BIM-driven computational design for robotic manufacturing in construction: a design-to-manufacturing approach

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Conception computationnelle pilotée par le BIM pour la fabrication robotique dans la construction : une approche de la conception à la fabrication

Walid ANANE

RÉSUMÉ

À mesure que la numérisation de l'industrie de l'architecture, de l'ingénierie et de la construction s'accélère, les technologies numériques et leur relation avec la conception et la construction atteignent un nouveau degré de complexité. L'intégration des données devient la quête des outils numériques ad hoc, et l'automatisation des flux de travail prend de l'ampleur. Ces évolutions globales contraignent l'environnement bâti à instaurer de profonds changements dans la façon dont les projets de constructions sont conçus et produits. Dans ce contexte, la modélisation des données du bâtiment (*Building Information Modeling* - BIM) a gagné du terrain dans les pratiques de conception grâce à sa capacité à englober les flux de travail de construction dans un environnement numérique. Parallèlement, l'intérêt pour la fabrication robotisée (*Robotic Manufacturing* - RM) pour la production industrialisée a considérablement augmenté grâce aux possibilités qu'elle offre en matière d'amélioration de la productivité. Cependant, l'utilisation conjointe de BIM et RM pour la construction n'a pas encore été assez étudiée dans la littérature scientifique. De plus, chacun de ces deux systèmes est caractérisé par ses logiciels et ses formats de fichiers propriétaires, ce qui implique un manque d'interopérabilité technologique entre la dyade BIM-RM.

La présente thèse par articles aborde l'opérationnalisation de la robotique dans la construction. Plus précisément, elle porte sur l'intégration technologique des outils BIM et RM pour rendre opérationnelle les robots industriels dans la construction. La revue de la littérature a d'abord révélé qu'une telle intégration est réalisable grâce aux outils de conception computationnels (*Computational Design* - CD). Elle a également révélé que la construction hors-site (*Off-Site Construction* - OSC) est un système approprié pour cette intégration technologique. Ces résultats ont été étudiés par la méthodologie de recherche en sciences du design (*Design Science Research* - DSR), qui a démontré l'interopérabilité technologique de la triade BIM-CD-RM dans les systèmes OSC. Cette convergence technologique a donné naissance au cadre de la conception à la fabrication (*Design-to-Manufacturing* - DtM), qui a été validé par un groupe de 16 évaluateurs.

Mots-clés : Conception à la fabrication; Interopérabilité; BIM; Conception computationnelle; Fabrication robotique; Construction hors-site

BIM-driven computational design for robotic manufacturing in construction: a design-to-manufacturing approach

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ABSTRACT

As the Architecture, Engineering, and Construction (AEC) industry's digitization accelerates, digital technologies and their relation to design and construction are reaching a new level of complexity. Data integration is becoming the quest of ad hoc digital tools, and workflow automation is gaining momentum. These global developments are forcing the built environment to implement drastic changes in how construction projects are designed and produced. In this context, Building Information Modeling (BIM) gained momentum in design practices through its ability to frame construction workflows in a digital environment. On the other hand, interest in Robotic Manufacturing (RM) for industrialized production has significantly increased thanks to the opportunities it offers to improve productivity. However, the joint use of BIM and RM in construction has not yet been sufficiently studied in the scientific literature. Moreover, each system is characterized by its software and proprietary file formats, implying a lack of technological interoperability between the BIM-RM dyad.

The present article-based thesis investigates the operationalization of robotics in construction. Specifically, it studies the technological integration of BIM and RM tools to operationalize industrial robots in construction systems. The literature review initially found that such integration is achievable through Computational Design (CD) tools. It also found that Off-Site Construction (OSC) is a suitable system for this technological integration. These findings were studied through the Design Science Research (DSR) methodology, which demonstrated the technological interoperability of the BIM-CD-RM triad in OSC systems. This technological convergence gave rise to the Design-to-Manufacturing (DtM) framework, which was validated by a board of 16 evaluators.

