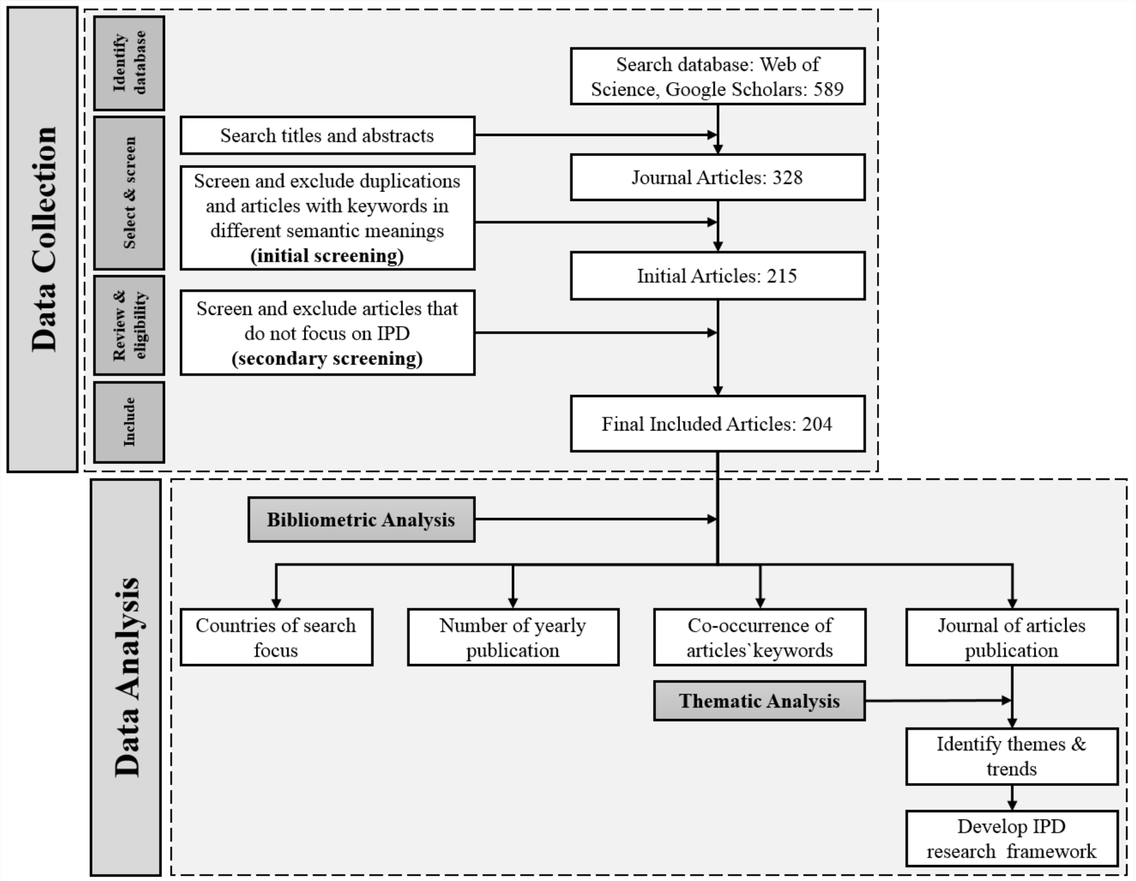


Figure 5.2 The flow diagram of the systematic literature review

5.4 Bibliometric analysis

The distribution of articles by the year and five-top countries of studies since 2010, is depicted in Figure 3. As we aim to identify the latest themes and trends in IPD literature, in this section, we focus on studies which have been published since 2010. The results show that more than 70% of IPD articles have been published since 2017. The maximum number of articles in a single year is published in 2020. The results show that the increasing trend in the number of articles is dominated by the Emerald journal of Engineering, Construction and Architectural Management (ECAM) with publishing more than 50% of its IPD-related articles since 2017. From a research method point of view, the majority of the researchers conducted empirical studies to develop their research, while fewer articles conducted theoretical studies and literature reviews. Case study is observed as the most popular method used for addressing IPD related topics (55% of publications). In most case studies, surveys and interviews have been conducted with the industry participants.

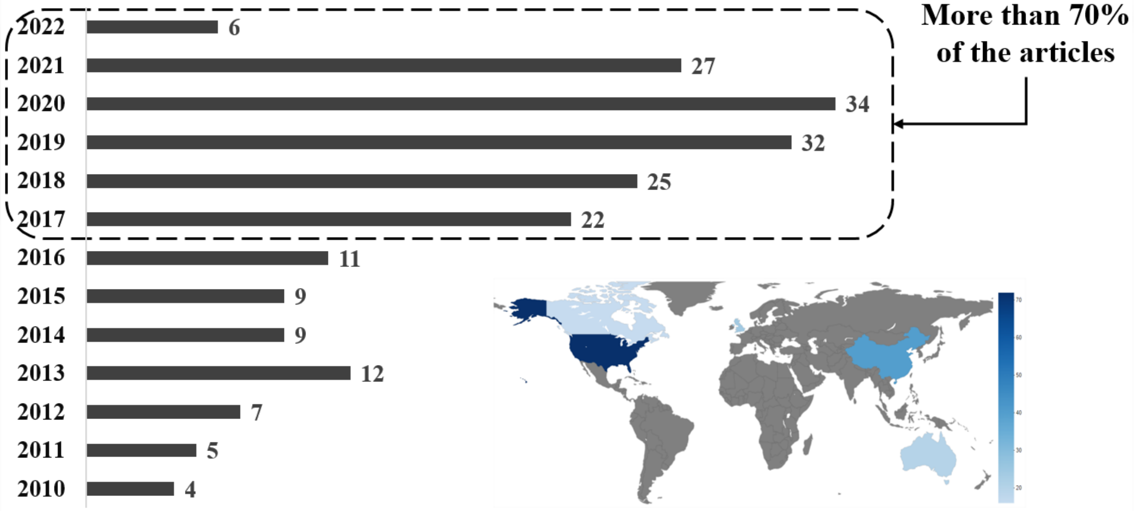


Figure 5.3 Distribution of articles since 2010, by the year-country in which IPD study is developed

The final characteristic identified in this section is the percentage of articles based on the country where the IPD research is developed. Results show that USA has the highest number of the articles about IPD with 37% of research conducted in this country. The remaining counts show that China (20%) has the second place while UK (12%), Australia (10%), and Canada (8%) are in the third, forth, and fifth places respectively. Figure 4, shows the co-occurrence of papers keywords extracted from IPD publications. As shown, keywords such as BIM, design, sustainability, and integration have been co-occurred with IPD most frequently.

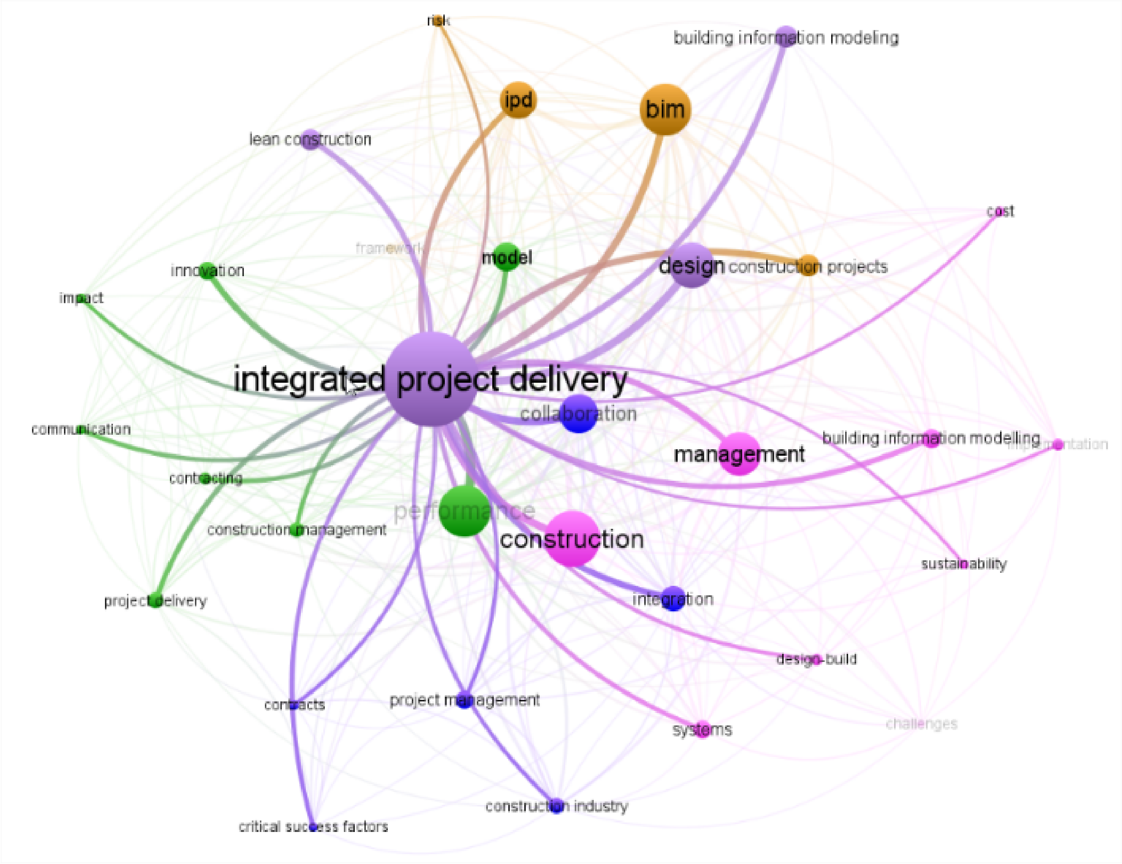


Figure 5.4 Co-occurrence of articles' keywords (VOSviewer)

5.5 Thematic analysis

Similar to all project delivery methods, IPD has three distinguishing characteristics: *operational* which defines the timing and sequence of events, practices, and management techniques; *contractual* which outlines the contractual responsibilities for defining, designing, and building a project; and *organizational* which defines the roles and relationships between the participants (Darrington et al., 2009; Thomsen et al., 2009). The IPD literature focus area is significantly wide, and a variety of research themes captured researchers` attention. In this section, first, IPD literature is reviewed and classified based on the three characteristics clusters: operational-cognitive, contractual-regulative, and organizational-structural. Next, the articles are analysed to extract the latest themes and trends under these clusters.

In order to identify the emerging themes and trends within these IPD characteristics clusters, we conducted a qualitative content analysis of the selected 204 articles, as recommended by

Oesterreich and Teuteberg (2016) with the following steps: formulating the research questions; developing the coding agenda, defining main categories, sub-categories, and coding rules for categories; revising the categories and coding agenda; final text analysing and summative checking of reliabilities; interpreting the results and conducting quantitative (frequency) analysis, if required.

Following this content analysis approach, associated with the three IPD characteristics, the most prominent emerging research themes from the literature are identified as: *technological* and *procedural* under the operational-cognitive cluster; *legal* and *commercial* under the contractual-regulative cluster; and *cultural/behavioural* and *structural* under the organizational-structural cluster.

With the assist of NVivo 12 software, the content analysis of the 204 articles, leads to the identified emerging sub-themes and trends under these six emerging themes in IPD domain, which are the basis of discussion on IPD evolvement over time in the following sections. As illustrated in Figure 5, the blue boxes specify the most studied emerging themes since 2002, while the yellow boxes specify the most recent studied themes, since 2017.

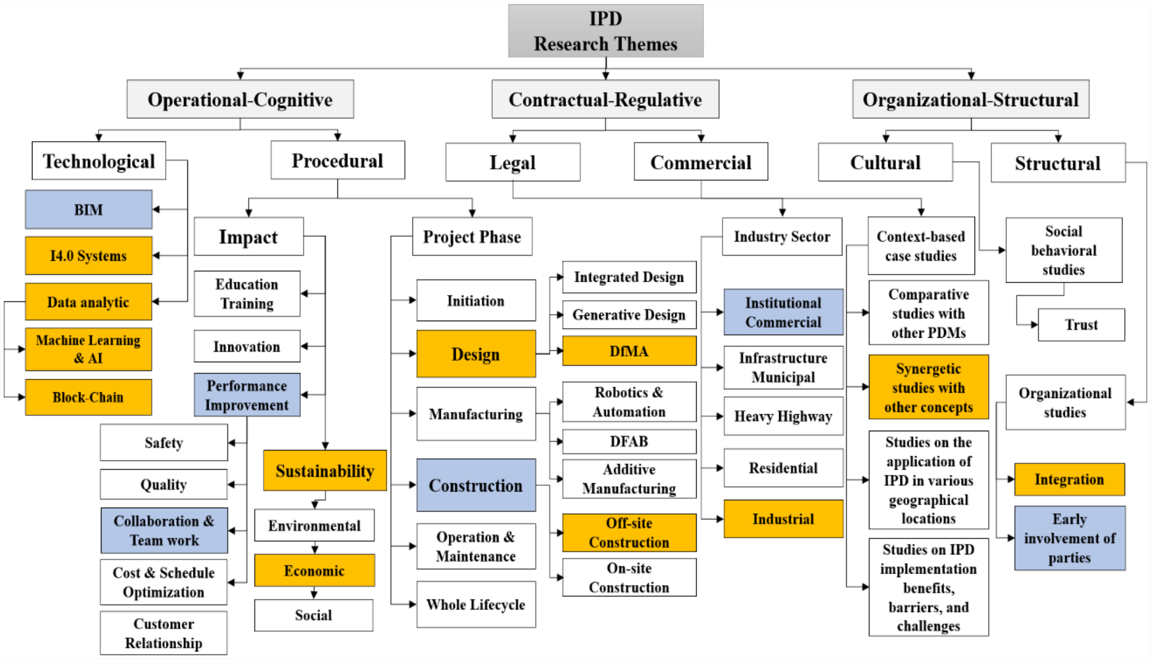


Figure 5.5 IPD research themes.

5.6 Operational-Cognitive

Comparing to other characteristics of IPD, literature shows more interests towards *operational-cognitive* aspects. Operational systems, are mainly discussed from: (a) procedural aspects, such as applying lean principles throughout the life cycle of the project, and collaborative decision making; or (b) technological aspects, such as applying cloud-based data sharing platforms in IPD projects. According to the literature, while IPD does not address a specific operational system by definition (Mesa et al., 2019), it encourages novel and modern ways of managing and executing the pre-construction, design, and construction process of projects (Darrington et al., 2010). From theoretical point of view, IPD is evolving toward having more lean and integrated operational systems. According to Koskela's (2000) theory of production (transformation, value, and flow), in an ideal IPD operational system, information can be readily transformed between teams, knowledge freely flows, and the ultimate project performance results fully satisfy the customer requirements. Literature shows that recently more studies focused on the impact of IPD operational systems on the flow of information. Several researchers attempted to explore the improvements of IPD *operational* environment (Ling et al., 2020; Marco & Karzouna, 2018; Heidemann & Gehbauer, 2011; Ahmad & Aibinu, 2017). Under the operational-cognitive theme, the sub-themes of *technology, impact,* and *project phase* got emerged from the literature.

Technology: Several studies investigated the technological related topics. The focus was either about proposing a new technology for improving IPD projects, or further investigating on currently applied technologies in the industry. Most studies demonstrated a technology application, rather than a technology development or its technical issues. As it was found in the keywords co-occurrence, the application of BIM (4D, 5D, 6D, 7D, 8D, nD) in conjunction with IPD to improve project performance outcomes gained significant attention (Dossick et al., 2013; Azhar et al., 2015; El-Adaway et al., 2017; Liao et al., 2020; Li et. al., 2020; Rankohi et al., 2022). Several theoretical and empirical frameworks were developed, based on the combination of BIM and Lean Construction (LC) practices into the IPD operational systems (Bao et al., 2013; Xu and Su, 2017). The proposed frameworks were validated in real life case studies, where scholars concluded that the integration of LC, IPD, and BIM allow the development of new models of cost, quality, and schedule optimization throughout the construction projects life cycle (Li et al., 2020). In addition to BIM, literature shows that the application of advanced industrial concepts and technologies, AKA as industry 4.0 (i.e., cloud-computing, Internet of things (IoT), blockchain, and Artificial Intelligence (AI)) combined with IPD for enhancing the performance of construction projects, has gained popularity over the recent years (Turk and Klinc, 2017; Elghaish, et al., 2020). In this regards, recently developed terms and concepts such integrated digital delivery (IDD) (Hwang et al., 2020), Integrated Design and Construction Project Delivery (IDCPD) (Wu et al., 2019), and Integrated Data Management (IDM) (Ma et al., 2018), are examples of IPD-inspired operational systems.

Impact: Several scholars explored the impact of IPD implementation in construction projects. The most prominent emerging topics were identified as *performance improvement, education/training, innovation, education/training,* and *sustainability*. Most impacts of IPD are covered within these categories and their sub-categories. The majority of articles investigated project *performance improvement* through applying IPD method and principles. Enhancing collaboration between projects stakeholders, was among the most cited impacts. The schedule and cost of IPD projects have been shown to be significantly less than projects with traditional delivery methods (Franz et al., 2017). El Asmar et al. (2015), provided a list of most prominent performance metrics in the IPD literature, called project quarterback rating (PQR). From this list, communication, schedule, cost, and quality have gained the most number of citations respectively. Performance metrics such as customer satisfaction, and safety gained the lowest attention. Regarding sustainability, several studies indicated that IPD provides the best operational systems for sustainable (Chen et al., 2019), green (Gunhan, 2019), ZEB (Kantola et al., 2016), prefabricated, and off-site (Wu et al., 2019) construction projects. These studies mainly focused on economic (saving costs and improving projects' financial aspects) and environmental (reducing global impact, reducing waste, providing just-in-time delivery, and increasing project speed) sides of sustainability, while leaving rooms for more studies on its social aspects. Finally, several studies are conducted on how IPD improves innovation in the construction industry, and how practitioners can use IPD to train new generation of project managers who work in integrated teams.

Project phase: IPD acts on a project level. The implementation of IPD in construction projects, is studied in various *project phase*s including initiation, design, manufacturing, construction, operation and maintenance. Some studies focused on the whole lifecycle of the projects. The majority of case studies investigated the IPD in construction phase of projects. From construction strategy perspectives, several scholars discussed the importance of IPD as a suitable method for off-site construction (OSC) and prefabricated buildings (Osman et al., 2017; Jin et al., 2018; Nawi et al., 2014). They stated that IPD would be an approach to overcome the fragmentation issue in traditional construction projects, and to boost the supply chain management in OSC and prefabricated projects (Li et al., 2017; Jin et al., 2018). Recently, more IPD studies focused on the design phase and explored synergy between IPD and various emerging design techniques such as integrated design, generative design, and design-for-manufacturing-and-assembly (DfMA). Finally, few studies focused on the overall project life-cycle, such as case studies which investigated the application of Lean construction principles and practices in conjunction with IPD (Koolwijk et al., 2018; Ma et al., 2018).

5.7 Contractual-Regulative

The IPD contractual relationships, are mainly investigated from: (a) legal aspects, such as multi-party contractual agreement; or (b) commercial and financial aspects, such as shared financial risk/reward, and fiscal transparency. IPD is experiencing development in the construction industry in recent years, however its contractual, legal, and business aspects lag far behind. Literature shows, few researchers attempted to explore IPD *contractual and regulative* environments recently (Assaad et al., 2020; Jobidon et al., 2021; Ahmed et al., 2021). Studies which focused on *contractual and regulative* aspects, mostly addressed project influencing actors or project types.

Building industry sector: the contractual aspects of IPD in municipal/infrastructure, residential, institutional/commercial, heavy/highway, and industrial projects are studied, from which the majority of case studies are conducted on institutional projects, such as hospital and public schools. The availability of funding and owners willingness to participate in research studies on institutional/commercial projects, are the main reason for it. The multi-party contractual nature of IPD, makes it suitable for projects in which a high-level of collaboration is required (Lahdenperä, P., 2015; Azhar et al., 2015). In this context, most case studies were conducted on public and complex infrastructure projects (Mesa et al., 2019; Tezel et al., 2017), while a few authors performed case studies on small size building projects (Zhang et al., 2018; Huo et al., 2019).

Geographical location: recently several scholars explored the implementation of IPD contracts in various countries, such as Middle-East (Hamzeh et al., 2019), Egypt (Othman and Youssef, 2020), Ukraine (Trach et al., 2020), Canada (Jobidon et al., 2021), Venezuela (Pradhananga et al., 2021), and Nigeria (Ebekozien et al., 2022). Finally, the review shows that recently more attention is putting toward applying IPD principles to improve other delivery methods contractual relationships. Literature refers to this as an IPD-ish or IPD-inspired approach, and promotes its application to overcome challenges related to the current IPD contractual deficiencies.

Comparative studies: several authors conducted comparative case studies between traditional and relational delivery methods, concluding that relational delivery methods (i.e., Alliancing, IPD, etc.), further improve project performance (Mesa et al., 2019; Sødal et al., 2014; Ashcraft, 2011). In such context, integrated principles such as IPD-ish and Lean philosophies, which could reinforce the structure of all project delivery methods, have gained popularity. However, studies also indicate that still traditional delivery methods with discrete and transactional contracting strategies, are the most common selected methods by project owners.

5.8 Organizational-Structural

Research on organizational structure of IPD has been conducted mainly on: (a) cultural and behavioural aspects, such as mutual respect and trust; or (b) structural aspects, such as team top-bottom integration and no hierarchy. Cultural-structural IPD research, are mostly conducted through theoretical and conceptual studies.

Integration: the organizational structure of an IPD project is constructed based on collaboration and integration throughout the project supply-chain. The *integration* in IPD literature is discussed from various perspectives. Viana et al. (2020), conducted a literature review study on IPD and divided integrative aspect of IPD dimensions in three groups: full integration, partial integration, and no integration. Hall et al., (2019), identified three integration dimenions: horizontal (inter-disciplinary), vertical (inter-functional), and longitudinal (across time from projects to projects). The majority of research studied the impact of IPD on enhancing multi-disciplinary team integrations (horizontal) (Franz et al., 2016; Fischer et al., 2017; Hall et al., 2019; Koolwijk et al., 2020), and project phase integration (vertical) (Hamidavi et al., 2020; Han et al., 2020; Jin et al., 2020), while only a few studies addressed longitudinal integration (Hall et al., 2019; Huo et al., 2020). The longitudinal integration, emphasizes on the team integration and knowledge transfer on a project level, and has direct impacts on project ultimate performance and sustainability (particularly social sustainability) (Montalbán-Domingo et al., 2019). For the case of pre-fabricated and off-site construction projects, the importance of longitudinal integration is even more highlighted (Wu et al., 2019). In addition, studies on the application of BIM for project asset management, goes along together with longitudinal integration in IPD projects (Farghaly et al., 2018).

Organizational structure: literature shows that the organizational structure of IPD projects has changed over time from a hierarchical structural to a no-hierarchy environment in which top and bottom management levels are integrated. The roles and relationships between the IPD participants, has evolved over time as well. Since the beginning, IPD promoted open communications between key project participants and integrated teams, which are composed of people from various backgrounds (Mesa et al., 2019; Sødal et al., 2014; Ashcraft, 2011; Tingting et al., 2017). Early involvement of key participants is one of the main characteristics of IPD which has been cited by several scholars (Mesa et al., 2019; Darrington et al., 2010; Ballard, 2003). This characteristic is supported by various tools and techniques such as the big room and lean construction methods. From a practical point of view, IPD organizational structures are moved from decentralized decision-making units to centralized decision-making authorities in construction projects. From a theoretical point of view, IPD organizational structures are constructed based on theories derived from organisational learning, cultural and organisational behaviour, governance and governmentality, institutional theory, stakeholder engagement, ethics, strategy and decision-making theories (Walker and Rowlinson, 2019).