Keywords: Design-to-manufacturing; Interoperability; BIM; Computational design; Robotic manufacturing; Off-site construction

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LIST OF ABREVIATIONS

3D	Three Dimensional
3DCP	3D Concrete Printing
AAD	Algorithmic-Aided Design
AEC	Architecture, Engineering, and Construction
AI	Artificial Intelligence
AM	Additive Manufacturing
API	Application Programming Interface
AR	Augmented Reality
BIM	Building Information Modeling / Management / Model
Brep	Boundary representation
CAE	Computer-Aided Engineering
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CD	Computational Design
CNC	Computer Numerical Control
DfM	Design for Manufacturing
DfMA	Design for Manufacturing and Assembly
DfX	Design for X
DSR	Design Science Research
DtM	Design to Manufacturing

ED	Evolutionary Design
FEDS	Framework for Evaluation in Design Science Research
GD	Generative Design
IFC	Industry Foundation Classes
IoT	Internet of Things
MEP	Mechanical, Electrical and Plumbing
MR	Mixed Reality
O&M	Operation and Maintenance
OBJ	Object File
OSC	Off-Site Construction
PD	Parametric Design
REST	Representational State Transfer
R.I.R	Rhino.Inside.Revit
RM	Robotic Manufacturing
SLR	Systematic Literature Review
STEP	Standard for the Exchange of Product model data
STL	Standard Triangle Language / Standard Tessellation Language
TCP	Tool Center Point
UI	User Interface
VDC	Virtual Design and Construction
VR	Virtual Realiy

INTRODUCTION

Digital technologies in the Architecture, Engineering, and Construction (AEC) industry have introduced a new data culture that has transformed the built environment's design practices (Gehry, Lloyd et Shelden, 2020). These technologies have shaped the digital age of the AEC industry through their distinctive outputs. However, this digital shift is uneven between the design and construction phases. Indeed, digital construction operations are seldom executed and are still dependent upon hand machinery (García de Soto *et al.*, 2022). This reliance hinders productivity when lacking human labor, as in the case of Canada's industry (Poirier *et al.*, 2018), making the digital transition to industrialized construction more prized than ever. For this reason, the digital disparity between design and construction phases needs to be revisited.

Although data collection was tedious before the digital age, today's design tools witness data abundance (Carpo, 2017). Systems such as Building Information Modeling (BIM) stand out from conventional Computer-Aided Design (CAD) through their native integration of information functions. This system has provided access to informed modeling and reinforced the value of data management (Shepherd, 2019). BIM is also a catalyzer for collaborative processes; it provides a digital environment that centralizes information for all stakeholders in a construction project (Race, 2019). This capacity helps to counteract the under-performance and non-optimal value generated by the AEC industry. However, BIM is not yet sufficiently deployed for digital production, especially for Robotic Manufacturing (RM) (Yin *et al.*, 2019).

Industrial robots have been operating in manufacture settings for over half a century (Gurgul, 2018). With the ever-increasing interest in automated production, this technology is being relatively employed in several industries (Dachs, Fu et Jäger, 2022). However, in contrast to the widespread adoption of industrial robotics in the automotive industry, their implementation in the AEC sector remains underdeveloped (Davila Delgado *et al.*, 2019). This mismatch stems from the Computer-Aided Manufacturing (CAM) tools used for robotic control, which are typically unsuitable for highly variable construction operations. Indeed, most of these robots are only controlled through proprietary programming languages and are not rapidly responsive to design changes (Garcia del Castillo Lopez, 2019). Such requirements render robots notoriously challenging to control and present a steep threshold for construction practitioners. Moreover, RM programming tools are not yet technologically integrated with BIM software (Davtalab, Kazemian et Khoshnevis, 2018). Their use is dissociated, meaning that design and robotic programming are performed in two different technological environments. This disparity between the tools of the BIM-RM dyad reflects weak technological interoperability, which has motivated the present research.

Interoperability is the ‘‘ability of two or more systems or applications to exchange information and to mutually use the information that has been exchanged’’ (International Organization for Standardization, 2017). Although this notion was originally limited to the technological paradigm, it evolved within different dimensions depending on the systems involved. Since the present research is purely technological, this thesis bridges design and manufacturing by exclusively focusing on the technological interoperability of BIM and RM tools. The starting context of this research is presented in Figure 0.1.