5.9 Discussion

The Sankey diagram in Figure 6, illustrates some of the IPD research focus overtime, with respect to the emerging IPD research themes. As shown, the volume of studies (width of the blocks) has significantly increased over the past decade. Studies on contractual aspects of IPD have been increased since 2017. Scholars identified new business models (Hall et al., 2022), which can improve IPD projects performance. Another area of recent focus is related to developing contractual guidelines which makes IPD adaptable to various building industry sectors such as off-site and modular construction (Ahmed et al., 2021). Regarding the IPD commercial aspects, the trend is toward studying circular economy and social sustainability in IPD projects. Trends related to the operational aspects of IPD, contains studies the application of smart technologies such as AI for financial management and block-chain for information exchange in IPD projects. In addition, scholars have conducted more studies on the synergetic effects of the implementation of IPD, Lean, DfMA, and BIM in construction projects, since 2020. From the organization perspective, IPD researchers conducted more studies related to integration (vertical, horizontal, and longitudinal), partnership, social, and behavioural aspect of IPD projects since 2019.

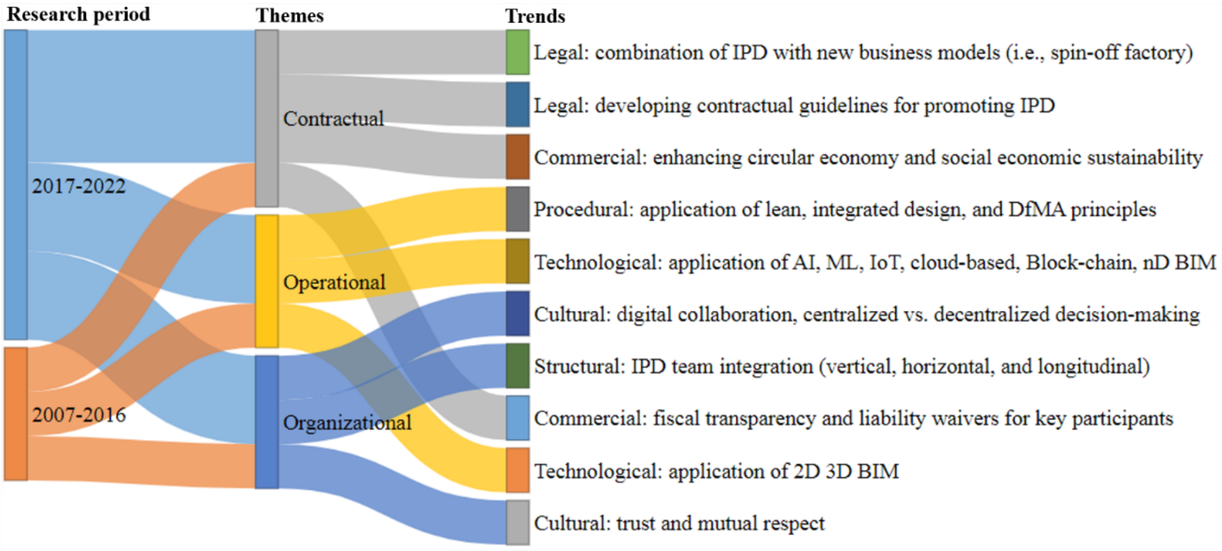


Figure 5.6 Sankey diagram of IPD research trends

Based on the results of this review, we proposed the IPD integration frameworks (Figure 7). IPD contractual, operational, and organizational principles and practices can enhance vertical, horizontal, longitudinal, and circular integration in construction projects. The framework illustrates an integrative organizational structure by applying various IPD tools and techniques which support integration throughout the project supply-chain. As shown a cloud-based AI-driven information hub is required to enhance the collaborative nature of IPD and assure proper implementation of IPD method. In addition to the information-hub, blockchain-enabled smart tools and techniques (Hamledari and Fischer, 2019), can help providing an extremely secured crypto-asset payment platform for sharing financial information in IPD projects.

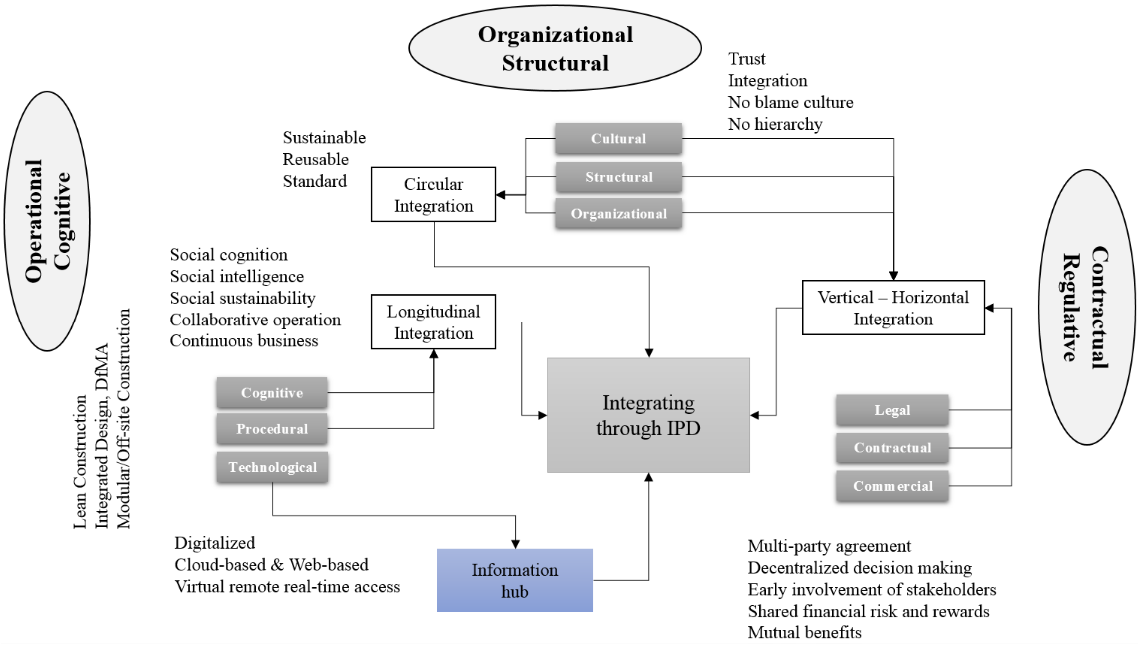


Figure 5.7 The proposed IPD integration framework

5.10 Conclusion

This study contributes to the existing body of knowledge by synthesizing the IPD literature to improve the conceptual lucidity, and clarifying the research themes and trends. Firstly, through the bibliometric analysis, an overview of the-state-of-the-art of IPD research and developments is provided. Since 2017, the number of publication about IPD got doubled. The most number of research about IPD is conducted in USA. Concepts such as BIM, design, and integration have been co-occurred with IPD most frequently. Secondly, through the thematic analysis, the most recent IPD research themes and future trends are identified. Research themes were identified in three main categories and their associated sub-categories as: *contractual-regulative:* legal, commercial; *operational-cognitive:* procedural, technological; and *organizational-structural*: cultural, structural. Literature shows that IPD contractual relationships is evolving from a distinct relational delivery method to a flexible IPD-ish contractual hybrid format, in which IPD philosophies can be applied within other types of project delivery methods such as traditional delivery methods. IPD operational systems are being reinforced by modern technologies and concepts. In this context, synergetic studies on the combination of lean, BIM, and industry 4.0 technologies with IPD, have gained attention among the IPD researchers. Regarding the organizational structure, IPD literature emphasizes on team integration and collaboration among all involved stakeholders. In this context, several scholars have investigated the cultural and behavioural aspect of IPD projects, in order to enhance integration and reduce isolation among IPD team members.

5.11 Future studies

Potential areas for future IPD studies extracted from the literature and associated with emerging research themes, are listed in Table 2. With emerging hot topics such as circular economy and sustainability in construction literature, more studies on synergy between IPD, Lean, and modern design/management tools and techniques are required. Also, there is a potential for conducting more studies on improving longitudinal integration, through IPD, particularly for the case of prefabricated and off-site construction projects (Wu et al., 2019). Longitudinal integration has direct impacts on project ultimate performance and sustainability (particularly social sustainability) (Montalbán-Domingo et al., 2019. In addition, studies on the application of BIM for project asset management, goes along together with longitudinal integration in IPD projects (Farghaly et al., 2018). Finally, more studies are required for improving legislative norms and contractual standards for proper implementation of IPD in various types of construction projects (i.e., OSC, prefabricated, green, sustainable, etc.).

Table 5.2 Potential areas for future studies about IPD

Dimensions	Future studies
Technological	Studies on the impact of digital transformation on IPD projects. Studies on the application of AI for managing big data in IPD projects. Studies on developing digital cyber-secured platforms for smart supply-chain-integration in IPD projects
Procedural	Studies on synergistic effects of IPD and other emerging tools, techniques, and practices. For instance studies about IPD, Lean, and I4.0 or IPD, BIM, DfMA, and automation/robotics. Studies on automatic supply-chain-management procedure for IPD projects
Legal/Contractual	Studies on improving legislative norms and contractual standards for proper implementation of IPD in various types of construction projects, particularly for off-site, prefabricated, green, and sustainable construction.
Commercial	Studies on the application of block-chain for improving commercial and financial aspects of IPD project. Studies on the most suitable financial investment methods for IPD projects (i.e., front-end investments, etc.).
Cultural/behavioral	Studies on recent cultural shift in the construction industry, and the impact of IPD on project success post pandemic. Studies on the impacts of IPD on social sustainability.
Structural	Studies on longitudinal integration among IPD project participants and the impact of IPD implementation on knowledge transfer within teams, cross organizations, and across projects.

5.12 Methodological limitations

This review is limited to the English literature only and articles published after 2007. There is a lack of empirical studies on real-IPD performance in the literature, as there is not enough projects that are completed under this relational delivery method. A review and synthesise of more empirical studies could help decision makers and policy providers to be informed about structuring organizations, contracts, and operational systems required for successful IPD projects.

CHAPTER 6 ARTICLE 3: THE NEW-NORMAL CHALLENGES AND IPD SOLUTIONS: A CANADIAN CASE STUDY

Chapter Information: An article based on this chapter has been published since 25 May 2022, as per the following reference:

Rankohi, S., Bourgault, M. and Iordanova, I. (2022), "The new-normal challenges and IPD solutions: a Canadian case study", Built Environment Project and Asset Management, Vol. ahead-of-print No. ahead-of-print. https://doi.org/10.1108/BEPAM-2021-12-15

Abstract

Purpose: According to the construction literature, the number of projects applying integrated project delivery (IPD) principles is expected to increase in the new-normal era. However, given that the pandemic is not yet fully over, accurate and measurable data is not yet available. Also, there is a lack of empirical studies that could provide guidelines as to the application of IPD principles at the various stages of construction projects. Thus, the goal of this paper is to address this knowledge gap through case studies.

Method: This paper follows a multi-step research methodology, namely, a literature review, case study, and focus group discussions in the context of Canadian construction projects.

Findings: Based on the conducted literature review and focus group discussions, we identified: (1) new challenges in the various stages of the construction projects' lifecycle, (2) their related proximity aspects (technological, organizational, geographical, and cognitive), and (3) IPD principles that can address the identified challenges within their associated proximities. The results show that IPD relational principles can improve a project's organizational and cognitive proximities, while IPD digital integrative principles can enhance a project's geographical and technological proximities.

Originality/Value: This study contributes to the theoretical checklists of challenges that the construction industry has experienced since the beginning of the pandemic, and to the practical guidelines of implementation of IPD principles to meet these challenges. The conducted case studies are timely and relevant, and their results provide new insights for key project stakeholders into the application of IPD to tackle new-normal challenges based on their proximity perspectives.

Keywords: New normal, Construction, Integrated project delivery, IPD, Proximity.

6.1 Introduction

The COVID-19 pandemic marked the years 2020-2021 with one of the greatest crises of the past several decades, took many lives, and pushed entire societies into isolation (Alraouf, 2021). The year 2022 is also faced with huge uncertainties, with the escalating war between Russia and Ukraine. The term "New Normal" has become a buzzword to define the anticipated impacts of these crises on human lives across the world (Alraouf, 2021). The catastrophe has been a catalyst for positive changes (Anderson et al., 2021), and people across the globe have accepted these changes as the new normal. The new normal has affected the construction industry as well and created new challenges at various stages of projects (Ebert and Travernier, 2021). Many of these challenges relate to the distance or closeness between various elements of the supply chain (Dallasega et al., 2018). For instance, interruptions in the supply chain during the pandemic can be related to the geographical proximity between manufacturing plants and construction sites. Recently, scholars studied the application of alternative construction tools and techniques to meet the new-normal challenges. Modular and off-site construction (Alsharef et al., 2021), relational delivery methods, such as integrated project delivery (IPD) (Assaad and El-Adaway, 2021), automated construction techniques (Magableh, 2021), smart technologies such as artificial intelligence (AI) and robotics (Ganesh, 2021; Sarkis et al., 2020) are examples of emerging solutions that can enhance various proximity aspects in projects. Proximity refers to distance. Based on the theory of proximity (Dallasega et al., 2018), it is a compound concept, which comprises more than just physical distance between two objects. It can include cognitive, cultural, organizational, social, and technological aspects. Integration enhances closeness and collaboration (Franz et al., 2016), thus improves proximity. According to Assaad and El-adaway (2021), the application of integrative project delivery methods, such as IPD, is expected to increase in the post-pandemic era. This discussion and similar studies have remained at the theoretical level and are not supported by empirical evidence. To the best of the authors' knowledge, no study has yet investigated how IPD integrating principles can address the "new-normal" challenges by enhancing closeness between various elements of construction projects. This could in part be because the pandemic is not yet fully over, and thus, accurate and measurable empirical data is not available at this time. Moreover, IPD is a recently developed delivery method, and the road to its successful application is still under construction. There is a lack of case studies that could provide practical guidelines for the successful implementation of IPD to meet the new-normal challenges in construction projects. This research aims to address this gap and increase the fundamental understanding of the implications of IPD in construction projects. The IPD principles that could be helpful to the construction industry in this new-normal era are discussed based on the four aspects of proximity: technological, organizational, geographical, and cognitive. The research questions are as follows:

1. What are the “New-Normal” challenges in the various stages of construction projects?
2. How can IPD principles address some of these challenges?

6.2 Methodology

To answer these research questions, a multi-step research method, consisting of a literature review, case study observations, and focus group discussions, was conducted. Figure 1 illustrates this study’s methodological process.

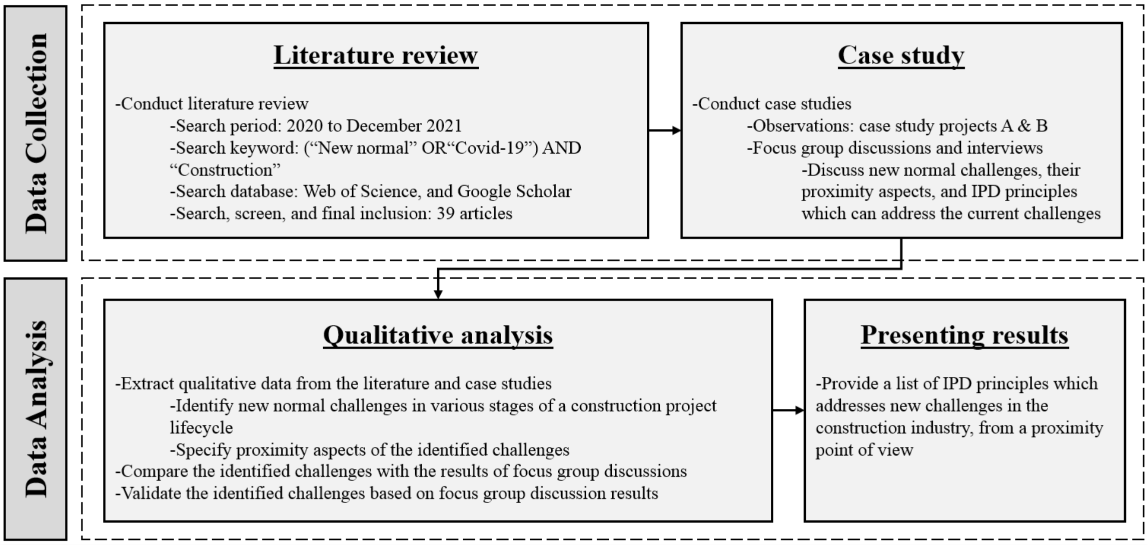


Figure 6.1 Methodology process of this study

In the data collection stage, first, a literature review was conducted to identify the new-normal challenges that affect the pre-construction, construction, and post-construction phases of a typical construction project. Considering the ever-evolving reality of COVID-19 and the immediate needs of policy makers to synthesize evidence and prepare guidelines for the public, we conducted a rapid review as devised by Brooks et al., (2020). A rapid review is “*A type of knowledge synthesis in* *which systematic review processes are accelerated and methods are streamlined to complete the review in a shortened timeframe"* (Brooks et al., 2020). Of the 2736 papers found, 39 were included in this review. The characteristics of the studies that met our inclusion criteria are presented in Figure 1. Following the literature review, we conducted case-studies and organized focus group discussions. Based on the review results, we developed a questionnaire and presented it in focus group discussions, since a questionnaire survey provides a valid, reliable, and rapid source of information with minimal resource requirements (Brooks et al., 2020). The owners, design professionals, general contractors, sub-contractors, and suppliers were interviewed. In the data analysis stage, we compared case studies' data with the identified challenges from the literature to validate the results. Finally, we conducted a qualitative analysis of the focus group discussions, case-studies, and interviews data, in order to identify the impacts of IPD principles.

6.3 Literature Review

In this section, first the construction literature is reviewed to extract the new-normal challenges in the various stages of a project lifecycle. Next, the extracted challenges are categorized based on their proximity aspects.

6.4 Project lifecycle

The identified issues are categorized based on the three stages of construction projects (Jaber et al., 2013): pre-construction, construction, and post-construction. *Pre-construction* consists of the initiation and planning phases. The initiation phase includes estimation, tendering, contracting, feasibility studies, and initial scheduling. The planning phase consists of defining the project scope, identifying resources, risks, developing a detailed budget, detailed design, and final scheduling. *Construction* or the performing phase refers to the execution of the plan, controlling and monitoring, carrying out project tasks, accomplishing project objectives, and delivering project scopes. *Post-construction* or the closing phase refers to the termination of the project, conducting project evaluations, and documenting lessons learned for future projects (Clement and Gido, 2012).

6.4.1 Pre-construction

The impacts of the pandemic on the pre-construction phase in terms of interruption and adjustment of initial schedules, estimation, and feasibility studies, were discussed by scholars (Gamil and Alhagar, 2020; Majumder and Biswas, 2020). The extreme price fluctuations, shortage of raw materials, and construction supply-chain interruptions make the initiation phase more complex than before.

Contracting strategies: scholars discussed contracting strategies during the pandemic. According to the literature, relational contracting methods are more flexible in addressing design alterations, material selection, and scope of work modifications throughout the project life cycle (Majumder and Biswas, 2020). The number of IPD applications is expected to increase in the future (Assaad and El-adaway, 2021). IPD allows project participants (owners, architects, engineers, contractors, subcontractors, and suppliers) to work together as a team, and collaborate from the early stages of the project to reduce unnecessary delays, change orders, and budget overruns. During the pandemic, IPD partners are incentivized to come to an agreement on how to proceed going forward, rather than hiding in their silos and relying on contract provisions as solutions (Assaad and El-Adaway, 2021).

Payment methods: studies focused on more flexible approaches during the pandemic. For instance, the cost-plus method was discussed as a flexible approach for both owners and contractors (Assaad and El-Adaway, 2021). From the owners' perspectives, cost-plus contracts, which establish a guaranteed maximum price, address their concerns related to the contractor's effort to augment costs, and provide some financial certainty that the project will stay on the target budget. This payment method also protects contractors from cost augmentation (i.e., for materials, tools, equipment, and labor), as long as the contract total price does not exceed the guaranteed maximum price (Assaad and El-Adaway, 2021).

Legal issues: researchers studied thorny legal issues and regulative challenges that the construction industry is facing during the pandemic (Kabiru and Yahaya, 2020; Rospigliosi et al., 2020; Sierra, 2021). The pandemic created project cost overruns and schedule fluctuations, which resulted in unforeseen changes to the original scopes of contracts (Aladag et al., 2021; Al Amri and Marey-Pérez, 2020). In this context, several studies focused on enforcing force-majeure clauses in the contract, to protect projects from the inevitability, unpredictability, and uncontrollability of

COVID-19 outbreaks (Zin et al., 2021; Manurung and Heliany, 2020; Rospigliosi et al., 2020; Aladag et al., 2021).

Risk mitigation strategies: researchers studied new risk assessment strategies in the initiation phase. The pandemic created inevitable new risks for construction projects, which must be considered in feasibility studies, such as the risk of the spread of the virus, financial implications, labor shortages, site closures, and supply chain disruptions (Majumder and Biswas, 2020; Kawmudi et al., 2020). Wang et al. (2020), found that people, material, construction machineries, construction techniques, and social/political COVID-19 prevention measures were the key risk factors during the pandemic. Casady and Baxter (2020), mentioned that many public projects were severely affected by the pandemic, due to a lack of risk management consideration of force majeure.

Design strategies: the literature discussed design strategies, tools, and specifications, which address the new-normal requirements. The pandemic crisis motivated designers to consider innovative and emerging design strategies, such as integrated design (ID), design-for-manufacturing-and-assembly (DfMA), and lean-led design (Awada et al., 2021; Chen et al., 2021). These strategies are based on the application of integration principles to increase project value and reduce wastes. Regarding design tools, the literature discussed the application of building information modeling (BIM) technologies to support design and construction phases and address rapid construction requirements (Chen et al., 2020; Chen et al., 2021). In terms of design specifications, many researchers focused on reconsideration in the design and operation of buildings according to the context of COVID-19, which emphasized social distancing, safety considerations, and reducing health risks in buildings (Awada et al., 2021; Chen et al., 2020; Fang et al., 2020; Cheshmehzangi, 2021, Stiles et al., 2020).

6.4.2 Construction

The construction phase consists of fabrication, delivery, on-site construction, off-site construction and on-site assembly tasks. In this context, the literature discussed topics such as supply-chain-interruptions, schedule delays, cost overruns, safety, construction strategies, and site progress monitoring.

Supply-chain interruptions**:** shortages of material, labor, and equipment caused a significant impact on the financial status of construction projects during the pandemic, and resulted in project delays, cost overruns, and reduced productivity (Quezon and Ibanez, 2021; Alsharef et al., 2021). As a result, stakeholders had to deal with the difficulties of obtaining new sources of funding and material for their projects (Anwar et al., 2020). In such a context, many construction projects had to be built with resources and workers from neighboring regions (Manurung and Heliany, 2020).

Schedule delays: several authors discussed the suspension of projects and schedule delays, as the impacts of the pandemic on construction performance (Kabiru and Yahaya, 2020; Majumder and Biswas, 2020; Gamil and Alhagar, 2020; Ogunnusi et al., 2020). Other studied types of delay included payment delays to contractors, length of modifications and approval delays, and material supply delays (Jallow et al., 2020; Chaisaard and Ngowtanasuwan, 2020; Majumder and Biswas, 2020).

Cost overruns: many studies focused on cost overruns. The pandemic caused extreme price fluctuations and led to additional construction costs due to sudden shutdowns and subsequent rework at resumption of construction activities (Ebekozien and Aigbavboa, 2021; Sierra, 2021; Wang et al., 2021; Alsharef et al., 2021; Majumder and Biswas, 2020; Manurung and Heliany, 2020; Mansoori et al., 2021).

Safety: several studies discussed safety concerns for site workers and studied how to maintain health, safety, and social distancing onsite (Stiles et al., 2020; Pasco et al., 2020; Sierra, 2021; Afkhamiaghd and Elwakil, 2020; Koh, 2020; Nasvik, 2020; Araya, 2021). The impact of health and safety guidelines on the construction activities was studied (Ezeokoli et al., 2020; Kawmudi et al., 2020; Majumder and Biswas, 2020), and researchers found that compliance with these guidelines (i.e., wearing personal protective equipment) limits construction activities onsite and affects construction quality and speed (Ebekozien and Aigbavboa, 2021; Amoah and Simpeh, 2020).

Construction strategies: regarding construction methods, a few studies discussed off-site construction (OSC) and prefabrication methods as possible solutions to challenges related to the speed of the construction work (Afkhamiaghd and Elwakil, 2020; Majumder and Biswas, 2020) and shortage of labour (Chen et al., 2020; Chen et al., 2021; Pasco et al., 2020).

Progress monitoring: to address challenges related to construction site monitoring, the literature discussed the use of emerging tools and techniques, such as an unmanned aerial vehicle (UAV) for data collection, analysis tools, and digital and smart platforms (Chen et al., 2020; Chen et al., 2021).

6.4.3 Post-construction

The new normal affects the termination, operation, and maintenance stages of construction projects. The literature lists several challenges in the operation and maintenance phases, namely organizational barriers, lack of proper logistics services, delays in documentation, obligatory telework, business transactions conducted online, and reduction of number of employees (Raoufi and Fayek, 2020; Lam et al., 2021). Another challenge found in the literature relates to preventive policies, and new operational and maintenance standards issued by governments in response to the pandemic. According to Kassim and Ismail (2020), several countries issued traffic control measures that led to the suspension of operational activities. This made the maintenance of construction projects more complex (Coppola and De Fabiis, 2021). Decreasing traffic flow reduced the return on investment and operational incomes from highways and caused severe challenges in the maintenance of these infrastructure projects (Cruz and Sarmento, 2021).

6.5 Proximity aspects of the identified challenges

Proximity is a multi-faceted concept, and it is considered as a construct involving technological, organizational, geographical, and cognitive closeness (Dallasega et al., 2018). According to Oerlemans et al., (2005), the distance between two or more entities is a major determinant of inter-organizational relations, knowledge transfer, innovation, cooperation, and collaboration. Technological proximity refers to an actor’s technological capabilities and competencies with regards to tools, technologies, devices, and processes to balance between inputs and outputs (process technology) and/or to develop new products or services (product technology) (Dallasega et al., 2018). Organizational proximity refers to project stakeholders whose interactions are integrated and facilitated by explicit or implicit behavioral rules and procedures, and who share the same system of representations, or set of philosophies (Dallasega et al., 2018). Geographical proximity refers to physical, geographical, environmental, territorial, spatial, or local proximities (Dallasega et al., 2018). Cognitive proximity refers to similarities in the way actors observe, interpret, comprehend and evaluate the environment (Dallasega et al., 2018). Table 1 identifies the proximity aspects associated with extracted challenges from the literature.

Table 6.1 The new normal challenges identified in the literature and their associated proximities

Project phase	*New normal challenges*	*Proximity*
Pre-construction	*Cost estimation concerns due to extreme price fluctuations*	*Cognitive, Geographical*
	Risk assessment difficulties due to uncertainties	*Organizational, Technological*
	Feasibility studies difficulties due to lack of information	*Cognitive, Technological*
	Silo effects due to linear contracting strategies	*Organizational*
	Rigid payment methods	*Organizational*
	Design changes due to the shortage of material	*Cognitive, Technological*
	Long approval process, and schedule delays	*Cognitive, Organizational*
	Reworks due to design uncertainties	*Cognitive, Technological*
	Lack of a proper digital platform for design collaborations	*Technological*
	New design requirements (added to the original scope) to address health and social distancing concerns	*Cognitive, Geographical*
Construction	*Construction supply-chain disruptions*	*Organizational, Geographical, Cognitive, Technological*
	Long construction process due to COVID restrictions	*Cognitive, Geographical*
	Shortage of raw construction material	*Geographical*
	Shortage of construction labor	*Geographical*
	Shortage of pandemic prevention material in plants	*Geographical*
	Shortage of pandemic prevention material on sites	*Geographical*
	Site closure/inaccessibility due to virus outbreak	*Geographical*
Post-construction	*Project termination date delays*	*Organizational, Geographical, Cognitive, Technological*
	Project ultimate cost overruns	*Organizational, Geographical, Cognitive, Technological*
	Legal issues due to the breach of contract terms and conditions	*Organizational, Geographical, Cognitive, Technological*
	Clients' low satisfaction due to reduction of project quality	*Organizational, Geographical, Cognitive, Technological*

6.6 Case Studies

To verify with practitioners the challenges we identified in the literature, we conducted a case study on two construction projects. These cases have a similar regional context as both are located in Canada. However, they were different in terms of stakeholder firms, construction methods (on-site versus off-site), and project type (residential versus industrial). We conducted interviews with the owners, design professionals (i.e., architects, structural and mechanical engineers, etc.), general contractors, sub-contractors, and suppliers. The experts selected for interviews and focus group discussions represented intermediate to senior-level construction industry practitioners in Canada. Experts with between seven and fifteen years of successful experience in the construction industry were selected, with expertise in various forms of contracts and project delivery methods including IPD, and familiarity with digital information technologies such as BIM. Their awareness of IPD, and other emerging construction technologies and techniques, attests to the reliability of their responses within the framework of meeting the new normal challenges based on IPD adoption in construction projects (Evans et al., 2021). The interviews were recorded, transcribed, and coded by the first author to understand the evolution of projects before and after the beginning of the pandemic. In the interview phase, participants shared their ideas about the strategic challenges they faced in various phases of the projects during the past two years. Then, IPD and its principles were addressed in focus groups discussions. As shown in Table 1, a list of the IPD integration principles and techniques (Barutha et. Al., 2021) was reviewed, followed by semi-structured interviews that averaged between 45 and 65 minutes. The following are some examples of questions: (a) what is your relationship with the project? (b) what are the new normal challenges in various phases of construction projects? and (c) how can IPD principles address some of these challenges?

6.7 Case A: a continuing care centre project in Western Canada

The first project is a multi-residential memory care facility, shown in Figure 2, located in Calgary, Alberta (AB). The project started in January 2020, around two months before the announcement of COVID-19 restrictions by the Government of Canada, on March 13, 2020. The owner awarded this project to a general contractor under the Design-Build (DB) delivery method. Before starting this project, the owner had built several similar senior-care projects in other provinces, with similar management, architectural, and design teams; under the same scope and definitions. This allows project teams to compare before and after pandemic specifications. The five-storey building was designed to have 182 independent units as well as a pool, theater, and other amenities. While the majority of the project was designed to be built on site, several prefabricated and modular units were also added to the scope of the work, in order to reduce project costs and construction lead time during the pandemic.

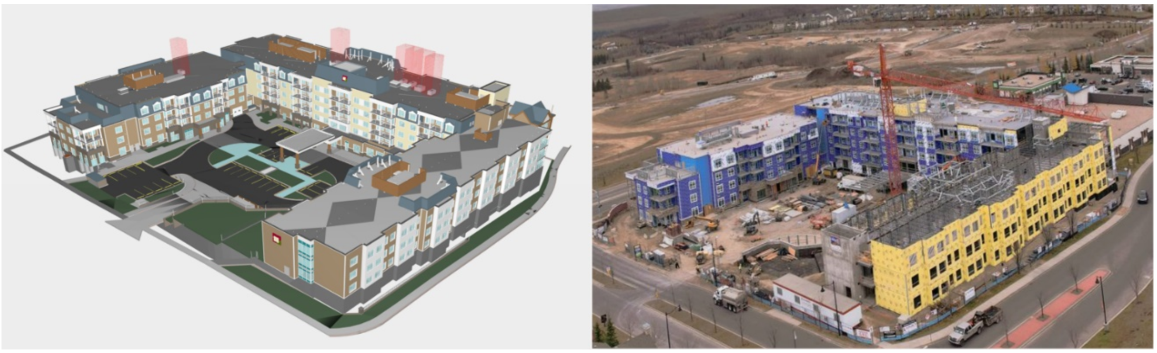


Figure 6.2 Case study A, a senior-care project located in AB, Canada (www.canam-construction.com)

To study this project, five focus group discussions were conducted and twenty people from various stakeholder teams (2 architects, 3 engineers, 2 senior directors, 3 project managers, 2 drafters, 3 fabricators, 3 site supervisors, and 2 BIM coordinators) were interviewed. The main discussion in the focus groups pertained to the participants' ideas on the impacts of the new normal on the delivery of construction projects. Most of the participants agreed that relational contracting strategies such as IPD, are more suitable for achieving project goals in the new normal era.

> “(…) *in the past, we used to have our meetings in-person, mainly between two or three principle parties. Since the beginning of the pandemic, we had no choice but to switch to online platforms for conducting the majority of our meetings. In these virtual meetings, not only principle stakeholders participated, but also all interdisciplinary teams could get together underneath one virtual roof. This allowed us to have a deep coordination between various disciplines who could sit down and review the architectural systems, structural systems, and MEP systems together. This virtual collaboration helped to shift the project linear structure into a more circular process, developing a synergistic relationship between traditionally-siloed stakeholders, and improving integration throughout the project supply-chain (...)*”, reported a senior director - case study A.

Following these discussions, a list of IPD principles and techniques was given to study participants, who were then asked to discuss which principles they used before and after the pandemic. The results show that the number of IPD principles applied in the project have increased, and that stakeholders have collaborated more interactively since the beginning of the pandemic. While the results of the focus group discussions confirmed the extracted new-normal challenges from the literature review, they also shed light on new opportunities, such as diversity and cultural shift in the construction industry.

> *“(...) since the pandemic started, our office employees were advised to work from home. The ability to work remotely helped us to save the travel time during the day, and spent*

> *extra hours on the projects. While in the beginning the new working-from-home environment was difficult for certain employees, I believe it helped others to create a work-life balance in the daily schedule. This can explain why the number of newly-hired "female" engineers and project managers in our company has increased since 2021. In the new-normal era, more diversity and inclusion can be achieved, (...)",* stated a structural engineer - case study A.

> *"(...) lately our teams became more open-minded and flexible in accepting the changes, and adapting themselves to new practices, new technologies, and new ways of doing things. Before the pandemic, team members were more change-resistant. (...) The pandemic created a "cultural change" in stakeholders' behaviors from rigidity towards more flexibility. (...) the industry was already moving towards a digital transformation even before pandemic. However, it was moving very slowly. I believe the COVID-19 crisis accelerated this process (...)",* said a project manager - case study A.

6.8 Case B: an industrial prefabricated project in Eastern Canada

Case study B is an industrial warehouse facility, shown in Figure 3, located in Montreal, Quebec (QC). Following the huge demand of ordering groceries online during the pandemic, the second largest food retailer in Canada signed a contract for this project in July, 2020. The center serves as a distribution facility to process online orders autonomously for Eastern Canada deliveries. This automated distribution center is designed for direct home delivery of groceries. The warehouse's automated system was designed by a British firm from the U.K., while the rest of the project was designed by Canadian-based companies. The design and construction of this project required extensive coordination between the electrical, mechanical, and sprinkler systems, to align with the special shelving systems, robotics, and digital platforms (www.gkc.ca/portfolio/voila_pc/). This was a major challenge during the pandemic.

The project was awarded under an alternative delivery method, which is a combination of Construction Management (CM), Design-Build (DB), and IPD methods. The general contractor also contracted separately with local suppliers and fabricators. Sobeys warehouse distribution center was mostly constructed off-site. The prefabricated wall panels were delivered and installed onsite. The construction of the 306,000 ft^2 innovative and fully robotized distribution center, in which IPD principles were applied throughout the project life cycle, was completed in 16 weeks. The urgency to respond to the huge demand of online grocery shopping during the pandemic made the project schedule significantly tight. From the initial planning phase, all stakeholders including the general contractor and suppliers, got together and participated in virtual "big room" meetings.

The early involvement of contractors and suppliers in the initiation and design phases significantly reduced the number of mistakes and reworks.

> *"(...) since day one, we organized big video meetings with all parties involved, the engineers, architects, suppliers, main contractors (...). In the beginning, some people were questioning this approach, but as we progressed, this level of integration resolved many unforeseen issues (...). The suppliers helped the architects and engineers to choose the right material, optimize their design, and even estimate the time and logistics required for the construction material (...)",* declared a senior director - case study B.

For this project, several design, management, and construction techniques were used to address the challenges caused by the pandemic and meet the project's tight budget and schedule. The design professional chose the design-for-manufacturing-and-assembly (DfMA) approach for this project. Throughout the project's life cycle and all stages of the supply-chain, various digital collaborative technologies were used by all project stakeholders. The application of digital technologies such as Smartsheet, BIM, and other similar systems for design, fabrication, construction, and assembly, made off-site and on-site collaboration more efficient. During the design phase, teams used interactive blueprint applications, such as Bluebeam and PlanGrid, which provided a collaborative way to review, share, and annotate information. Blueprints were synched into the cloud to facilitate real-time communication and knowledge transformation between various onsite and off-site actors. At the fabrication stage, a web-based ERP system, which granted access to real-time information about the availability of materials throughout the supply chain, was used by design and engineering teams. This system enabled users to access bi-directional information flow to support decision making on off-site and on-site activities. The 5D (3D + schedule + cost) BIM model, which was linked to real-time extracted information from the site as-built activities, provided a Digital Twin for the management team in order to track the project progress in real-time.

To study this project, four focus group discussions were conducted and twenty five people from various stakeholder sides (3 architects, 4 engineers, 2 senior directors, 4 project managers, 3 drafters, 3 fabricators, 3 site supervisors, and 3 BIM/digital coordinators) were interviewed. In the focus groups discussions, participants were asked about their ideas on the challenges of the new normal they faced during this project. Then, the IPD method was discussed, its principles were identified, and participants were asked to specify which IPD principles were applied in this project. To understand the impact of the new normal, we asked the participants to compare this project with similar construction projects that had been delivered before the pandemic.

Figure 6.3 Case study B, Sobeys distribution center in QC, Canada (www.canam-construction.com)

As shown in Table 2, both case study results confirm that since the beginning of the pandemic, more IPD principles and techniques are being used in projects.

Table 6.2 IPD integrating principles in Case studies A and B

Project phase	***IPD-ish principles***	***Case study A***		***Case study B***	
		before 2020	*after 2020*	*before 2020*	*after 2020*
Pre-construction	*Multi-party agreements*				✓
	Contract incentives		✓	✓	✓
	Joint risk assessment		✓		✓
	Multiparty management team		✓	✓	✓
	Cluster-based Management		✓		
	Mutual liability waiver				✓
	No dispute charter	✓	✓		✓
	Strategic alliance/partnership	✓	✓	✓	✓
	Team building/partnering	✓	✓	✓	✓
	Co-location		✓	✓	✓
	Constructability planning			✓	✓
	Front end planning				
	Pull-planning				✓
	Integrating technologies	✓	✓	✓	✓
	Charrette workshop		✓		✓
	Target value design				
	Value engineering		✓	✓	✓
	Six Sigma (Quality improvement process)			✓	✓
	Standardized design techniques	✓	✓		✓
Construction	*Pre-fabrication*			✓	✓
	Pre-assembly		✓	✓	✓
	Modular, Off-site construction			✓	✓
	Kaizen workshop		✓		✓
	Value stream mapping				✓
	Waste minimization techniques	✓	✓		✓
	Integrating technologies	✓	✓	✓	✓
Post-construction	*Digital project delivery*		✓		✓
	Lessons learned documentation		✓		
	Building material passport				✓

6.9 Results and Discussion

The results of the case studies and focus group discussions demonstrated that IPD principles can address new-normal challenges. These results are aligned with previous studies which claimed that emerging relational delivery methods (such as IPD) are expected to increase in the post-pandemic era (Alsharef et al., 2021; Assaad and El-Adaway, 2021). Meanwhile, our research shed more lights on how IPD can address new-normal challenges within various proximity boundaries. The findings of this study show that IPD organizational principles such as co-location and strategic alliancing, address supply-chain interruption challenges throughout the projects life-cycle and improve organizational and geographical proximities. IPD design principles such as target value design, integrated design, and Charrette workshops improve cognitive proximity, mostly during pre-construction and construction phases. Finally, IPD integrating technologies such as BIM and web-based tools improve technological proximity in all phases of construction projects. In the remaining of this section, IPD enablers of various proximity dimensions are further discussed.

6.10 IPD enablers of technological proximity

Digital technologies that can enhance a project stakeholder's capabilities in sharing knowledge and accessing information, contribute to improving a project's overall technological proximities. As discussed, many of the challenges highlighted in construction projects during the pandemic are due to the lack of proper tools and techniques to access information. Moreover, the absence of digital collaboration platforms that can allow actors to communicate and transfer knowledge efficiently, results in several challenges over the life cycle of the project. In this regard, IPD principles that focus on information access and knowledge sharing across various phases (vertical integration) and within different teams (horizontal integration), could improve performance metrics in the new-normal era. As shown in Figure 4, the identified IPD principles related to technological proximity in this study are: digital project delivery; integrating, web-based, and cloud-based technologies; building information modeling (BIM); and building material passport. These IPD principles increase collaboration through digital tools and processes, which enhances technological proximity by integrating multiple sources and actors in a centralized system. For instance, web-based and cloud-based collaboration technologies facilitate information exchange among upstream and downstream supply-chain partners, and reduce the risk of out-of-date, duplicated, and incorrect information (Dallasega et al., 2018).

6.11 IPD enablers of organizational proximity

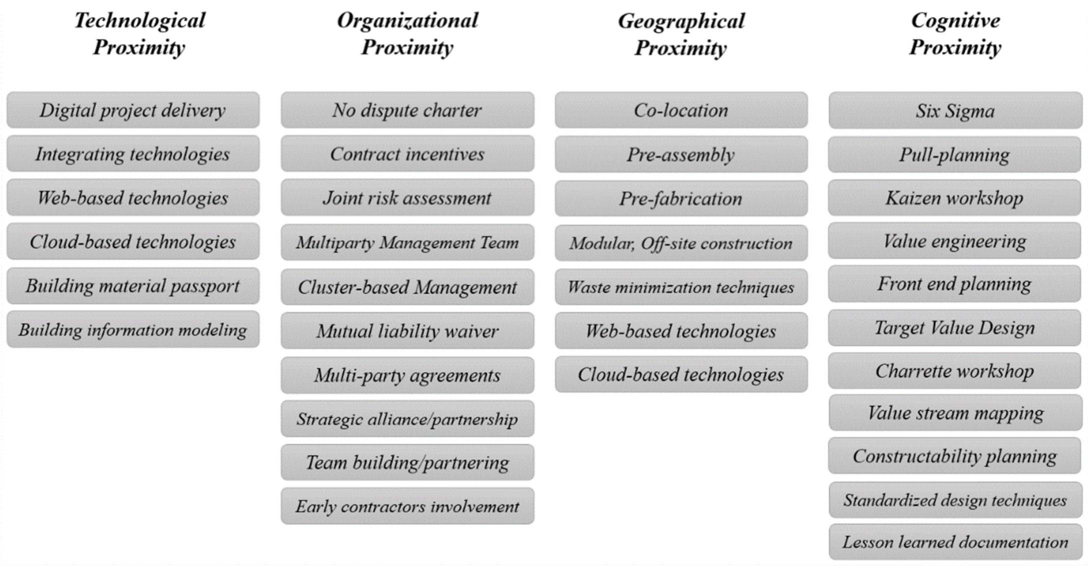
Organizational proximity in the supply-chain will be improved through cooperation and coordination, mainly between contractors and suppliers. Focus on team integration is one of the unique characteristics of IPD. IPD principles such as multiparty agreement, team partnership, strategic alliance, joint risk and rewards, and early involvement of contractors, emphasize on improving collaboration and cooperation between project stakeholders. As shown in Figure 4, IPD principles listed under organizational proximity, facilitate interactions between owners, architects, engineers, contractors, and suppliers in construction supply-chain networks. Based on the focus group discussions, the early involvement of stakeholders in key decision-making activities synchronizes designing, purchasing, ordering, fabrication, delivery, assembly, and construction processes. This synergy improves project performance metrics by harmonizing supply-chain activities between sub-contractors and supplier companies, fabrication plants, and construction sites.

6.12 IPD enablers of geographical proximity

As identified in the literature, during the pandemic, the shortage of labour and material led to construction managers looking for local resources, partners, and solutions. In this context, geographical proximity is required to address these new-normal challenges. As shown in Figure 4, IPD principles such as co-location (physically and virtually), pre-fabrication, off-site construction, web-based and cloud-based technologies can enhance geographical proximity and address some of the new-normal challenges in the industry. For instance, collaborative technologies and digital platforms increase geographical proximity, which leads to less logistics, storage, and coordination costs throughout the supply chain (Dallasega et al., 2018). Collaborative technologies and shared interfaces between various stakeholders make the approval processes quicker, more efficient, and more precise with less revision cycles required. Delays and re-works can be reduced by applying web services technologies, which allow project stakeholders to retrieve updated real-time supply chain information efficiently (Dallasega et al., 2018). Digital cloud-based platforms integrate teams and share material availability real-time data between suppliers, carriers, and contractors.

6.13 IPD enablers of cognitive proximity

Accessibility of updated, real-time, and high-quality information has an impact on how supply-chain actors perceive, interpret, understand and evaluate data (Dallasega et al., 2018). In order to support the execution of business processes and provide a common understanding of procedures, standardized routines and harmonized workflows are required. Studies have discussed vertical and horizontal integrations in construction supply-chain and have focused on cognitive proximity. In order to align cognitive understandings among teams, company operating systems should be linked to ensure information flow. Teams should be integrated throughout the project life cycle, and collaborative platforms should foster a mutual understanding of project data, to avoid mistakes, misinterpretations, and repetition. Processes such as design-for-manufacturing and assembly, integrated design, lean-led design, lean-led construction, and so on, emphasize on a high level of cognitive proximity (Dallasega et al., 2018). Collaborative technologies, such as BIM, harmonize knowledge transfer and allow transparent and real-time monitoring of supply-chain information, which enhance cognitive proximity. As shown in Figure 4, IPD principles such as Six Sigma, pull-planning, value engineering, and target value design, as identified in the group discussions, can address several current challenges by promoting cognitive proximities (Dallasega et al., 2018).



Technological Proximity	*Organizational Proximity*	*Geographical Proximity*	*Cognitive Proximity*
Digital project delivery	*No dispute charter*	*Co-location*	*Six Sigma*
Integrating technologies	*Contract incentives*	*Pre-assembly*	*Pull-planning*
Web-based technologies	*Joint risk assessment*	*Pre-fabrication*	*Kaizen workshop*
Cloud-based technologies	*Multiparty Management Team*	*Modular, Off-site construction*	*Value engineering*
Building material passport	*Cluster-based Management*	*Waste minimization techniques*	*Front end planning*
Building information modeling	*Mutual liability waiver*	*Web-based technologies*	*Target Value Design*
	Multi-party agreements	*Cloud-based technologies*	*Charrette workshop*
	Strategic alliance/partnership		*Value stream mapping*
	Team building/partnering		*Constructability planning*
	Early contractors involvement		*Standardized design techniques*
			Lesson learned documentation

Figure 6.4 Proximities and IPD principles

6.14 Conclusion

This study focused on identifying the challenges that arose in the construction industry as a result of the global pandemic, and investigating the impacts of IPD principles to address these challenges by improving various aspects of proximity in a project's life cycle.

First, we reviewed the construction literature published after March 13, 2020, to identify various challenges construction projects encountered during the new-normal era. Then, we classified these challenges into three projects stages: pre-construction, construction, and post-construction. In the pre-construction stage, the most cited challenges were cost estimation uncertainties, risk assessment difficulties, feasibility study concerns, silo-effect problems due to the linear structure of contracting strategies, and rigid financial payment methods. The design challenges were identified as: design changes due the shortage of material, delays due to long approval processes, reworks and duplications due to design uncertainties, and lack of a digital platform for design collaborations. In the construction stage, challenges were identified as: construction supply-chain disruptions; long construction process due to pandemic restrictions; shortages of material and labor; construction quality; and site closures due to outbreaks. The most cited post-construction challenges were project termination delays; cost overruns; legal issues due to breaches in contracts; clients' dissatisfaction due to the poor quality of projects; reduced return on investment; and less maintenance budget. Finally, the proximity aspects of each challenge were identified.

Next, we conducted two Canadian case studies, to collect data and validate the results of the review. Several focus group discussions and interviews were also conducted with projects stakeholders, in which IPD principles were discussed, and study participants were interviewed to list principles that could address the new-normal challenges. The participants filled out a questionnaire survey to specify IPD principles that had been applied in the case study projects before and after the pandemic. Finally, the concept of proximity was discussed, and IPD principles that contributed to enhancing four proximity aspects (technological, organizational, geographical, and cognitive) were identified. An analysis of the results shows that the number of IPD principles that have been applied in case study projects has increased since the beginning of the pandemic. The principles that are the most applied in the new-normal era relate to the technological (integrating technologies, digital platforms, cloud-based and web-based technologies) and relational aspects of IPD (multiparty alliance, cluster-based management, and shared risks/rewards). As identified, IPD principles such as co-location, strategic alliancing, offsite construction, and prefabrication techniques address supply-chain interruption challenges and improve organizational and geographical proximities. IPD design principles such as target value design, integrated design, and Charrette workshops improve cognitive proximity. Finally, IPD integrating technologies such as BIM and web-based tools improve technological proximity in construction projects.

6.15 Implication for research and practice

These findings could have several implications for accelerating the application of IPD in the construction sector:

For governments and policy-makers: a continuous support to construction companies interested in using IPD is recommended. Policy makers can collaborate with practitioners and researchers to develop guidelines, prepare standards, develop reforms, and improve the application of IPD 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 IPD in construction projects.

For researchers: IPD is not optimal in isolation. More studies on the synergetic combination of IPD with new technologies (IoT, 3D printing, nD BIM, digital cloud-based platforms, etc.), and emerging business models (spin-off company, virtually integrated, etc.) are required.

6.16 Future studies

We encourage further studies to investigate how various stakeholders (owners, contractors, suppliers, engineers, and architects) can benefit from IPD principles to meet the new-normal challenges. Also, more studies on the contractual aspects of IPD are required to understand how policy makers can modify IPD contracts to adapt to the new-normal situation. Given that we conducted a rapid review of an emerging and evolving field of study in the construction industry, we were only able to provide an initial understanding of the topic. Supplementary studies may interpret our findings in different and new perspectives.

6.17 Limitations

Given the qualitative nature of this study conducted at the current stage of the pandemic, the authors were unable to access full business case studies that can quantitatively evaluate the challenges the construction industry is facing in the new-normal era. The pandemic is still not completely finished, therefore accurate quantitative data is not available at this time (Assaad and El-Adaway, 2021). Current challenges have made it difficult for many companies to keep track of data during the pandemic. In the current situation, these challenges make data collection difficult and sometimes impossible.

CHAPTER 7 C-DFMA FRAMEWORK: A CONSTRUCTION-ORIENTED DFMA DEPLOYMENT FRAMEWORK

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, termed C-DfMA in this paper, 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 construction-oriented DfMA implementation challenges. To address these challenges a C-DfMA framework was then 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. The study provides insight into the challenges of implementing DfMA in the construction industry. The investigated challenges contribute to the theoretical and practise-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.

7.1 Introduction

Design for manufacture and assembly (DfMA), is a combination of two terms: design-for-manufacture (DfM) and design-for-assembly (DfA) (Lu et al., 2020). This approach, which is known as both a philosophy and methodology, has existed in the manufacturing industry for decades (Tan et al., 2020). In this method, products are designed based on maximizing amenability for downstream manufacturing and assembly (Gao et al., 2020). DfMA began during World War II (1939-1945), when Ford and Chrysler developed design principles in their weapon production procedures (Lu et al., 2020). In the late 1960s and early 1970s, formal exploration of DfMA began with the research efforts of Boothroyd and Dewhurst (Boothroyd, Dewhurst, and Knight, 1994) and has since then remarkably developed within the manufacturing industry (Lu et al., 2020).

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 (Wuni et al., 2021; Wasim et al., 2020). The Royal Institute of British Architects (RIBA) initiated the first studies about the application of DfMA in construction a decade ago. In 2013, 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 (Lu et al., 2020). Later in 2020, RIBA published a revised version of its Plan-of-Work, which provided an updated DfMA-based guideline for accomplishing construction projects (RIBA, 2020). In addition to conceptual development, some attempts have been made to develop DfMA methods in practise. 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 (Bryden Wood, 2017). In this regard, various countries have supported similar initiatives: Singapore in 2016 (Building and Construction Authority of Singapore's DfMA for BIM), the UK in 2018 (UK government's National Infrastructure and Construction Pipeline), and Italy in 2019 (the Italian public procurement process) (Alfieri et al., 2020).

The construction-oriented DfMA encompasses several central criteria, such as: technology rationalization, product and process integration, logistics optimization, and material-specifications (Tan et al., 2020). Gao et al., (2020) categorized various interpretations of DfMA in the construction literature into three groups: a philosophy which 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 (Lu et al., 2020).

Although studies on DfMA have gained attention in recent years, the number of studies in the literature is still limited. There is a dearth of knowledge regarding the challenges of implementing DfMA methods in construction. 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 seem to oppose the widespread application of DfMA (Lu et al., 2020). DfMA is a collaborative strategy that relies on integration. However, in construction projects, unsupportive organizational, contractual, and operational systems and procedures create fragmentation of stakeholders' responsibilities (Hall et al., 2022; Zhu et al., 2018), thus inhibiting the proper implementation of collaborative strategies, such as DfMA.

According to a study performed by Thomsen et al. (2009), the proper "stakeholders' integration" stems from three fundamental aspects: organizational structure, contractual guidelines, and operating systems and processes. *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. *Contractual framework* refers to the regulative guidelines which align the stakeholders' goals and objectives with the overall project's objectives, through framing compensation structures and addressing risk allocations among project participants. And finally, *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 (Darrington et al., 2009).

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 (Hall et al., 2022; Wuni et al., 2021; Malaeb and Hamzeh, 2021; Lu et al., 2020). 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 which improves organizational integration (Zhang et al., 2013; Azhar et al., 2014; Kasali et al., 2015; Koolwijk et al., 2018; Manata et al., 2021; Rankohi et al., 2022). 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. Previous studies have documented and recognized a scatter 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 which can address the challenges and facilitate the adoption of C-DfMA. The main goal of this study is to improve current C-DfMA theorization and application. The paper will address two objectives:

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

7.2 Methodology

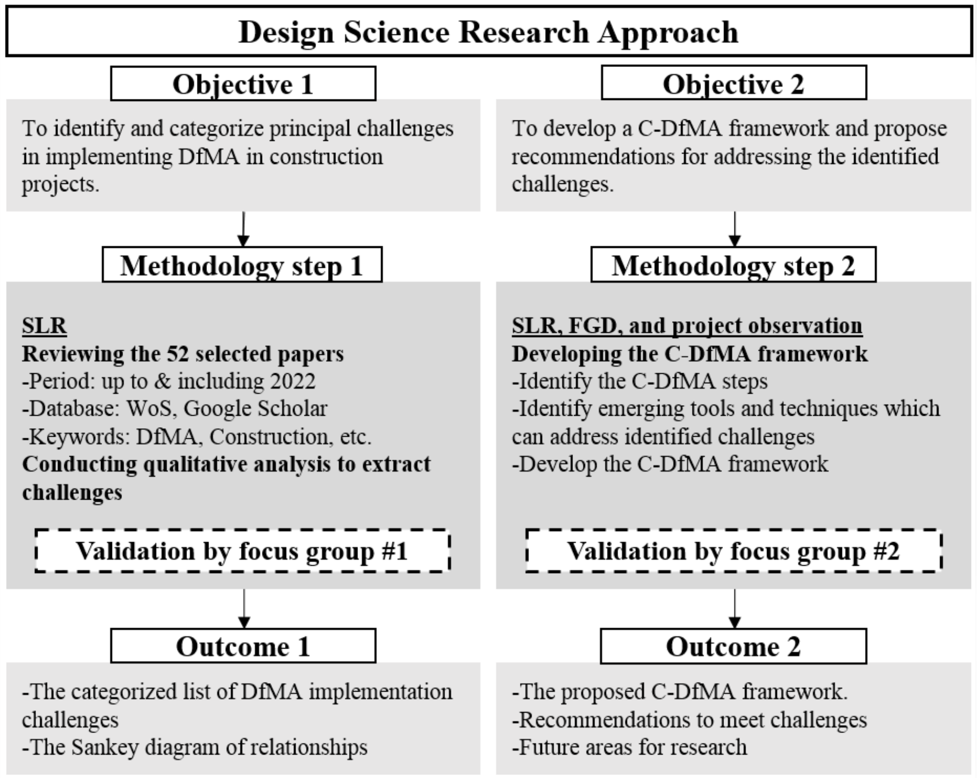
To develop knowledge and contribute to the body of theory and practice in this field, this study adopted an exploratory research approach for examining the current challenges of applying DfMA in construction and investigating and proposing alternate courses of action. To achieve this goal, we followed a design science research (DSR) approach, which is a multi-step research method, consisting of systematic literature reviews, focus group discussions, and case studies (Malaeb and Hamzeh, 2021). Deriving from the community of practice, DSR is an analytical and creative approach, which develops exploratory and instrumental research techniques to achieve practical desired outcomes (Schultz, 2017). 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 (Malaeb and Hamzeh, 2021). The DSR method involves people exploring, inducing, developing, and testing models around user-centred values, interests, challenges, and concerns (Malaeb and Hamzeh, 2021). 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 (Liu et al. 2017). According to Sun et al., (2020) each focus group consists of 5 to 25 experienced experts in the area of study. This method has been widely adopted for qualitative research (Sun et al., 2020; Hasan et al. 2019; Ma et al. 2020; Wang et al. 2020) 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 (Sun et al., 2020).

As shown in Table 1, two different focus groups (FDGs #1 and #2) were selected for this study, consisting of 10 and 14 participants respectively. Both groups were led by facilitators who encouraged participants to interact and contribute constructively. The goal of the study was explained at the FGD onset. During the discussion, participants were provided with the study results, and the results were validated through focus group discussions by the panel experts.

Table 7.1 Profile of focus groups' 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	5-15
Director	1	10-20	0	NA
Academia				
Professors	1	10-20	0	NA
Consultant				
Architect	2	10-20	2	5-10
Engineer	2	10-20	2	5-10
Contractor				
Site supervisor	0	NA	2	5-10
Project manager	1	10-20	2	5-10
Supplier				
Fabricator	3	10-20	3	5-10
SC manager	0	NA	1	5-10
Total	**10**	**10-20**	**14**	**5-20**

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



To identify and categorize principal challenges in implementing DfMA in construction projects.

To develop a C-DfMA framework and propose recommendations for addressing the identified challenges.

SLR
Reviewing the 52 selected papers
-Period: up to & including 2022
-Database: WoS, Google Scholar
-Keywords: DfMA, Construction, etc.
Conducting qualitative analysis to extract challenges

SLR, FGD, and project observation
Developing the C-DfMA framework
-Identify the C-DfMA steps
-Identify emerging tools and techniques which can address identified challenges
-Develop the C-DfMA framework

-The categorized list of DfMA implementation challenges
-The Sankey diagram of relationships

-The proposed C-DfMA framework.
-Recommendations to meet challenges
-Future areas for research

Figure 7.1 Stages of the DSR research approach for this study

7.2.1 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 (Kedir and Hall, 2021). The results of this SLR led to the extension of knowledge in the construction-oriented DfMA research domain. A detailed explanation about 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. Focus group #1's discussions were conducted for the following objectives: (1) validate the extracted challenges from the literature, (2) associate the identified challenges to the related stakeholders and phases, and (3) discuss and develop strategies to address them. The FGD process is non-linear, and several iterations were done to validate the results.

7.2.2 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 C-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 C-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 done to validate optimal and feasible solutions.

7.3 Challenges to the adoption of DfMA in construction

To formulate the preliminary list of challenges, a systematic literature review (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 which 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: (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: (1) lack of focus in the construction industry, and (2) only focus on DfMA generally. Using these criteria, we conducted the search in May 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 topic pertinent.

To extract the DfMA implementation challenges from the 52 selected articles, a qualitative content analysis, recommended by Oesterreich and Teuteberg (2016), 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 were 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 C-DfMA challenges, and their relationships to project phases/stakeholders.

7.3.1 Identified challenges

Similar to any evolving research topics in the construction industry, several scholars have discussed particular challenges pertaining to the implementation of DfMA methods. Wuni et al. (2021) discusses several challenges in applying design-for-excellence in industrialized construction, the most cited of which being: “limited relevant knowledge and practical experience.” Lu et al., (2020) 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 C-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 C-DfMA in construction projects (Gosling et al., 2016; Gao et al., 2019). The second most cited challenge identified by the literature relates to the lack of collaborative environment in the construction industry (Wuni et al., 2021; Gao et al., 2020; Zhu et al., 2018). In fact, early involvement of project stakeholders in design, open communication, collaboration, and information sharing are pre-requisites for the proper implementation of C-DfMA (Gao et al., 2019; Zhu et al., 2018). Non-involvement of project stakeholders during the design stage in projects with traditional delivery methods was found to inhibit effective application of C-DfMA (Zhu et al., 2018; Lu et al., 2020). The third most cited challenge concerns the lack of legislative frameworks of specified codes, guidelines, and standards for the implementation of C-DfMA methods (Abueisheh et al., 2020; Zhu et al., 2018). Literature shows that limited industry guidelines, codes, and standards in various countries invoke a deficiency of systematic design metrics, and inhibit the development of C-DfMA best practices (Wuni et al., 2021; Abueisheh et al., 2020; Gao et al., 2020; Che Ibrahim et al., 2020; Lu et al., 2020). In this context, some scholars discussed inadequate tools and lack of affordable technologies as challenges to the adoption of C-DfMA in construction projects (Lu et al. 2020; Wuni et al., 2021; Gao et al., 2020; Zhu et al., 2018). Due to the compounding effect of these constraints, project stakeholders do not have a common understanding of relevant C-DfMA principles in the industry (Lu et al., 2020). Some scholars identified “higher design costs” as compared to the cost of traditional methods as a barrier to the proper implementation of C-DfMA methods in construction projects (Abueisheh et al., 2020; Lu et al., 2020; Peltokorpi et al., 2018). The extra cost is linked to additional organizational investment needs, namely, required specialized labour and technical skills (Bogue, 2012; Lu et al., 2020), performance evaluation needs during the design and first-run prototypes (Gosling et al., 2016; Abueisheh et al., 2020), undeveloped market and limited competition among C-DfMA solutions (Lu et al., 2020; Bogue, 2012; Peltokorpi et al., 2018), and complex code compliance requirements (Abueisheh et al., 2020). Unattractiveness to clients due to the deep-rooted poor image of post-war prefabricated buildings, was also considered as a significant challenge to the implementation of C-DfMA (Lu et al., 2020; Gao et al., 2018).

The primary list of DfMA implementation challenges are 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 which 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.

Table 7.2 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	Liu et al. (2021)
	L4	Lack of clarity in terms of guarantees and insurance	Bao et al. (2021)
	L5	Lack of DfMA platforms which conform with the CCDC contracts	Favi et al. (2021)
	L6	Lack of clear scope of work, confusions, and duplications	Wuni et al. (2021)
	L7	Lack of references to several manufacturers in the contract	Li et al. (2021)
	L8	Lack of vertical, and horizontal integration between stakeholders	Gao et al. (2020)
	L9	***Lack of longitudinal integration, teams disband at project termination***	***FGD#1***
	L10	Lack of clear roles and responsibilities of stakeholders	Wuni et al. (2021)
	L11	Complex litigation and long negotiations between key stakeholders	Bank et al. (2018)
	L12	***Lack of agility and flexibility in the contract***	***FGD#1***
Technological	T1	Management of interfaces with subsystems	Said et al. (2017)
	T2	Difficulty in identifying appropriate DfMA tools/techniques in each phase	Bank et al. (2018)
	T3	Lack of coordination between phases and contractors	Vaz et al. (2021)
	T4	***Lack of capabilities to manage the module configuration process***	***FGD#1***
	T5	Lack of coordination and collaboration between stakeholders	Wasim et al (2022)
Procedural	P1	Need to evaluate performance at every design stage	Tan et al. (2020)
	P2	***Lack of innovation as product architecture is locked***	***FGD#1***
	P3	Management of assembly works and interface tolerances	Cruz et al. (2021)
	P4	Need for additional project planning and design efforts	Wuni et al. (2021)
	P5	Necessity of first-run prototypes	Gao et al. (2021)
	P6	Management of customer expectation in design	Chen et al. (2018)
Cultural	Cu1	Customer rejection due to poor image of industrialized construction	Gao et al. (2018)
	Cu2	Early commitment requirements and communication among stakeholders	Zhu et al. (2018)
	Cu3	***High criticality of the know-how that must be shared with other stakeholders***	***FGD#1***
	Cu4	Conflicting cultures between engineering and design teams	Wuni et al. (2018)
	Cu5	***Lack of trust and collaboration between buyers and their suppliers***	***FGD#1***
Commercial	Co1	Few market options available	Shang et al. (2020)

	Co2	Lack of competition among prefabricated and modular solutions	Wuni et al. (2021)
	Co3	***Increased organizational complexities and investment requirements***	***FGD#1***
Geographical	G1	Requires both trade and location-based division of procurement	Gao et al. (2020)
	G2	Complex code compliance and inspection process	Wasim et al (2022)
	G3	***Few local options available***	***FGD#1***
	G4	***Logistics and transportation management complexities***	***FGD#1***
	G5	Scarce availability of resources for component development	Bogue (2012)
Economic Financial	F1	Higher capital costs and investment requirement	Sun et al. (2020)
	F2	***Difficulty in financial management and lack of an efficient payment method***	***FGD#1***
	F3	Higher design costs than the traditional design methods	Lu et al. (2020)
Technical Cognitive	Tc1	***Specialized labour requirements***	***FGD#1***
	Tc2	Definition of standard details and connections	Tan et al. (2021)
	Tc3	Limited DfMA knowledge and experiences	Wuni et al. (2021)
	Tc4	Reduced performance in the first few installations due to learning curve	Bao et al. (2021)
	Tc5	Inability to exercise early design freeze	Gao et al. (2019)
	Tc6	Lack of awareness of DfMA benefits among owners/developers	Wuni et al. (2021)

7.3.2 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. As shown, the biggest volume of challenges occurred in the design, manufacturing, and contracting phases; however, DfMA challenges can arise in all of the 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.).

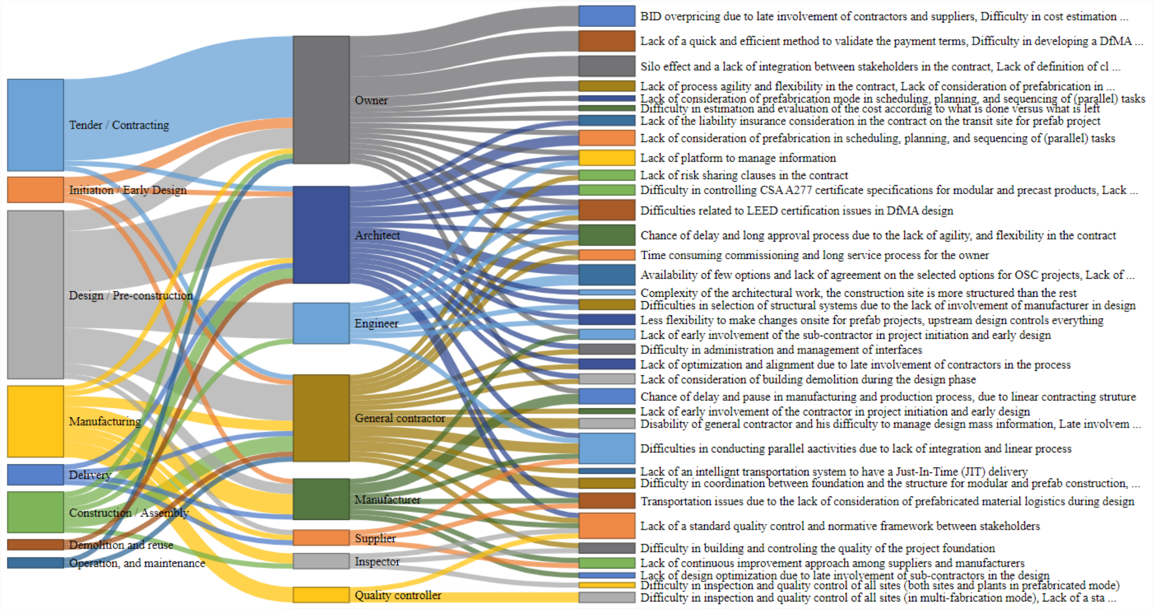


Figure 7.2 Relationship between challenges, stakeholders' roles, and project phases

7.4 Step 2: C-DfMA framework

This section presents the results of our qualitative data analysis and develops a conceptual framework for implementing DfMA in construction projects. In this regard, we introduce the term C-DfMA to the literature, a term that refers to a construction-oriented DfMA. Following the systematic literature review and focus group #1 discussion, we developed the initial C-DfMA framework based on the steps provided by the RIBA Plan of Work 2020. In the next stage, we verified the initial C-DfMA framework and RIBA steps in 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 are conducted under different delivery methods and business models. The research strategy relies on piloting, observation, interpretation, and data collection. The data was collected through observation and direct discussions with representatives of the different stakeholders involved within the projects.

Project A, a multi-residential facility in Gibson, British-Colombia, Canada. The project consists of a four-storey multi-residential building with a total area of 9,930.4 square metres (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, starting in December 2021 and terminating in May 2022; a very tight schedule, despite the shortage of labour, 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 labour, 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 C-DfMA 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 C-DfMA framework was found to be challenging in this project, as the project delivery method and business model were not supportive of the C-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 C-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 less fabrication errors occurred. The integrated teams adapted more quickly 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 metre (350,000 square foot) electric resistance welded (ERW) pipe facility is designed to produce hollow structural sections and standard pipes. The project began in November 2021 and is scheduled to open 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 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 labour, water accumulation on the job site made the site assembly very challenging. This project used a hybrid contracting model which combined a design-build method and integrated project delivery principles, also known as a type of IPD model. As with case A, to verify the C-DfMA framework on this project, first the general DfMA concept and challenges were explained to the project participants, and then the initial framework sequential steps were assessed for each project phase. Compared to case A, the implementation of the C-DfMA 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 decisions-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 material production processes in-house. 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 C-DfMA framework and enabled the project stakeholders to follow the framework steps efficiently. The application of the C-DfMA framework improved project performance metrics from the project's initiation phase to close-out and execution. The design was optimised, the fabrication and assembly time was reduced, the materials were delivered just-in-time, and site safety was improved significantly. Ultimately, the project completed ahead of the original schedule, and compared to project A, less change orders occurred during the project.

The verified C-DfMA 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 stage 5 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 C-DfMA. For instance, during the initiation phase, project objectives including the requirements for C-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 C-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 which enhance collaboration among project participants and improve supply-chain integration. During the verification stage of the two studied projects, it was found that the C-DfMA steps could only be implemented efficiently in projects that are 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 (Langston & Zhang 2021) 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 I4.0 technologies, which support the flow of information throughout the project, including Internet of Things (IoT), reality capture (RC) technologies, and smart logistics tracking applications. 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) (Lu et al., 2021). Real-time sharing of the site information enables just-in-time deliveries of factory produced sub-assemblies and efficient planning of the crane logistics (Wuni & Shen, 2020). Consequently, several quality control activities are considered in the framework, in which multidiscipline design models, manufactured parts, and assembled structures are checked for errors, collisions, and omissions as well as for quality assurance metrics.

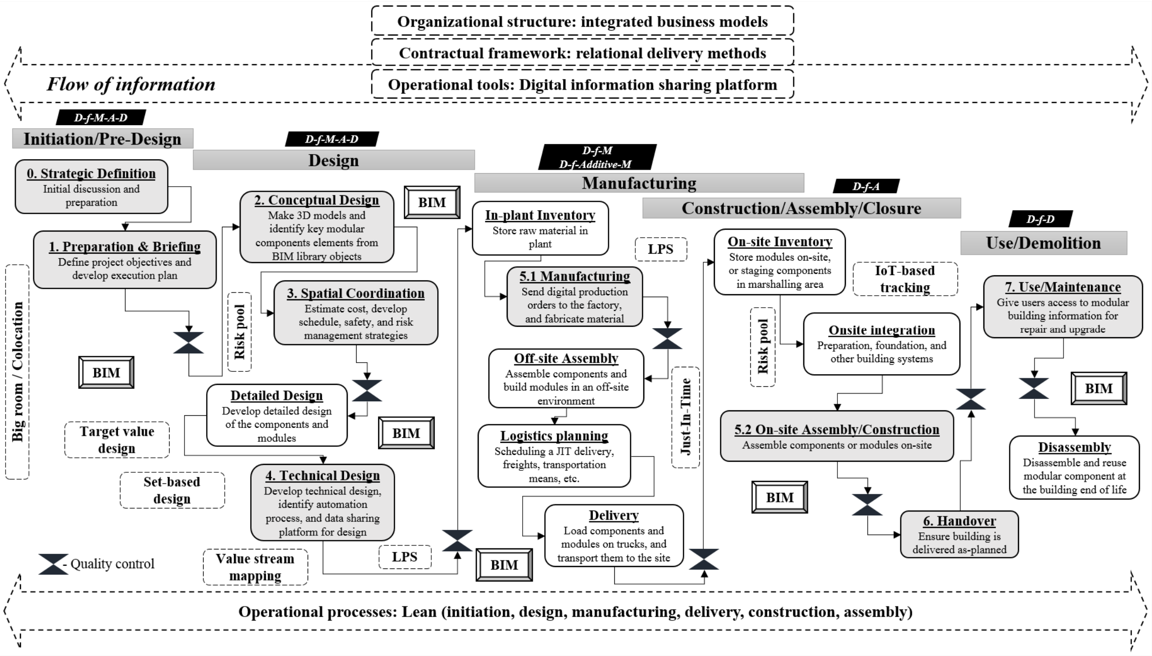


Figure 7.3 Flowchart of C-DfMA framework

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 C-DfMA framework in the studied projects, the framework was validated in the discussion with focus group #2, as explained in the methodology section.

7.5 Results and discussion

The results of this study indicate that most of the challenges to the full implementation of DfMA in construction projects are related to a lack of integration that is a result of applying unsupportive organizational structures, contractual frameworks, and operational systems. Conversely, integrated business models, relational project delivery methods, and collaborative operational systems can improve collaboration (Hall et al., 2022) and thus, enhance the implementation of collaborative strategies such as C-DfMA (Wuni et al., 2021). As shown in Table 3, the results show 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 C-DfMA by promoting the required collaborative working environment.

Table 7.3 Categories with which DfMA challenges are associated

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

7.5.1 Organizational structures

Organizational structures are influenced by both business models and project delivery methods, which are different yet related concepts (Hall et al., 2022; Davies et al., 2019). 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 (Baden-Fuller & Morgan, 2010; Davies et al., 2019). 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 task and scatter once the project is completed (Davies et al., 2019). Big project-based firms and organizations can have multiple delivery methods that can be deployed within their business model and broader organizational strategy (Davies et al., 2019). 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 (Hall et al., 2022). Deploying a relational delivery method under proper business models can result in repetitive project teams (Kamar et al., 2014), which can resolve challenges related to longitudinal fragmentation, sustainability, and circularity. This is aligned with the goal of the C-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 C-DfMA in construction projects. Three emerging integrated business models are suitable for this:

Vertical integration: in this model, firms are structured as integrated hierarchical firms, which control production architecture and processes in-house, by developing their own off-site factories (Hall et al. 2022). Nothing is outsourced in this model, and the C-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 and it is mostly applicable to modular housing projects with repeatable and flexible modules. The Swedish company BoKlok is a successful example of this model (Hall et al. 2022).

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 (Cao et al., 2021). These firms do not own the manufacturing technology, but through industry 4.0 supply chains principles, they can manufacture parts through periphery supply-chain partner suppliers (Hall et al. 2022). Compared to vertical integration, this model requires more time to develop new products. Project Frog is an example of this model (Hall et al. 2022).

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 (Hall et al. 2022). The DPR Construction and their spinoff factory Digital Building Components, is an example of this model (Hall et al. 2022).

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 (Hall et al. 2022). The achieved integrated supply-chain facilitates the proper implementation of the C-DfMA framework in construction projects.

7.5.2 Contractual frameworks

Project delivery methods frame contractual guidelines within projects, which define 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 (Assaad et al 2020), and this leads to construction projects encountering vertical, horizontal, and longitudinal fragmentations. This is why proper implementation of C-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 (Hall et al., 2022). In this context, relational project delivery methods that emphasize on 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 (Hall et al., 2022). Similar to DfMA, integrated project delivery (IPD) is known as both a philosophy and a method which enhance integration throughout the project life cycle (Alvez and Lichtig, 2020; Rankohi et al., 2022). In projects in which IPD acts as a philosophy, aka IPD-ish projects, collaboration is not required contractually, 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 (Mesa et al., 2016). While DfMA focuses on product/process integration, it needs to be accompanied with a contractual framework, such as IPD, which focuses on people integration.

7.5.3 Operational systems and processes

To apply C-DfMA strategies in construction projects efficiently, 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 (Cao et al., 2021). 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) (Abrishami and Martín-Durán, 2021). Lean operational systems focus on the definition of production systems that can deliver the project from initiation/design through to construction (Darrington et al., 2009). In fact, some emerging concepts in the construction industry, such as IPD and integrated business models, use lean as a foundation (Alves and Lichtig, 2020). 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 C-DfMA framework, the lean operational processes are concrete, observable, specific, and act as part of the body of the framework. On the other hand, Industry 4.0 (I4.0) technologies are tools which are required for the implementation of these lean processes. I4.0 technologies enable proximity and integration for construction supply chains (Dallasega et al., 2018). 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 (Cao et al., 2021). Therefore, an information-sharing platform for implementing the C-DfMA framework, should support both product and project level information management. Emerging I4.0 tools and technologies can be useful in deploying the C-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 (Elghaish et al., 2021). To further enhance the implementation of the C-DfMA framework in prefabricated projects, the I4.0-based information-sharing platforms could support various degrees of mass-customization (Cao et al., 2021).

7.6 Conclusion

7.6.1 Summary and contributions

This study presented insight into and a comprehensive review of the challenges, constraints, and problems of implementing construction-oriented DfMA. From the literature review and focus group discussions, 45 challenges were identified and categorized into 8 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 C-DfMA framework to address the identified challenges. We discussed opportunities for enhancing the implementation of C-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, and lean-based operational tools and digital technologies enable a suitable environment for the full implementation of the C-DfMA framework and addressing the identified challenges. The research conducted in this paper contributes to the body of knowledge and has important practical implications such as:

- Providing the existing challenges in the implementation of DfMA in the construction industry, and categorizing them;
- Investigating the relationships between identified challenges and project phases/stakeholders; and
- Developing a C-DfMA framework and exploring how synergy between DfMA and emerging business models, delivery methods, lean processes, and I4.0 tools and techniques can address the identified challenges.

Ultimately, this research should support the broader adoption of DfMA in construction projects.

7.6.2 Future areas of studies

This study revealed that C-DfMA cannot be implemented efficiently in isolation. Further study on the application of the C-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, 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:

7.6.2.1 Organizational structures

Integrated trust-based organizational structures: The results show that practitioners can use the proposed framework as a guide to plan their project-based solutions to build trust with future project partners. In fact, the implementation of the C-DfMA framework can enhance longitudinal integration. More studies are recommended on the impact of the proposed C-DfMA framework on long-term trust-building activities.

7.6.2.2 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. Also, several standard forms of IPD contracting are available in North America (i.e., CCDC-30 in Canada, and AIA C-191 and ConsensusDocs 300 in the U.S.). Further study is needed on the synergic impact of IPD and C-DfMA on enhancing off-site construction projects, in particular, on developing the optimal IPD contractual guidelines for reinforcing this synergic impact.

7.6.2.3 Operational systems and processes

Collaborative information sharing systems: There is an increasing need for a collaborative and integrative environment for the successful implementation of C-DfMA in construction projects (Bakhshi et al., 2022; Qi et al., 2021). Thus, more studies on collaborative information-sharing systems on multiple levels (project, organization, and industry) are required.

Technological adaptation: There is little empirical research in the literature on C-DfMA technological adaptation in the construction sector. Initial research on this topic focused on the combination of BIM, and cloud-based technologies with C-DfMA (Tan et al., 2020; Gbadamosi et al., 2019). More in-depth research and multiple case studies for the application of AI, data analytics, block-chain, and IoT technologies are required to improve C-DfMA adaptation in the industry.

Smart flexible supply chain: Recently, the construction industry has encountered severe uncertainties (i.e., Covid-19 crisis, war, etc.). In this context, supply-chain flexibility becomes vital (Hall et al., 2018). More studies on developing smart, dynamic, agile, integrated, and practice-oriented supply-chain are required to improve C-DfMA implementation strategies.

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

Design for robotics and additive manufacturing: Due to increasing labour 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 (Estakhrianhaghighi et al., 2020; Shi et al., 2021). However, current industry practices are not prepared for the full-scale application of these techniques. The integration of C-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 C-DfAM are required.

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 C-DfMA and emerging IoT-based tracking technologies for recycling material and developing smart-decision making tools for stakeholders are recommended.

7.6.3 Limitations of the study

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

- Identifying additional C-DfMA implementation strategies;
- Further developing and validating the C-DfMA framework within bigger focus group discussions; and
- Testing and applying the C-DfMA framework in other case study projects in different contexts (publicly funded, infrastructure, and complex projects).

CHAPTER 8 GENERAL DISCUSSION

The results of this research were presented in Chapter 3 through 6 regarding the specific topics that each Chapter addressed. As shown in Figure 7.1, Chapter 3 and 4 mostly focus on the conceptual aspects of IPD while Chapter 5 and 6, mostly address its practical aspects. This chapter provides an overall view of this thesis by summarizing these studies and linking the achieved results about IPD. The chapter also highlights the main contributions of this dissertation as to different areas of IPD research and practice. Furthermore, the limitations of this dissertation are discussed, and recommendations for future studies are presented.

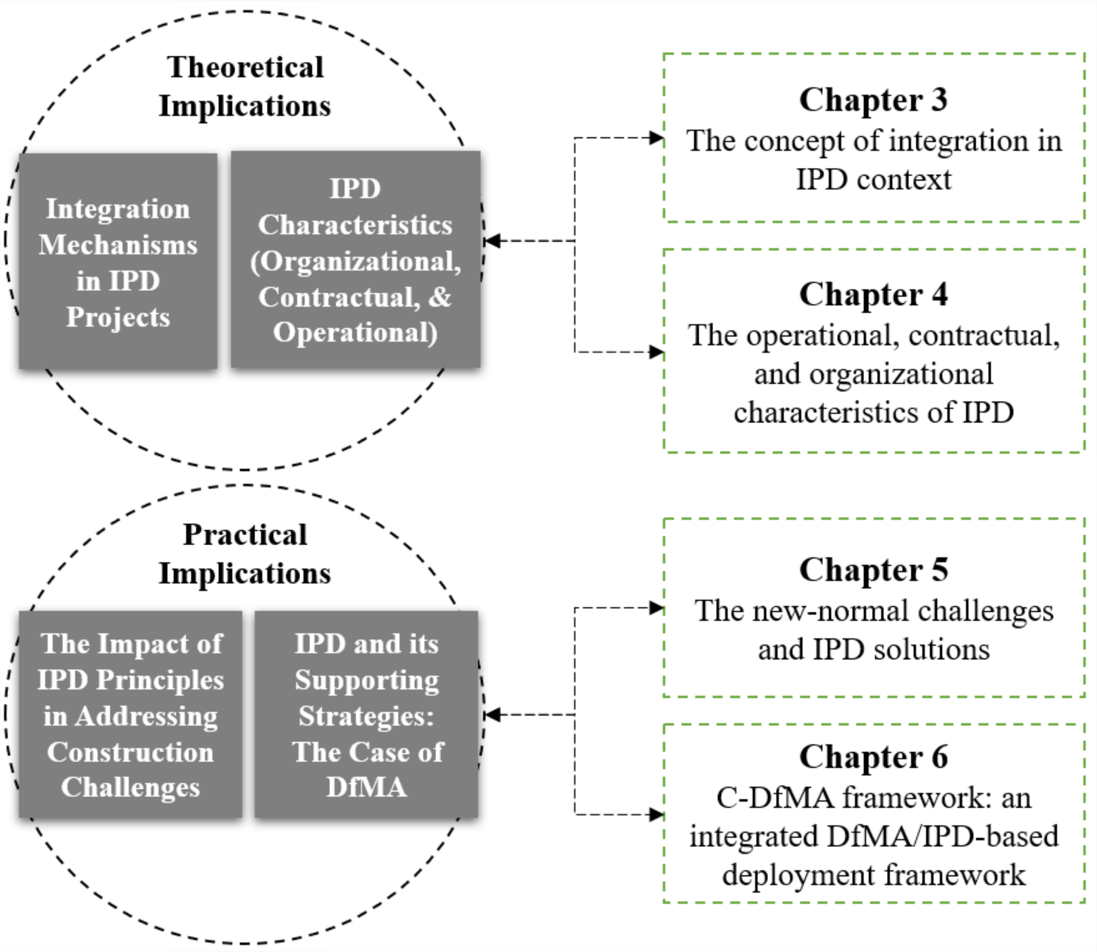


Figure 8.1 The focuses of this study

8.1 IPD Conceptualization

8.1.1 Integration mechanisms in an IPD-context

The first study (Chapter 3) was conducted to explore the “integration” aspects of IPD and identify various integration strategies that have been applied in IPD projects. Through a systematic review method, all integrating mechanisms cited in IPD literature were identified, and their integration strength, scope, duration, and depth were discussed. Then, the extracted integration mechanisms were classified into seven clusters: knowledge, organization, design, system, product, process, and supply-chain integration. Finally, the directions (vertical, horizontal, and longitudinal) of integration were discussed and divided into three contexts: (i) on-site construction projects, delivered traditionally, (ii) on-site construction projects, delivered through IPD, and (iii) off-site construction projects, delivered through IPD. The resulting study indicated that IPD *operational systems*, which have their roots in lean concepts, are associated with most integration clusters (i.e., product, process, system, and design integrations). These systems, mostly focus on products integration, and apply various operational tools and techniques to enhance supply-chain integration and deliver high quality construction products. Due to the project-based nature of the construction industry, IPD operational systems usually provide short-term impacts, which are not transferable from project to project. On the other hand, IPD *contractual framework* and *organizational structures* mostly focus on people. They are associated with clusters that promote a high-level of integration among project stakeholders, such as knowledge and organizational integration clusters. These integration clusters can have long-term impacts, which go beyond project life cycle. For instance, trust-building activities in IPD contracts can be repeated in IPD core teams in future projects. In summary, Chapter 3’s study helps researchers and practitioners to effectively use what is known thus far about the concept of integration in IPD literature and understand research limitations. It also provides a point of departure for future theoretical and empirical explorations.

8.1.2 IPD operational, contractual, and organizational characteristics

The integration impacts of IPD identified in Chapter 3 lead to the question: what are the operational, contractual, and organizational specifications of IPD projects. Therefore, the second study (Chapter 4) was conducted with the objective of recognizing the state of the art of IPD characteristics in the construction industry. First, a thorough bibliometric analysis to review the state of the art of IPD research and developments was conducted. The results show that the number of studies about IPD have doubled since 2017. The concepts that have been co-occurring with IPD most frequently are BIM, design, and integration. The results of the thematic analysis showed that the most prominent emerging IPD research themes are *technological* and *procedural* under the operational-cognitive cluster; *legal* and *commercial* under the contractual-regulative cluster; and *cultural/behavioural* and *structural* under the organizational-structural cluster. Most scholars have shown interest in the *operational-cognitive* aspects of IPD, compared to the *contractual-regulative* and *organizational-structural* characteristics. In this context, synergetic studies on the combination of lean, BIM, and industry 4.0 technologies with IPD, have gained attention among researchers. Several scholars explored the impacts of IPD operational systems implementation in construction projects. The most prominent emerging topics were identified as *performance improvement, education/training, innovation, education/training,* and *sustainability*. Studies on the contractual aspects of IPD have increased in number recently. The literature shows that the IPD-contractual relationships are evolving from a distinct relational delivery method to a flexible IPD-ish contractual hybrid format, in which IPD philosophies can be applied within other types of project delivery models such as traditional delivery methods. Some scholars identified new integrated business models (such as spinoff factories), which can improve IPD-project performance. Another area of recent focus is related to applying IPD in off-site and modular construction projects. Regarding the organizational structure, IPD literature emphasizes team integration and stakeholder collaboration. In this context, several scholars have investigated the cultural and behavioural aspects of IPD projects to enhance longitudinal integration and collaboration among IPD team members. In summary, it was concluded that IPD contractual, operational, and organizational principles and practices can enhance vertical, horizontal, longitudinal, and circular integration in construction projects. Based on the results of this review, an IPD integration framework was developed. The framework illustrates an integrative organizational structure by applying various IPD tools and techniques that support integration throughout the project supply-chain. In this framework, an information-sharing platform is required to enhance the collaborative nature of IPD and ensure proper implementation of IPD principles. To achieve a high-level of fiscal transparency and security, in addition to securing the information-hub, a secured crypto-asset payment platform is required.

8.2 IPD Implementation

8.2.1 IPD principles to meet construction challenges

According to the literature, the application of IPD in construction projects is expected to increase in the post-pandemic era (Assaad and El-adaway, 2021). The increasing trends of IPD studies identified in Chapter 4 lead us to the wonder what is needed to ensure that construction projects fully benefit from the implementation of IPD. First, it is important to identify and characterize the existing challenges in construction projects and to explain how IPD can address them. The third study (Chapter 5) was conducted with the objective of identifying current challenges in construction projects, and exploring IPD characteristics, which can address them. This project was conducted during the global pandemic, which caused changes in normal industry practices and created new challenges in construction projects. Thus, I named the identified issues of the new-normal challenges and discussed how IPD integrative tools and techniques could help to improve various proximity dimensions to address these challenges. First, the construction literature published after the pandemic was reviewed to identify various challenges construction projects encountered during the new-normal era. Then, the identified challenges were classified into three stages: pre-construction, construction, and post-construction. In the pre-construction stage, the most cited challenges were cost estimation uncertainties, risk assessment difficulties, feasibility study concerns, silo-effect problems due to the linear structure of contracting strategies, and rigid financial payment methods. The design challenges in the pre-construction stage were identified as: design changes due to the shortage of material, delays due to long approval processes, reworks and duplications due to design uncertainties, and lack of a digital platform for design collaborations. In the construction stage, challenges were identified as: construction supply-chain disruptions; long construction process due to pandemic restrictions; shortages of material and labor; construction quality; and site closures due to outbreaks. The most cited post-construction challenges were project termination delays; cost overruns; legal issues due to breaches in contracts; client dissatisfaction due to the poor quality of projects; reduced return on investment; and less maintenance budget.

After extracting the challenges, the proximity aspects of each challenge were identified. Proximity is a multi-faceted concept and refers to the distance between two or more entities. It is considered as a construct involving technological, organizational, geographical, and cognitive closeness

(Dallasega et al., 2018). Next, two Canadian case studies were conducted, to collect data and validate the results of the review. Several focus groups and interviews were conducted with project stakeholders, in which IPD principles were discussed, and study participants were interviewed to list principles that could address the new-normal challenges. The participants filled out a questionnaire survey to specify IPD principles that had been applied in the case study projects before and after the pandemic. Finally, the concept of proximity was discussed, and IPD principles that contributed to enhancing four proximity aspects (technological, organizational, geographical, and cognitive) were identified. An analysis of the results showed that the number of IPD principles that have been applied in case study projects has increased since the beginning of the pandemic. This was aligned with scholars who stated that the number of projects applying IPD principles is expected to increase in the new-normal era. The principles that are the most applied in the new-normal era relate to the technological (integrating technologies, digital platforms, cloud-based and web-based technologies) and relational aspects of IPD (multiparty alliance, cluster-based management, and shared risks/rewards). As identified, IPD principles such as co-location, strategic alliancing, offsite construction, and prefabrication techniques address supply-chain interruption challenges and improve organizational and geographical proximities. IPD design principles, such as target value design, integrated design, and charrette workshops improve cognitive proximity. Finally, IPD integrating technologies such as BIM and web-based tools improve technological proximity in construction projects.

8.2.2 IPD and its supporting strategies / environments

In Chapter 3, the "design integration" was identified as an integration cluster in IPD literature. The results showed that IPD supports collaborative design processes within a multi-disciplinary team environment. It was also discussed that IPD is a suitable model for both on-site and off-site construction projects and that applying IPD in off-site construction projects creates a full supply-chain vertical integration during the project's life cycle, which can reduce the project duration. This provided more depth into previous studies, which promoted the application of IPD for OSC (Jin et al., 2018; Hall et al., 2018; Xu et al., 2021; Ng et al., 2021; Hall et al., 2020).

In Chapter 4, some IPD studies which focused on exploring synergy between IPD and various emerging integrative design techniques such as integrated design process (IDC), generative design (GD), and design for manufacturing and assembly (DfMA) were discussed. In Chapter 5, it was identified that IPD operational principles, such as integrated design and charrette workshops, improve cognitive proximity and address various design and construction challenges in projects. This evidence all advocates the synergy between IPD and integrated design practices, such as DfMA, and their potential synergetic impacts on enhancing onsite and off-site construction project outcomes. As an innovative integrated design strategy, design for manufacturing and assembly (DfMA) shows a great synergy with integrative approaches to project delivery, such as IPD, particularly for prefabricated projects (Staub-French et al., 2022). In the second conference article (see Appendix A), a study was conducted about the synergy between IPD and DfMA, in which it was identified that these two concepts support each other's implementations in construction projects. In order to investigate further into this, the fourth study (Chapter 7) was conducted with the objective of identifying the challenges to the implementation of DfMA in construction projects and exploring collaborative and integrative strategies which can resolve them. First, by conducting a systematic literature review and several focus group discussions, we identified 45 challenges and categorized them into eight categories: contractual, technological, procedural, cultural, commercial, geographical, financial, and technical/cognitive. The results indicated that the majority of identified challenges were related to the contractual and operational aspects of construction projects and the associated stakeholders. Next, based on the results of the review and project observations, a construction-oriented DfMA (C-DfMA) framework was developed, to address the identified challenges. The opportunities for enhancing the implementation of C-DfMA, through applying emerging organizational structures, contractual frameworks, and operational tools and techniques in the construction industry were discussed. The results show that integrated business models, relational and integrated delivery methods (such as IPD), and lean-based operational tools and digital technologies create a suitable environment for the full implementation of the C-DfMA framework and addressing the identified challenges.

8.3 Contributions of this study

This thesis contributes to the body of knowledge about IPD from both a theoretical and practical perspective. The results of this study are intended to impart knowledge to researchers and practitioners so that they have a better understanding of IPD characteristics and its implementation requirements in practice. As shown in Figure 7.2, the conceptual and practical contributions of this research can be categorized into four clusters, which will be discussed in this section.

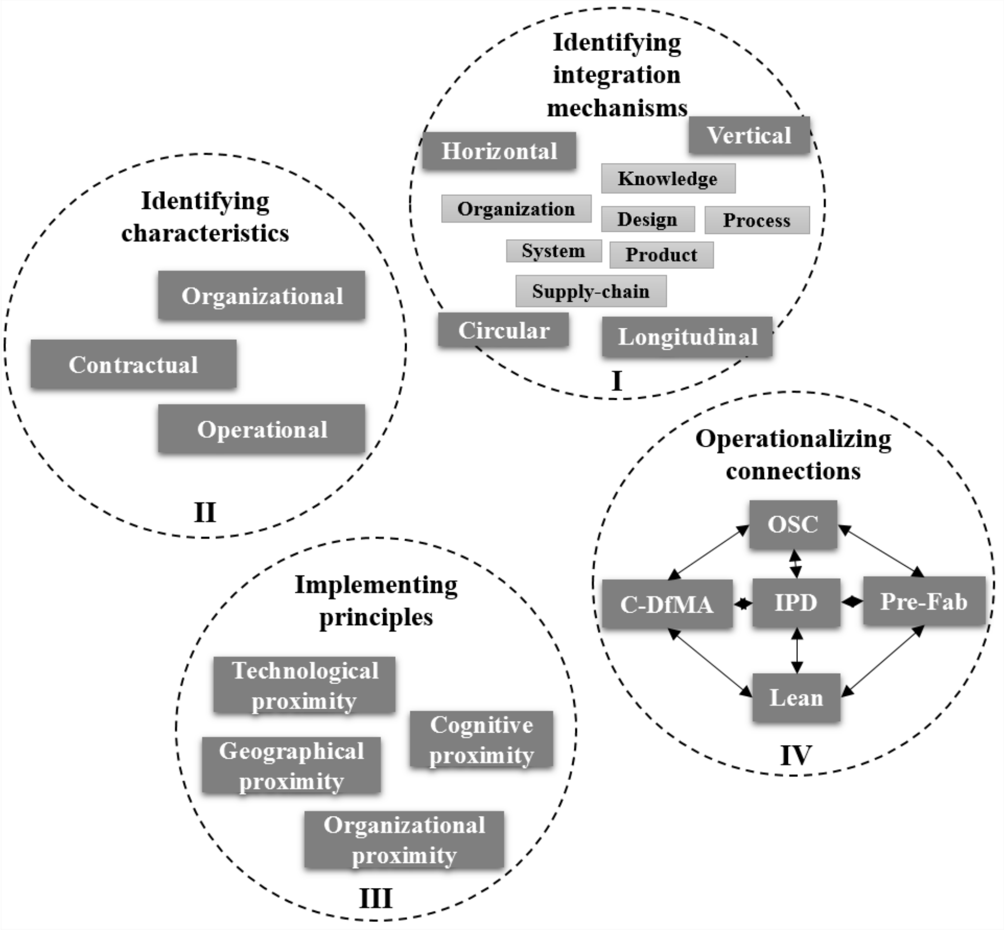


Figure 8.2 Results of this research divided into four clusters

8.3.1 Contributions to the academy

This study contributes to the construction literature by shedding more light on the conceptual aspects of IPD. The results of this study will help researchers to have a better understanding of the IPD contractual framework, organizational structures, and operational tools and techniques.

Integration concept in IPD studies

As shown in cluster I, in Figure 7.2, the study contributed first to the theorization of IPD by illustrating more in depth the fundamental understanding of the concept of “integration” in IPD projects. The literature showed a gap in identifying integration mechanisms in IPD studies. In addition, there was a confusion among scholars about using various integration terms while referring to the same mechanisms (for instance team, people, organization, and stakeholder integration). To address this, all integration mechanisms in IPD literature were extracted and framed into seven IPD integration clusters (knowledge, organization, design, system, product, process, and supply-chain integration). Moreover, the integration dimensions (strength, scope, duration, depth) and directions (horizontal, vertical, longitudinal) of IPD principles and their impacts on construction projects were discussed.

IPD contractual, organizational, and operational characteristics

Next, the latest IPD contractual, organizational, and operational characteristics were identified (cluster II, Figure 7.2). The results enhance knowledge about IPD, not only as a distinct relational delivery method, but also as a philosophy which can be applied to a flexible IPD-ish contractual hybrid format. From this, a conceptual IPD integration framework was presented, covering various tools and technologies that could be applied in IPD projects to enhance vertical, horizontal, longitudinal, and circular integrations.

IPD enablers of proximity

Following the identification of IPD characteristics and integration mechanisms, the research focused on understanding their impacts on addressing construction challenges. The study highlighted several recurrent, new-normal challenges facing the construction industry after the pandemic. In doing so, IPD enablers of technological, organizational, geographical, and cognitive proximities were suggested as possible solutions (cluster III, Figure 7.2). From this, a conceptual framework was proposed, based on the IPD principles that contribute to various dimensions of proximity in construction projects.

Interaction between IPD and DfMA in construction projects

It was identified that, as a collaborative method and philosophy, IPD does not work most efficiently in isolation. In recent IPD literature, some scholars discussed the synergy between IPD and other emerging integrative techniques (such as BIM, lean, and integrated design strategies) in construction projects. However, they did not investigate this in detail. This study addressed this gap by selecting DfMA and exploring its interplay with IPD. The challenges to the implementation of a DfMA strategy in construction projects were identified in eight categories: contractual, technological, procedural, cultural, commercial, geographical, economic, and cognitive. Then, the relationship between the challenges, stakeholder roles, and project phases were highlighted. The results of this showed that DfMA and IPD mutually facilitate and strengthen each other. Finally, a conceptual C-DfMA framework was introduced to the literature, based on the operationalization of the connection between DfMA, IPD, and other integrative tools and techniques (cluster IV, Figure 7.2), and which could resolve the identified challenges.

8.3.2 Contributions to the industry

Although most studies in this thesis focused on the conceptual and theoretical aspects of IPD, there are several valuable insights for industry practitioners that can be extracted from this thesis.

Enhancing practitioner knowledge about IPD: According to the literature, the current generation of professionals has limited knowledge of IPD. In this context, the academia must create appropriate pathways to facilitate the transfer of knowledge about IPD and its implementation in construction projects. The results of this thesis can increase the competence level of architecture, engineering, and construction industry practitioners by identifying specific IPD mechanisms.

Supply-chain integration and IPD: it was identified that IPD can enhance supply-chain integration in construction projects, due to its collaborative nature. The longitudinal integration in projects, as a result of applying IPD, creates long-term trust and collaborations between project partners. The discussion of integration in this study extends beyond any single phase, to the supply chain integration. Supply-chain integration practices such as DfMA, when applied in conjunction with IPD, can increase systematic innovation opportunities. In this context, owners and industry practitioners can apply the proposed C-DfMA framework to improve future collaboration and supply-chain longitudinal integration in IPD-based construction projects.

Post-pandemic challenges and IPD: the construction industry is undergoing a paradigm shift from traditional practices toward more collaborative, sustainable, and digital methods such as IPD. This shift accelerated post pandemic. In this thesis, the latest pre-construction, construction, and post-construction challenges, are classified. Based on the case studies and focus group discussions with industry professionals we conducted, IPD proximity enablers are framed in this study, which can be applied to various types of construction projects to address such challenges.

Interplay of IPD and its supporting concepts:

> **Prefabrication and IPD:** this study explored how the mutual application of IPD and prefabrication in an off-site construction environment enhances supply chain partnerships and improves project outcomes. It was concluded that IPD and prefabrication support each

other's applications in various contexts, yet, we do not see many cases in practice in which prefabricated projects are delivered through IPD. The results of this thesis can encourage owners and practitioners to take advantage of IPD-prefab mutual implementations.

C-DfMA and IPD: Based on the project observations and focus group discussions with industry practitioners, a C-DfMA framework was proposed to improve the current state of applying DfMA strategies in practice. For practitioners, one of the takeaways from this study was that IPD and C-DfMA support each other's implementation. The success of implementing either one is associated with the other's application. Both C-DfMA and IPD are collaborative and sustainable methods, which focus on organizational integration and early involvement of practitioners and provide longitudinal integration of the supply-chain in projects. This study highlighted the multidimensionality of C-DfMA and IPD, and advocated their coupling, while incorporating complementary business models and digital technologies to enhance project performance metrics.

Flexible hybrid IPD-ish projects: in this study, various contractual, operational, and organizational characteristics of IPD are framed. This can help industry practitioners to decide whether IPD is the right fit for their construction projects or not. In addition, the results of this study enable decision-makers and owners to apply the most feasible IPD principles in their projects, even if their projects are being delivered with other delivery methods.

8.4 Limitations of the research

This study has several inevitable limitations with respect to the achieved results.

Scope of the research

In this research, a few systematic literature reviews were conducted. The performed literature reviews only included English resources and publications. In addition, to achieve high quality results, only peer-reviewed journal, and conference articles were selected. This means that white and grey papers and industry reports were excluded from the scope of this review. Conducting an extensive review of the industry reports about IPD could be the focus of a follow-up research.

Conceptual versus empirical studies about IPD

IPD is still a new concept in both the literature and the industry. This thesis mostly focused on theoretical studies to improve the conceptual understanding of IPD, and less empirical studies were conducted. From an empirical research perspective, the selected case studies in this thesis, were IPD-inspired or IPD-ish projects, in which IPD philosophy and principles had been applied within a different delivery method. In fact, none of these projects used a standard form of IPD contract. This might be related to the rarity of IPD projects in Canada, particularly during the pandemic, when most construction sites in Canada faced limitations and temporary closure. More specifically, an IPD project in Canada, in which the Canadian standard form of IPD agreement, such as CCDC-30, was signed, is rare. Conducting real IPD case studies to validate these results, could be the focus of a follow-up research.

Sample size

The sample size of the participants in case studies, interviews, and focus group discussions was rather small to infer or suggest generalizability. As this study is still embryonic, the author wishes to warn readers against overgeneralizing of findings and recommends that generalization, inference, or future replication is countered-balanced by the inclusion of additional and larger case study samples in order to improve the veracity of these findings.

Industry applications

In this study, project contexts that could benefit from IPD were investigated, such as prefabricated and OSC projects. However, I did not study projects in which IPD might not be the optimal delivery method or philosophy. Construction, engineering, and architectural practitioners can see this study's results as a positive sign that IPD, when implemented correctly, has potential for enhancing integration and improving project results. Meanwhile, it is necessary for owners to proactively define their business needs and conduct feasibility studies before selecting the delivery method. While IPD has several benefits, it might not be the best fit for all project contexts.

8.5 Future studies

This work's findings confirmed that IPD philosophy and principles can enhance integration in construction projects. The scholars and industry practitioners should tread the path toward IPD adoption with caution and enthusiasm. Successful adoption of IPD-inspired contracts does not solely rely on their benefits but also to a large extent on their impact on today's industry practices.

This necessitates a deeper focus on 1) understanding business needs, 2) establishing a reliable link between IPD and its supporting concepts, strategies, and implementation environments, and 3) adapting to the transformation of the industry. The following section discusses these three focus areas and expands on relevant future research directions:

Focusing on business needs: IPD in Canada

As discussed, the implementation of IPD in Canada, particularly in Quebec, is still very limited. Among the contracted IPD projects in Canada, only a few projects applied the CCDC-30 contract, which is the standard form of Canadian IPD agreement. Most of these projects use American IPD agreements, such as Hanson Bridgett or ConsensusDOCs IPD contracts. This shows that there is a need to investigate the Canadian business needs and to develop a customized IPD contract that addresses those needs. In addition, more studies are required for improving legislative norms and contractual standards for the proper implementation of IPD in various types of construction projects in Canada (i.e., OSC, prefabricated, green, sustainable). More research and development activities for identifying the optimal financial investment methods for IPD projects (i.e., front-end investments, etc.) are also required.

Adapting to the transformation of the industry

The results of this study showed a trend towards digital integration in the industry. However, both IPD and disparate digital agendas across projects disrupt integration routines. To address issues related to disruption and improve digital integration in IPD projects, studies that explore the relationship between integration, disruption, and transformation are required. In this study, it was found that IPD strongly advocates “organizational integration.” However, this conflicts with the current siloed environment of the construction industry along with the ingrained mindset of the industry practitioners. More efforts are required to increase the industry’s understanding and knowledge about IPD, particularly regarding the impact of IPD on the digital transformation of construction projects.

From another perspective, it was identified that although IPD has a great potential for improving long-term integration (longitudinal integration) between project stakeholders, the literature seems to favor vertical and horizontal organizational integration. More studies on longitudinal integration are recommended, particularly in relation to the impact of IPD on enhancing circular integration in off-site and prefabricated construction projects.

The construction industry has vigorously evolved recently, particularly since the beginning of the pandemic. It was identified that the application of IPD is expected to increase post-pandemic. Our study on the new-normal challenges was conducted during the pandemic. Given the qualitative nature of this study, we were unable to access full business case studies that can quantitatively evaluate the challenges the construction industry is facing in the new-normal era. Therefore, we encourage further studies post-pandemic to investigate how various stakeholders (owners, contractors, suppliers, engineers, and architects) can benefit from IPD principles to meet the new-normal challenges. Also, more studies on the contractual aspects of IPD are required to understand how policy makers can modify IPD contracts to adapt them to the new-normal situation.

Establishing a reliable link between IPD and its supporting concepts

The results of this study revealed that IPD cannot be implemented efficiently in isolation. More studies on the application of IPD proposed-frameworks in this research, combined with newly developed business models (spin-off company, virtually integrated, etc.), integrated design and construction practices (DfMA, OSC, prefabrication, etc,), and tools and technologies (IoT, 3D printing, nD BIM, cloud platforms, etc.) are required.

8.6 Conclusion

In conclusion, the construction industry is moving into more integrated methods and strategies, such as collaborative delivery methods and integrated design and construction strategies, such as IPD and DfMA. The results of this study revealed that these integrated strategies and methods cannot be implemented efficiently in isolation. Thus, we conducted research on IPD and DfMA, extracted their characteristics, identified existing challenges to their proper implementations, and proposed several frameworks in various chapters of this research, which can enhance the industry participants awareness of these integration techniques and their proper implementation combined with other newly developed business models, digital tools, and advanced technologies.

CHAPTER 9 CONCLUSION AND RECOMMENDATIONS

This chapter highlights the key takeaways from each article and concludes on the implications of this dissertation on the implementation of IPD as project delivery method in construction projects.

9.1 Summary of chapters

In my first study, I explored the concept of "integration" in IPD literature and identified how IPD-integrating strategies affect various elements of construction projects. All IPD-integrating techniques cited in the literature were extracted, and their integration dimensions (strength, scope, duration, and depth) were discussed. I classified the extracted IPD integration-related terms into seven clusters: knowledge, organization, design, system, product, process, and supply-chain integration. Finally, I explored IPD integration directions (vertical, horizontal, and longitudinal) and illustrated them in three contexts: (i) on-site construction projects, delivered traditionally, (ii) on-site construction projects, delivered through IPD, and (iii) off-site construction projects, delivered through IPD. The study results indicated that IPD operational systems, which have their roots in lean concepts, are associated with most of the integration clusters. Due to the project-based nature of the construction industry, IPD operational systems usually provide short-term impacts, which are not transferred from project to project. On the other hand, IPD contractual framework and organizational structures mostly focus on people. They are associated with clusters that promote a high-level of integration among project stakeholders, such as knowledge and organizational integration clusters. These integration clusters can have long-term impacts, which go beyond project life cycle. For instance, trust-building activities in IPD contracts can results in repeated IPD core teams in future projects. The results also showed that applying IPD in off-site construction projects creates a full supply-chain vertical integration during the projects' life cycle, which can reduce the project duration.

In my second study, first, I conducted a thorough bibliometric analysis to review the state of the art of IPD research and developments. The results showed that the number of publications about IPD has doubled since 2017. Next, I conducted a thematic analysis to identify the most recent IPD research themes and future trends. Results showed that the most prominent emerging research themes from the literature are identified as: technological and procedural under the operational-cognitive cluster; legal and commercial under the contractual-regulative cluster; and cultural/behavioural and structural under the organizational-structural cluster. The literature shows that IPD contractual relationships are evolving from a distinct relational delivery method to a flexible IPD-ish contractual hybrid format, in which IPD philosophies can be applied within other types of project delivery methods such as traditional delivery methods. Scholars identified new integrated business models (such as spinoff factories), which can improve an IPD project's performance. Another area of recent focus is related to developing contractual guidelines, which makes IPD adaptable to off-site and modular construction projects. Based on the results of this review, I developed IPD integration frameworks. IPD contractual, operational, and organizational principles and practices can enhance vertical, horizontal, longitudinal, and circular supply-chain integration in construction projects.

In my third study, I reviewed the construction literature published after the pandemic to identify various challenges construction projects are encountering during this new-normal era. Then, I classified these challenges into three stages: pre-construction, construction, and post-construction. After extracting the challenges, I identified the proximity aspects of each challenge. Next, I conducted two Canadian case studies, to collect data and validate the results of the review. Several focus group discussions and interviews were also conducted with project stakeholders, in which IPD principles were discussed, and study participants were interviewed to list principles that could address the new-normal challenges. The results showed that the number of IPD principles that have been applied in case study projects has increased since the beginning of the pandemic. The IPD principles that are the most applied in the new-normal era relate to the technological (integrating technologies, digital platforms, cloud-based and web-based technologies) and relational aspects of IPD (multiparty alliance, cluster-based management, and shared risks/rewards). As identified, IPD principles such as co-location, strategic alliancing, offsite construction, and prefabrication techniques address supply-chain interruption challenges and improve organizational and geographical proximities. IPD design principles such as target value design, integrated design, and charrette workshops improve cognitive proximity. Finally, IPD integrating technologies such as BIM and web-based tools improve technological proximity in construction projects.

In my fourth and last study, I conducted a systematic literature review and several focus group discussions. First, I identified 45 challenges of applying the DfMA method in construction projects, and then, I categorized these challenges into 8 categories: contractual, technological, procedural, cultural, commercial, geographical, financial, and technical/cognitive. The results showed that the majority of identified challenges were related to the contractual and operational aspects of construction projects and the associated stakeholders. Next, based on the results of the review and project observations, I developed a construction-oriented DfMA (C-DfMA) framework, to address the identified challenges. I discussed opportunities for enhancing the implementation of C-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 and integrated delivery methods, and lean-based operational tools and digital technologies create a suitable environment to fully implement the C-DfMA framework and address the identified challenges.

9.2 Final words

The construction industry is clearly experiencing a paradigm shift from traditional methods toward more integrated, sustainable, and collaborative approaches such as IPD. This shift has started but is far from being widespread. Many scholars advocate the tremendous impacts of collaborative approaches in enhancing construction projects performance; however, we have not experienced their full implementation in practice yet. In a situation where the construction industry is constrained by legislation and public sector agendas, it is reasonable to conclude that the awareness of industry practitioners about IPD is still low. As an innovative method, IPD can be a disruption to the current traditional practices. This makes its implementation complex, which relies on several preconditions that may take long to be fulfilled. In this context, researchers must help to pave the way for the full implementation of this collaborative method, which can improve the future of construction projects to certain a extent. I believe the present study paves the way for further detailed research on the interplay of IPD and other emerging integrative and collaborative strategies. This thesis aims to enhance the body of knowledge in IPD via its main academic and practical contributions.

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APPENDICES

Appendix A INTEGRATION AND I4.0 TRACKING SYSTEMS FOR STEEL MANUFACTURING INDUSTRY

Appendix Information: An article based on this Appendix has been published, as per the following reference:

Rankohi, S., Bourgault, M., Iordanova, I., Danjou, C., Garcia, P., Grondin, J., (2021), Integration and I4.0 Tracking Systems For Steel Manufacturing Industry, *Proceedings of the Canadian Society of Civil Engineering Annual Conference (CSCE21)*, 237-247.

Abstract: Industry 4.0 technologies have revolutionized manufacturing industries in many domains. Although the construction industry still lags behind other industries in terms of digitization and automation, disruptive I4.0 technologies, are gradually transforming the traditional nature of this industry. Internet of Things or IoT, associated with tracking technologies, can improve automation through real time capturing, accessing, tracking, and sharing information; which ultimately leads to more decentralized decision-makings. While these technologies can help improve project performance metrics, their impacts on project integration is still unknown. In this paper, we aimed to understand the impact of the propose IoT tracking system, on integration in terms of (a) horizontal, (b) end-to-end digital, and (c) vertical integrations. To achieve this goal, we conducted a case study on digital transformation of a steel fabrication plant in Quebec, Canada. We developed a smart steel manufacturing IoT-based architecture and proposed an automated identification tracking method for tracking steel products. Finally, we implemented the proposed system in a case study, and discussed its impact on three levels of integration in construction projects.

INTRODUCTION

Industry 4.0 consists of advanced technological opportunities and management strategies, which aims to provide new business models for the manufacturing industries (Siepmann and Graef, 2016). A key technology for industry 4.0 is the Internet of things (IoT). According to Atzori et al. (2010), digitalization through IoT can be achieved in three paradigms: internet-oriented (middleware), things oriented (sensors), and semantic-oriented (knowledge). In application domains where the three paradigms intersect, the usefulness of IoT can be fully unleashed (Gubbi et al. 2013). Tracking material for the steel manufacturing industry is an example of such application domain, in which IoT can significantly improve the current traditional procedure.

The growing needs for digitalization and automation in steel manufacturing industry, along with the difficulties in the current traditional procedure of steel fabrication and delivery, motivated the authors to propose an IoT architecture, which supports digital and automated tracking of structural steel products. More specifically, this paper presents a multi-layer IoT architecture which is applied in a case study, through designing data collection, transmission, and analyzing web-based applications for steel products tracking, as well as knowledge reuse for inventory management purposes. Finally, the impact of this digital procedure on project integration (horizontal, vertical, and longitudinal) has been discussed.

BACKGROUND AND MOTIVATION

The Internet of Things (IoT) refers to several heterogeneous intelligent objects (things) that are fully interconnected, and capable of communicating through the Internet using various protocols (Valente and Neto, 2017). The IoT provides new capacities to the "things" including remote actuation to interconnected devices through wireless networks and smart sensors (Li et al., 2014). Smart sensors along with cloud computing took the market in various areas including retail, asset tracking, logistic, inventory management in supply chains, and production lines (Valente and Neto, 2017). This paper proposes an innovative solution based on IoT, cloud computing, and RFID technology for identifying, tracking, and positioning steel products, which has been successfully developed and piloted in a steel manufacturing warehouse.

IoT and tracking technologies

Multiple tracking technologies are currently being applied in the manufacturing industry, such as Bluetooth, GPS, QR code, WiFi, etc. The proposed technology for tracking of steel products in this study is RFID, which stands for Radio Frequency Identification. RFID is a method for storing and retrieving remote data using antennas called "RFID tags". These tags are small objects, such as self-adhesive labels, that can be stuck or incorporated into different objects. As shown in Figure 1, once tags are triggered by an electromagnetic pulse from a nearby RFID reader device, the tag transmits digital data (such as an identifying number) back to the reader.

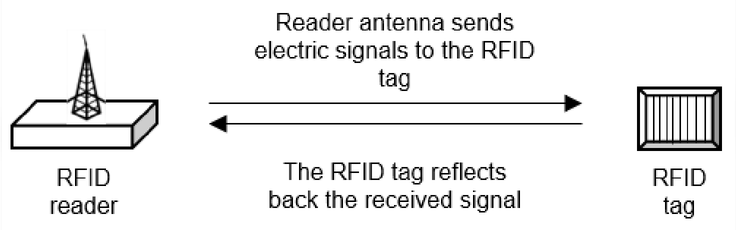

Figure 1: RFID reading process

There are two types of RFID tags: passive and active. Passive tags are powered by energy from the RFID reader's interrogating radio waves, while active tags are powered by a battery and thus can be read at a greater range (up to hundreds of meters) from the RFID reader. In this study, we chose passive RFID due to two reasons: (a) reliability: this technology is very robust and it has been widely used for industrial applications with satisfactory results, (b) price: passive RFID tags are less expensive than other similar technologies, such as UWB (Ultra-wide-band).

We conducted a case study on a steel manufacturing plant similar to the study performed by Valente and Neto in 2017. We have selected a Canadian steel manufacturing plant, to explore the application of IoT for improving inventory management practices for a particular structural steel bar product in the plant warehouse. The company produce many of these steel bars per year, and loss significant costs with its current traditional inventory management process. Based on the proposed IoT solution, the steel bars will be tracked with RFID technologies, allowing inventory managers to save time and cost by accessing real time digital information of their inventory.

Proposed IoT Architecture

Identification of transformation objectives

To conduct this case study on the application of IoT and RFID technologies for inventory management, we have selected a special steel bar product. The selected steel bars are temporary support required during the installation of other structural steel elements, and they have to be returned to the plant after being used by the client onsite. During the process of sending, installing, and returning these steel bars, many of them have been lost, damaged, or stolen; making the company to undergo significant annual costs to replace them. The inventory management process of the selected steel bars was significantly manual, time-consuming, and error-prone as well. The company was continuously looking for possible approaches to improve and automate the warehouse management process using industry 4.0 technologies.

In order to understand the digital transformation objectives for transforming the steel bar inventory, we have conducted virtual and physical observations, interviews, and a Kaizen blitz with the plant director, inventory managers, and employees. During the observations and interviews, we investigated the existing problems for the inventory management, collected evidence, and gathered information to categorize deficiencies and define improvement objectives. Table 1, summarizes the main problems and associated objectives that have been identified during interviews. In order to identify the improvement areas, we classified the objectives under process, product, and service.

Table 1: Steel bars inventory problems, improvement goals, and objectives

	Improvement Area	***Problem***	***Objective***
Product	*Steel bars*	*High annual loss, and expensive fabrication costs*	*Reduce fabrication costs by: automatic tracking of returned bars, real-time clients updating of the missing pieces, and increase clients responsibilities*
Process	*Inventory management*	*Manual and inefficient inventory management process*	*Reduce inventory management costs by having less manual works, through automatic tracking and inventory monitoring and control*
Service	*Rental services for the clients*	*Costly service, broken lines of communication with the client for returning steel bars*	*Improve quality of service to the clients by developing a mobile application which can provide access to bars information i.e., delivered and returned steel bar types, quantities, number of racks, BOLs, costs, etc.*

We have conducted a Kaizen blitz with plant stakeholders, to visualize inventory management steps and identify process “wastes”, such as over-production, over-processing, lost time, poor service, extra inventory, and information gaps. As shown in Figure 2, we focused on bars’ return management process (as it was the area where most issues belong to), and developed planning steps diagram in a push/pull similar format. The color-coded boxes represent steps that could be eliminated or improved through a digital transformation of the inventory. The blue boxes represent steps that could be improved/eliminated by a tracking system that the company’s employees could use; while grey boxes represent those steps that could be transformed if clients could use an online or mobile steel bars tracking application. As shown, color-coded steps represent more than 50% of the total tasks. This means there was more than 50% chance of increasing the efficiency and improving the whole process.

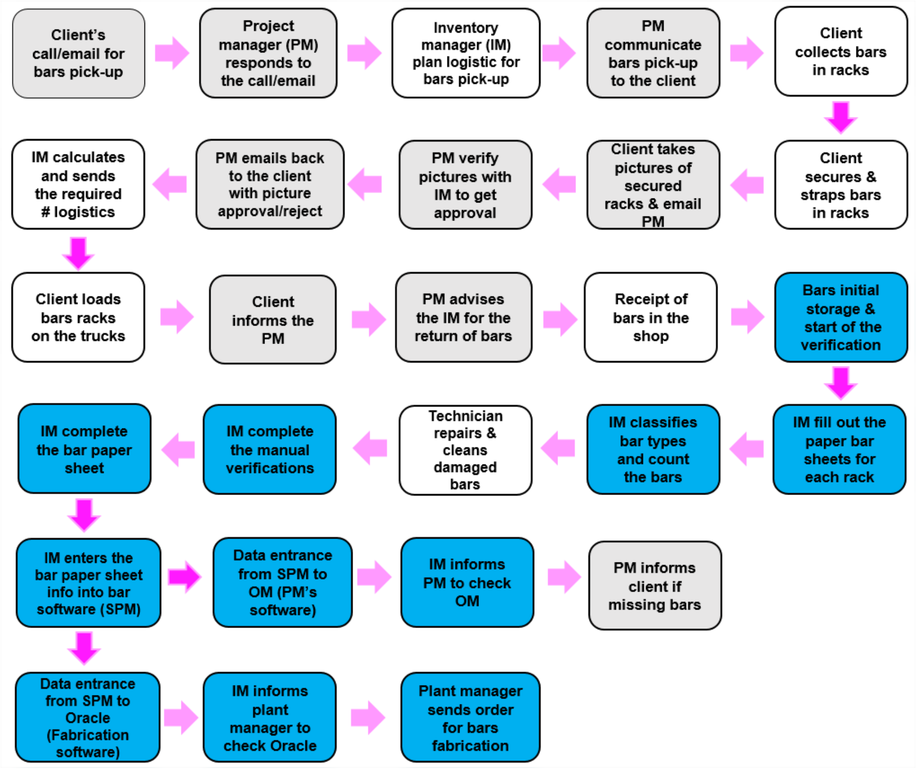

Figure 2: Steel bar inventory return planning steps (Kaizen blitz)

Based on the results of the Kaizen blitz, we came up with the idea of developing a steel bar IoT tracking application for the company, which could be used by both clients and the bar inventory management team. In terms of the strategic positioning of our proposed solution, as shown in Figure 3, we consider this tracking application as an improvement to the company steel bar tracking/inventory process, as well as providing a monitoring service for the clients (through a web-based mobile application).

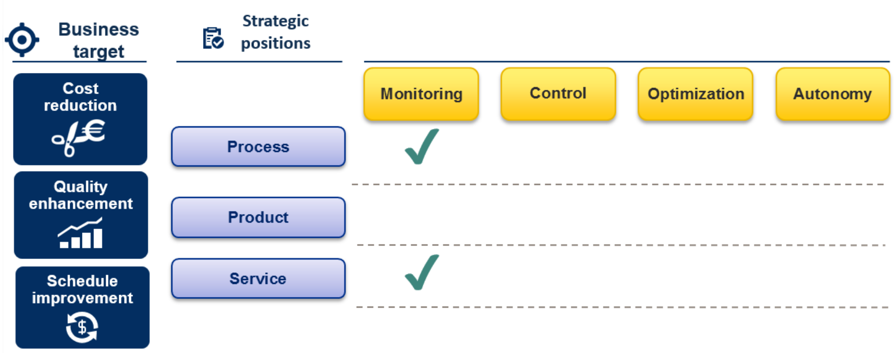

Figure 3: Strategic positioning of the proposed solution for transforming steel bars inventory

IoT Architecture

The proposed IoT architecture, as shown in Figure 4, is developed and implemented in a case study project in the plant. The developed steel bar tracking application is based on using barcodes, RFID antennas, and readers for sensing and collecting data. The data transmission is done by WiFi; the integration layer is covered by the same company providing the RFID readers; and finally, analysis and decisions layers are the inventory operators and company engineers' responsibilities. As shown in Figure 4, the proposed architecture consists of three main layers: *system, network, and service layers.*

The *system layer* consists of coding, information acquisition, and information access phases. In the coding phase, an ID number is assigned to each objects. Then the objects can be recognized in the whole cycle of the IoT. For instance, clients are provided with barcodes (installed on the racks or shown on pdf drawings). They scan these barcodes with their smart phones, which direct them to the company's web-based steel bar application. This application is equipped with mobile tag reader technologies, which are used by the clients to make sure they have collected all received steel bars in returning racks. In addition, clients can use this application to send automated alerts to project managers to inform that the steel bar racks are ready for pick-up. The information acquisition phase is the source of the IoT. In this phase, data is collected and objects are identified via RFID tags.

The information access phase is to transmit the obtained information from the collection phase to the network layer. The information transmission network can be mobile communication network (i.e., GSM, TD-SCDMA, WiMAX, WiFi, etc.). The proposed *network layer* is a network platform, working based on IPV6. It consists of a large intelligent network, which is capable of utilizing all the resources in the network. Within the network layer, we have the information integration layer over the cloud, to manage and control the collected data in the network in real-time. In order to provide a good service interface to the application service layer for the clients, the data is reorganized, filtered, integrated, and transformed into the content service in the SOA. Finally, the *service layer* integrates the service capabilities and provides the application service to the clients.

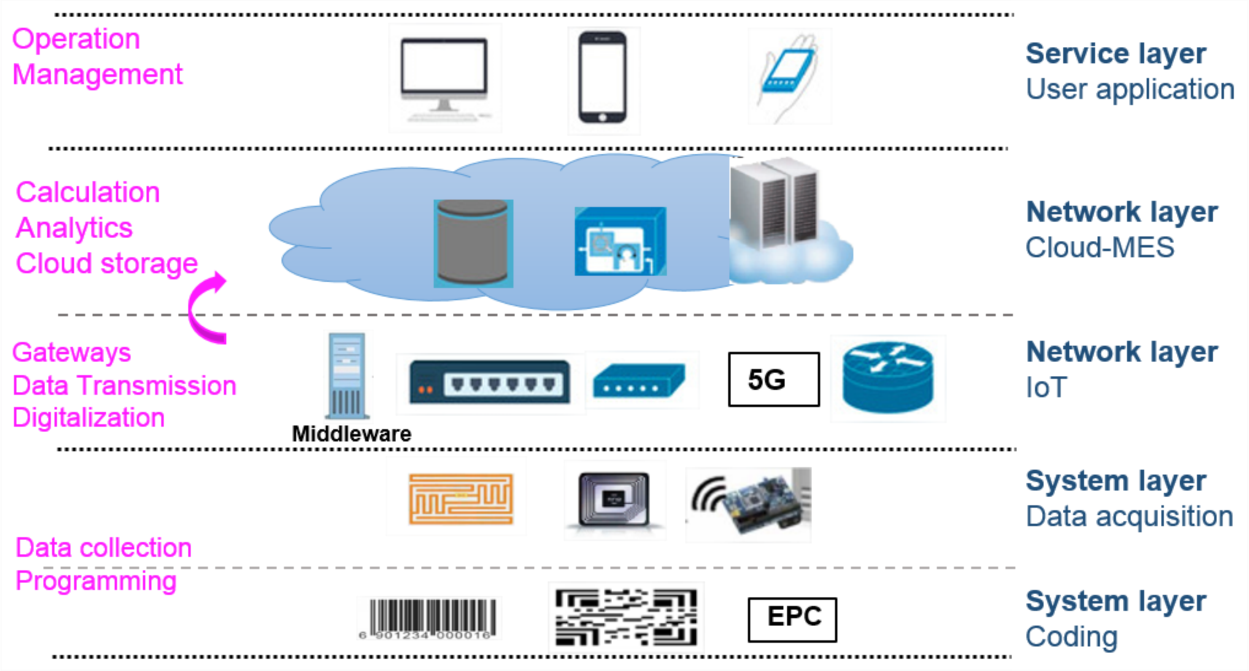

Figure 4: Main layers of the proposed IoT architecture

Autonomous process

The proposed autonomous steel bar inventory management process has the following steps:

Step 1: racks full of steel bars pass through the shipping doors located in the inventory shop floor, before being placed on the trucks to be shipped to the site. RFID reader identifies the tags, which pass through the doors. For the reading purpose, tags are placed on each of the steel bars so they all have a unique ID, which contains information such as the type of the steel bar. When the bars are passing through the exit gates, two RFID antennas emit Radio Frequency waves that are captured by the antennas of each of the labels and are returned to the RFID antennas with the information regarding the identification number of each of the bars. This captured information is transmitted from the RFID antennas to an antenna's hub. Each hub can gather information from multiple antennas at the same time. RFID readers read the information from the antenna's hub and a specific software transforms it to be exported. The exported information can be used by the client via online user application, transmitted by API, and integrated with the company's inventory management system.

Step 2: clients receive the steel bars onsite, use them as temporary supports during the installation of other steel elements, and remove them once the installation process is complete. Once removed, the clients put used bars back in racks, scan racks' barcodes with their smart phones, use company's web-based application, upload pictures of loaded racks, enter preferred pick-up date, receive pictures' safety approval note, and the pick-up date confirmation.

Step 3: the returned racks to the shop pass through the shipping doors and the tags' reading information is recorded again by RFID readers.

Step 4: the collected data is automatically transferred to the cloud-based platform, comparison charts are generated, and difference between sent and received bars are calculated automatically in real-time. An automatic notification, which shows the total differences (if any), is sent to the project managers, inventory managers, and the clients.

Step 5: the inventory management team can quickly and easily make business decisions based on the received tracking information (i.e., charging clients who did not return all bars, fabricating the missing bars, etc.).

Further applications

In addition to obtaining real-time control over the steel bar inventory, the implementation of IoT in this process helps clarifying the causes of lost or broken bars, optimizing the life cycle of the bars and improving the quality of the final product. It could also be the first step for developing a fully autonomous steel bars inventory processing in the shop, including all steps (inspection, cleaning, classification and decisions) as well as fully autonomous decision-making system such as the timing of increasing/decreasing the steel bar inventory or when to charge a customer. In addition, the same tracking technology can be applied to other company's products. Furthermore, it could help the company to continue with its Industry 4.0 and lean strategy, accelerating the integration of IoT in other processes such as manufacturing, or the global inventory.

DISCUSSION

The tracking and monitoring service provided by IoT enables integration with the enterprise systems to support decentralized decision-making activities. The integration of product tracking in the daily operation of a steel manufacturing plant will increase automation levels by reducing manual tasks in various procedure, for instance in inventory management practices (Mourtzis et al., 2018). While IoT increases the automation, it also affects the project integration.

According to Kaur and Kaur (2017), IoT provides a platform for person-to-person (P2P), machine-to-machine (M2M) and person-to-machine (P2M) communications and interactions (shown in

Figure 5). In this study, we aimed to understand the impact of these interactions on three levels of project integration as described by Oesterreich et al. in 2016. According to Oesterreich et al., three levels of integration are required to implement Industry 4.0 technologies: horizontal, end-to-end digital and vertical integrations.

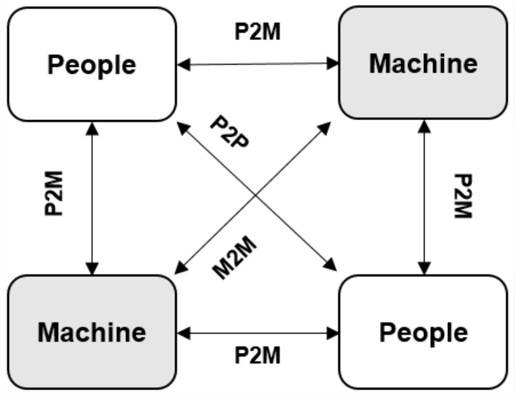

Figure 5: IoT communication scenarios

Horizontal integration (HI) through value networks which refers to the integration of IT systems, processes and data flows between various stakeholders and companies. For example, integration between different clients, suppliers, and external partners enables stronger collaboration with value chain partners across enterprise borders. In this case study, the proposed IoT solution helped various partners from different disciplines (external customer, internal teams, engineers, and sale department) work together simultaneously and more efficiently. The P2P (i.e., the client to the plant management team, the logistic team to the client, etc.), and P2M (i.e., reader alerts for the missing steel bars to the inventory management team) communication and collaboration over the cloud platform, made the whole process shorter and less error-prone than the traditional method.

End-to-end digital integration (EI) of engineering across the entire value chain results in a reduction of internal operating costs through facilitating highly customized products. In this model, cyber-physical systems are required to enhance digital integration of the value chain. In the conducted case study, the M2M (i.e., automatically printed customized digital BOL) communication improved digital integration through reducing manual paper work, which was being performed by the inventory management team.

Vertical integration (VI) and networked manufacturing systems result in a smart manufacturing environment. For example, integration of IT systems, processes, and data flows within the enterprise business units from product development to manufacturing lines, inventory, logistics, and sales for cross-functional collaborations. In the case study, the P2P (i.e., the plant management to the pre-construction team, the procurement to the design team, etc.), and the P2M (i.e., notification alerts for the shortage of steel bars in the inventory to the design and fabrication teams) communications enhanced vertical integration between various business units. These digital collaborations through IoT platform provided team members with a real-time access to the project information and ultimately reduced the amount of human errors.

As shown in Figure 6, P2P and P2M collaborations improve horizontal and vertical integrations, while M2M digital communication and collaboration mostly affect the end-to-end digital integration.

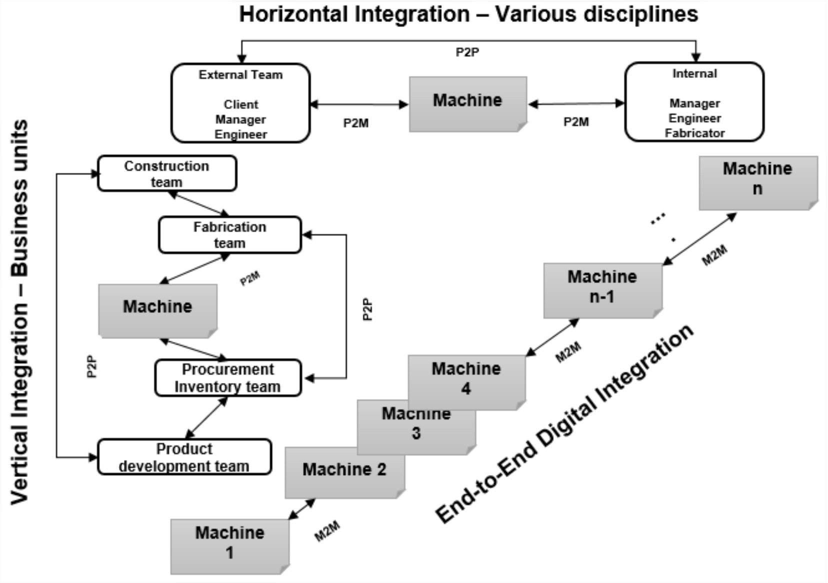

Figure 6: Industry 4.0 technologies and project integration levels

CONCLUSION

In this article, the primary goal was to propose an Industry 4.0 solution for improving the traditional process of a warehouse management in structural steel manufacturing industry. In addition, we aimed to explore the impact of the proposed solution on projects integration levels as described by Oesterreich et al. (2016): horizontal, end-to-end digital, and vertical. Based on the outcomes of this research, the following conclusions are drawn:

The IoT technologies are currently accessible for various industrial applications; however, their widespread adoption by the construction sector has not taken place yet (Oesterreich et al., 2016). Studies demonstrate practical ways for the adoption of IoT and RFID tracking technologies to digitise and automate the construction material inventories for fabrication plants. We developed an IoT and RFID tracking system and conducted a case study in a steel manufacturing plant. The results of our case study showed that the developed platform provides new possibilities for digitalization and integration in the steel fabrication industry. The web-based cloud-based automated tracking application helped project managers to reduce project costs and improve the overall efficiency of the warehouse management practices.

The impact of the developed IoT tracking architecture on project integration has been investigated in this study. As per the results, people-to-people, machine-to-machine, and people-to-machine communications through IoT technologies have impacts on projects integration in the context of industry 4.0: horizontal, vertical, and end-to-end digital integrations. While IoT-based communications can affect all levels of integration, horizontal and vertical integrations are mostly influenced by person-to-person and person-to-machine communications and digital collaborations, while machine-to-machine communication mostly affects the end-to-end digital integration. We have concluded that the digital collaboration provided by the developed IoT solution, improves the integration in our case study project.

It is recommended to conduct further research and studies on different types of projects in order to understand the positive or negative impact of I4.0 technologies and decentralize decision-making strategies on a global integration from a project and organizational point of view.

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

Appendix Information: An article based on this Appendix has been published, as per the following reference:

Rankohi, S., Bourgault, M., Iordanova, I., Carbone, C., (2022), Towards Integrated Implementation of IPD And DfMA for Construction Projects: A Review, *Proceedings of the 2022 MOC Summit,* University of Alberta (accepted for publication).

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 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.

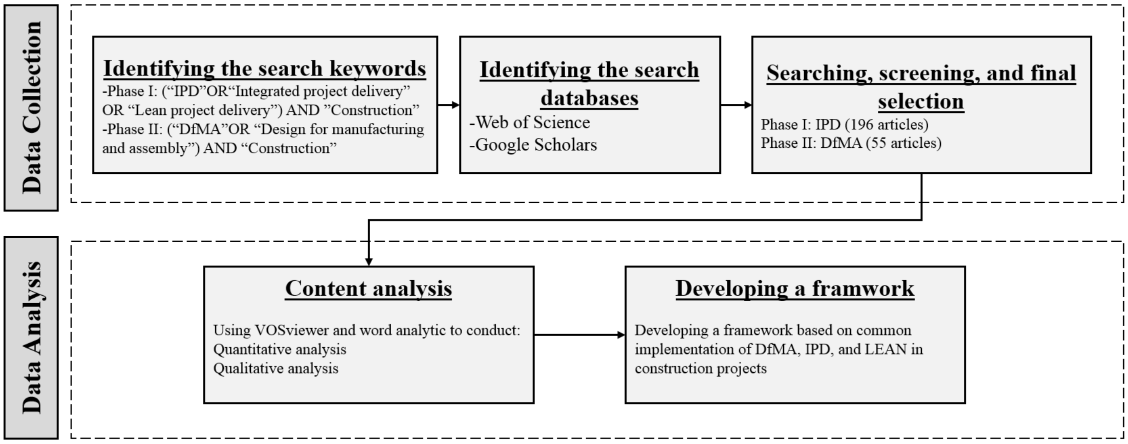

Figure 1: Flow diagram of research method.

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 the flow 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.

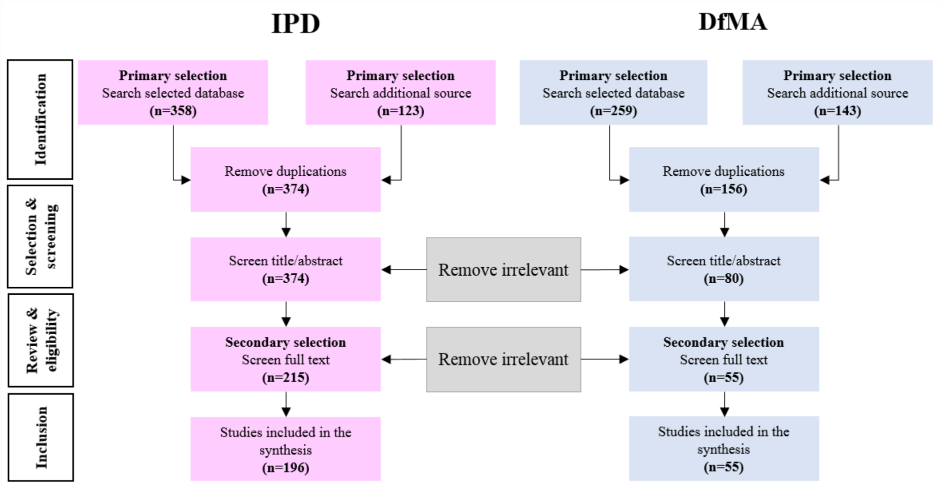

Figure 2: the flow diagram of the selected articles.

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.

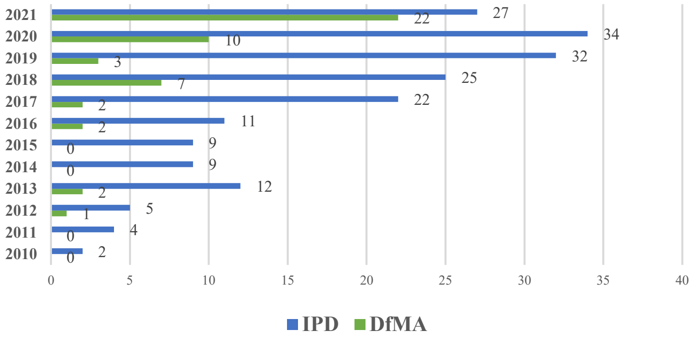

Figure 3: Distribution of articles by the year of publication.

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.

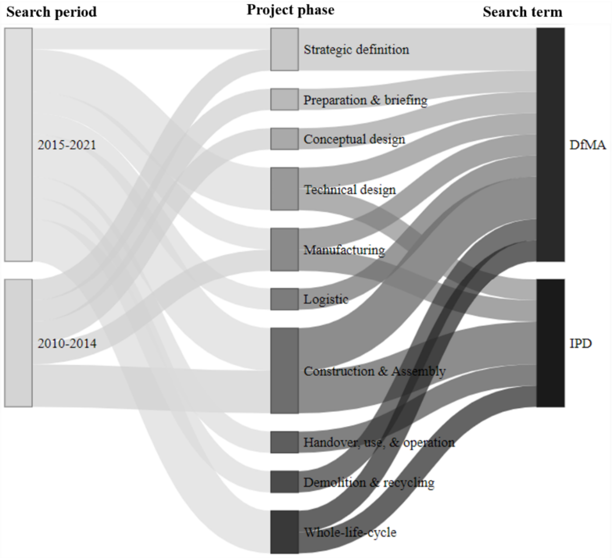

Figure 4: Sankey diagram of IPD & DfMA studies with respect to project phases.

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.

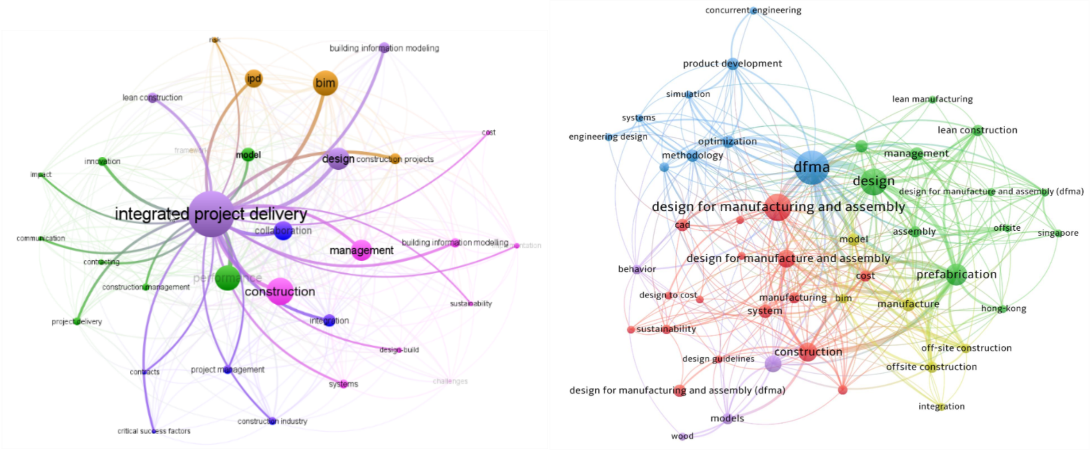

Figure 5: Co-occurrence of IPD (left) & DfMA (right) articles' keywords (VOSviewer).

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.

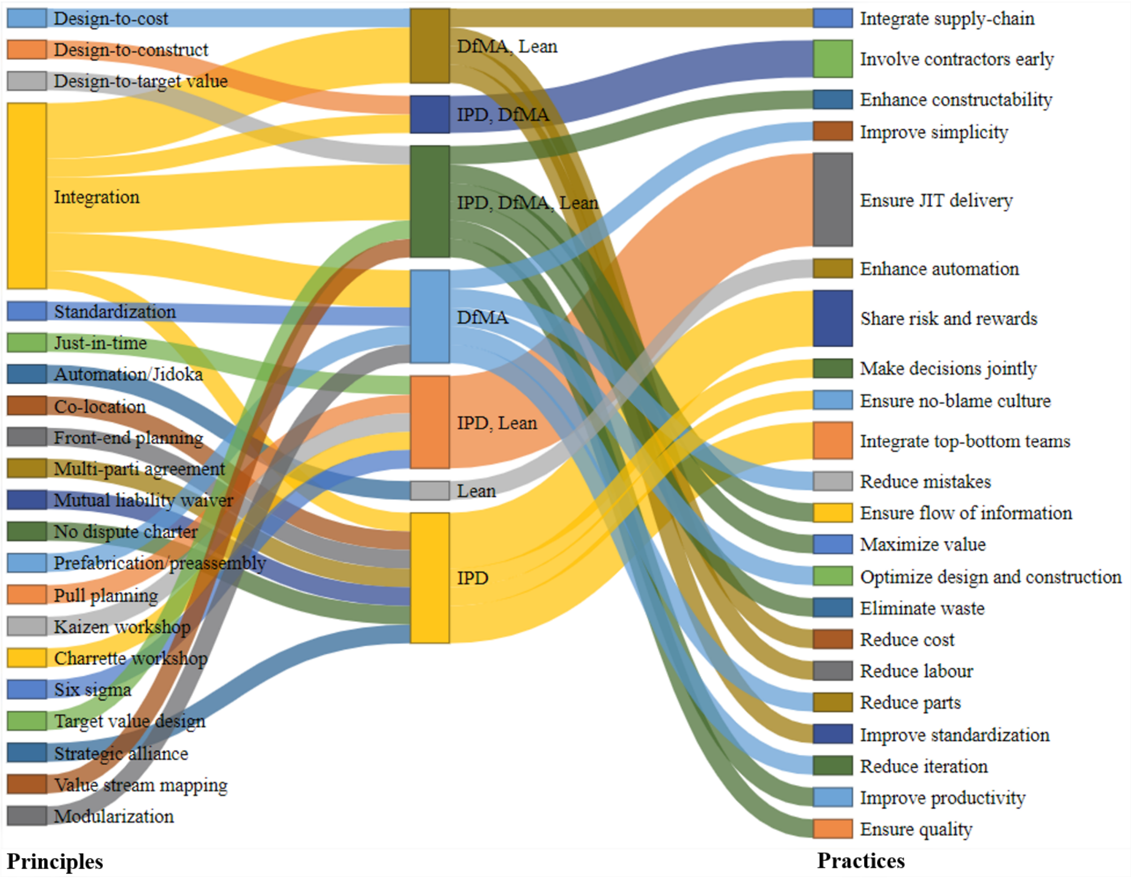

Figure 6: Sankey diagram of relationship between IPD, DfMA, and LEAN.

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.

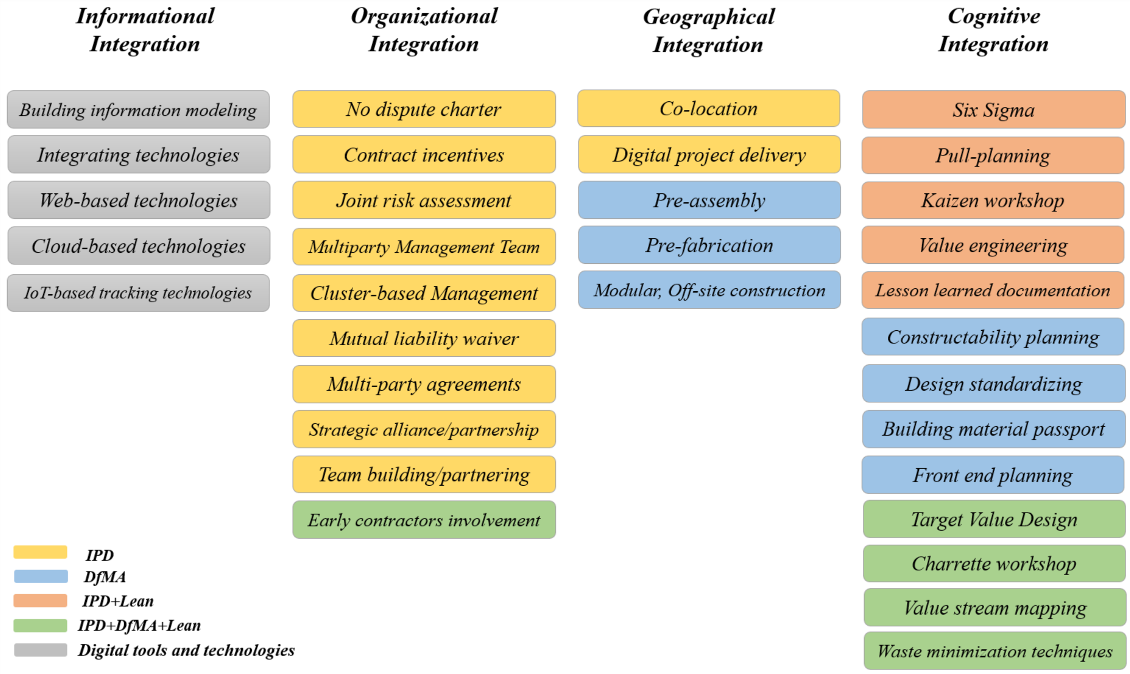

Figure 7: Various modes of integration based on IPD, DfMA, and Lean principles.

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, CCDC-30 (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).

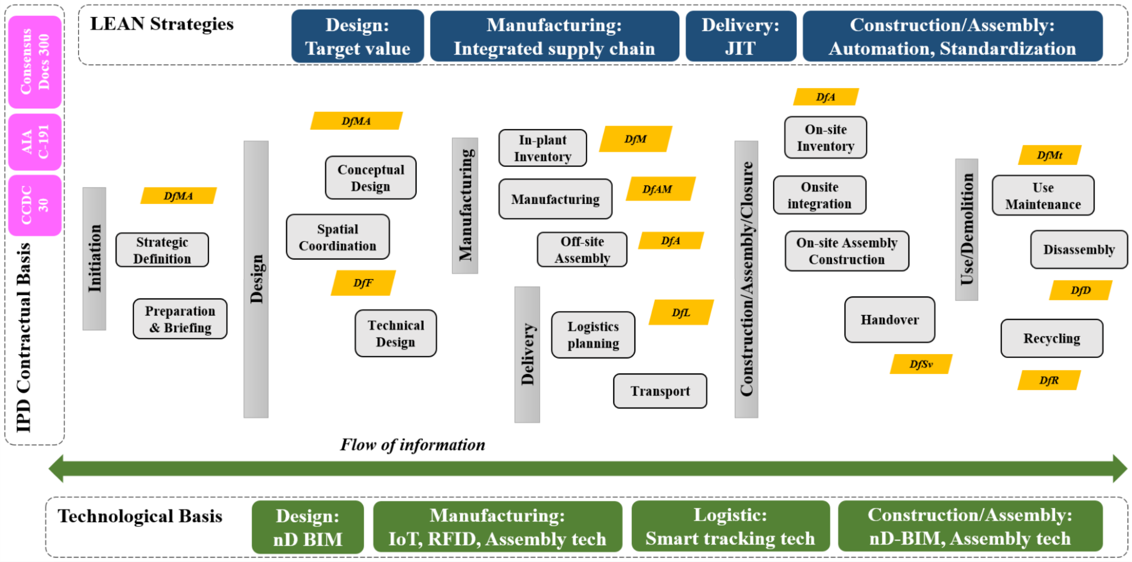

Figure 8: The proposed conceptual framework.

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.

Acknowledgments

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Appendix C DESIGN-FOR-MANUFACTURING-AND-ASSEMBLY (DFMA) FOR THE CONSTRUCTION INDUSTRY: A REVIEW

Appendix Information: An article based on this Appendix has been published, as per the following reference:

Rankohi, S., Bourgault, M., Iordanova, I., Carbone, C., (2022), Design-for-Manufacturing-and-Assembly (DfMA) for the construction industry: A review, *Proceedings of the the 30th Annual Conference of the International Group for Lean Construction* (IGLC30), University of Alberta (accepted for publication).

Abstract

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

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

Introduction

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

Methodology

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

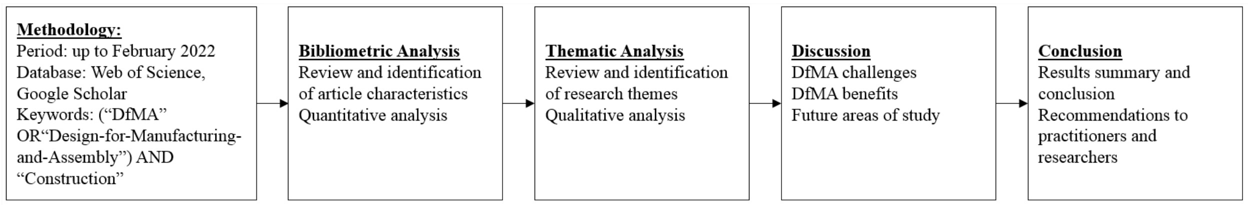

Figure 1. Methodology process of this study.

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

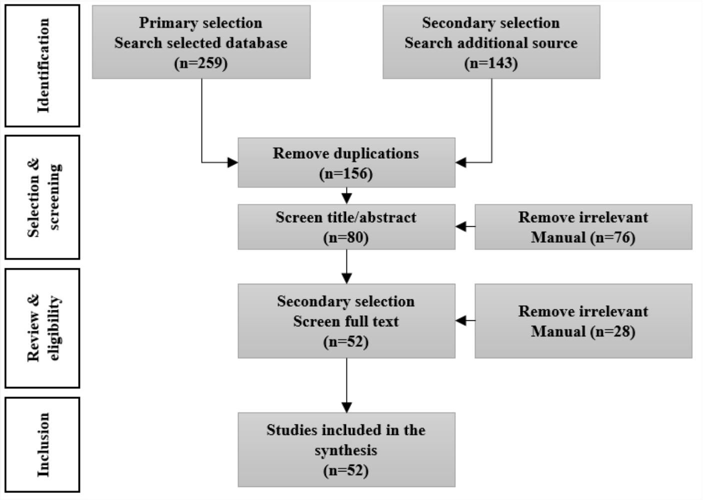

Figure 2. The flow diagram for the process of selecting journal articles.

To capture all DfMA research in the construction domain, the period of publication was not limited to certain years, and the study covers all previous years up to the present, February 2022. In the screening process, a multi-stage filtering method is conducted to extract relevant articles from the initial general searching results. In each stage, each article’s keywords and abstracts were reviewed to check whether they were in the scope of this study. Finally, only the articles whose main research focus was on DfMA in the construction industry were included. A total of 259 articles were found in the searched databases. After multiple screening of the articles by authors and excluding articles such as Subject Index and Editors Notes, the total number of selected articles was 52. The article selection process is depicted in the flow diagram (Moher et al., 2009) in Figure 2.

Bibliometric Analysis

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

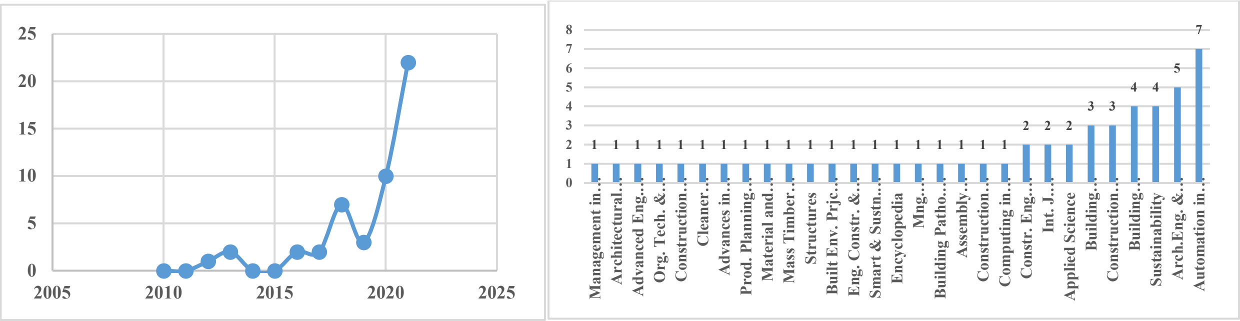

Figure 3. Left: total number of articles by year; right: total number of articles by journal.

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

Thematic analysis

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

DfMA Technologies

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

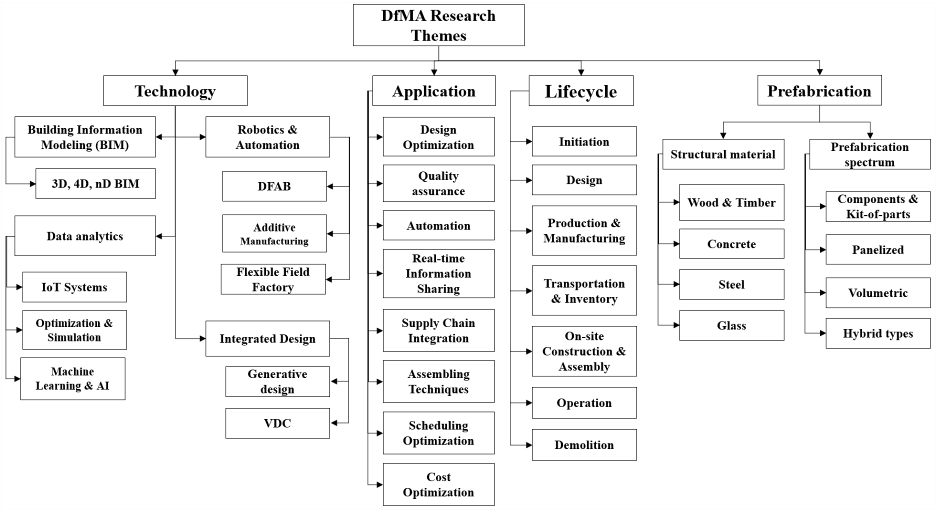

Figure 4. Identified themes in DfMA literature.

DfMA Application Areas

The second theme is *application* areas. Many studies discussed the application areas of DfMA method in construction projects, and provided case study evidence to support their findings. The most cited application areas are: design optimization (Gao et al., 2020), quality assurance (Wuni et al., 2020), automation (Yazdi et al., 2022), supply chain integration (Li et al., 2021), assembly techniques improvement (Soh et al., 2021), cost-scheduling optimization (Bakhshi et al., 2022).

DfMA and Project life-cycle

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

DfMA and Prefabrication

The fourth theme is *prefabrication*. DfMA principles have been applied to variety of prefabricated projects for various materials. Literature shows that many studies discussed the application of

DfMA in prefabricated and offsite construction projects (Bao et. al. 2021; Vaz-Serra et al., 2021; Tan et al., 2021). The majority of studies discussed DfMA techniques for improving steel and timber panelized prefabricated projects, while other studies focused on component based, kit-of-parts, and volumetric modular strategies.

Results and Discussion

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

Benefits

Several benefits are identified in the DfMA literature as: improved quality; reduced fabrication and construction cost; reduced construction time; reduced construction labor and improved health and safety; enhanced Sustainability and circular economy. Literature shows DfMA can improve the quality of construction projects throughout the design to manufacturing and construction phases (Bao et al., 2021; Favi et al., 2017). DfMA optimization reduces the cost of construction projects. Many studies have identified the impacts of DfMA research on cost reduction in the construction industry (Lu et al., 2020; Tan et al., 2020; Wasim et al., 2020). Several studies about applying DfMA in production, supply chain, and assembly, reported reduced construction period (Yin et al., 2019; Yuan et al., 2018; Qi et al., 2021). The majority of these studies applied a combination of advanced technologies (IoT, RFID, BIM, Cloud), optimization techniques and simulation algorithms. Literature states that the application of DfMA increases labor productivity by reducing or eliminating labor-intensive tasks on-site (Bakhshi et al., 2022; Machado et al., 2016). This results in improvements in health and safety during onsite assembly. Finally, few studies focused on sustainability and the environmental impact of applying DfMA in construction projects (Favi et al., 2017; Gao et al., 2018). In particular, studies with focus on DfD indicate increased sustainability as an impact of DfMA on reducing construction waste and carbon emissions, and improving circularity.

Challenges

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

Limitation of this study

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

Future areas of study

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

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

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

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

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

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

Conclusion

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

Bibliometric analysis results:

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

Countries: UK was the dominant country in which DfMA studies are conducted.

Thematic analysis results:

Technology: The majority of articles focus on DfMA adoption technical requirements, and technology application in construction projects, with less articles focusing on systems technological development.

Application areas: Over half of the articles had a principal focus on design optimization, supply chain integration or information access/sharing.

Project life-cycle: The main focus is on the design and manufacturing phases.

Prefabrication: DfMA literature emphasized on the application of DfMA for prefabricated construction from components/kit-of-parts, to panelized and volumetric modules. In terms of material, steel and wood have got the most attention, while several authors studied the application of DfMA for pre-cast concrete beams, and glass curtain walls.

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

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