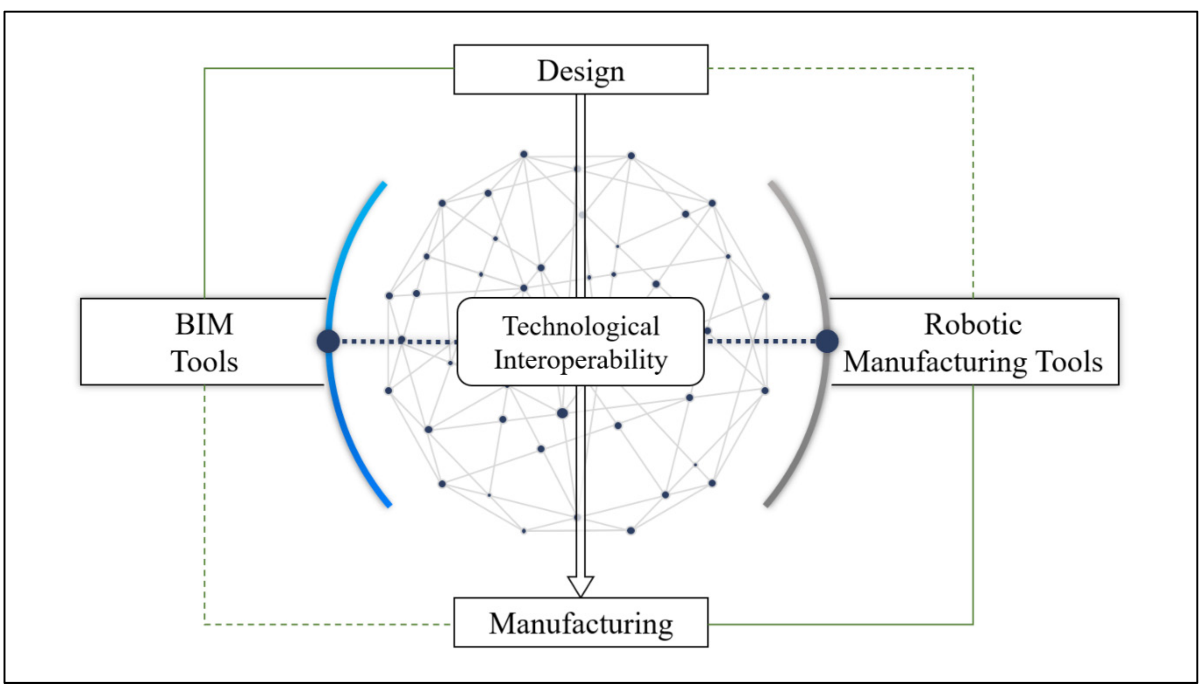

Figure 0.1 The starting context of the research project

The illustration of the starting context of this work highlights the disjunction between the BIM and RM tools. Such disjunction implies the technological fragmentation of the construction system, shown by dashed lines. Therefore, this research effort focuses on technological interoperability and extends to digital integration. In this sense, design decisions orchestrate manufacturing operations from the earliest stages of the design phase. This technological integration gives rise to the Design-to-Manufacturing (DtM) approach. Using the Design Science Research (DSR) methodology, this approach is presented as a framework; it is then demonstrated and evaluated by practitioners. Two research questions have initiated this work:

- Q1: How can technological integration between BIM and RM be achieved?
- Q2: Currently, which construction system is technologically suitable to put into practice the BIM-RM integration?

This article-based thesis comprises four papers, two journal articles (submitted for review) and two conference proceedings (published). Both journal articles are presented as chapters, and the two conference proceedings are presented as appendices to complement the last chapter. Each paper can be read as a standalone article, and the research methodology (Chapter 2) is a thread that ties them all together. Therefore, this thesis is structured as the following:

- Chapter 1: BIM and robotic manufacturing technological interoperability in construction – a cyclic systematic literature review (*first journal paper - submitted to the Journal of Digital Manufacturing Technology*);
- Chapter 2: The DSR methodology that drives this research;
- Chapter 3: BIM-driven Computational Design for Robotic Manufacturing in Off-Site Construction: A Design-to-Manufacturing Approach (*second journal paper - submitted to the Journal of Automation in Construction*);
- Appendix I: The use of BIM for robotic 3D concrete printing (*first conference paper - published in the Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021*);
- Appendix II: Modular Robotic Prefabrication of Discrete Aggregations Driven by BIM and Computational Design (*second conference paper - published in the special issue of Procedia Computer Science*).

The structure of this thesis is presented in Figure 0.2, it illustrates the DtM framework as the central element of this research, and guides the reader through the different chapters that have supported its completion. It is important to mention that three chapters are implicit in this structure, the Discussion (Chapter 4), the Conclusion, and the Recommendations.

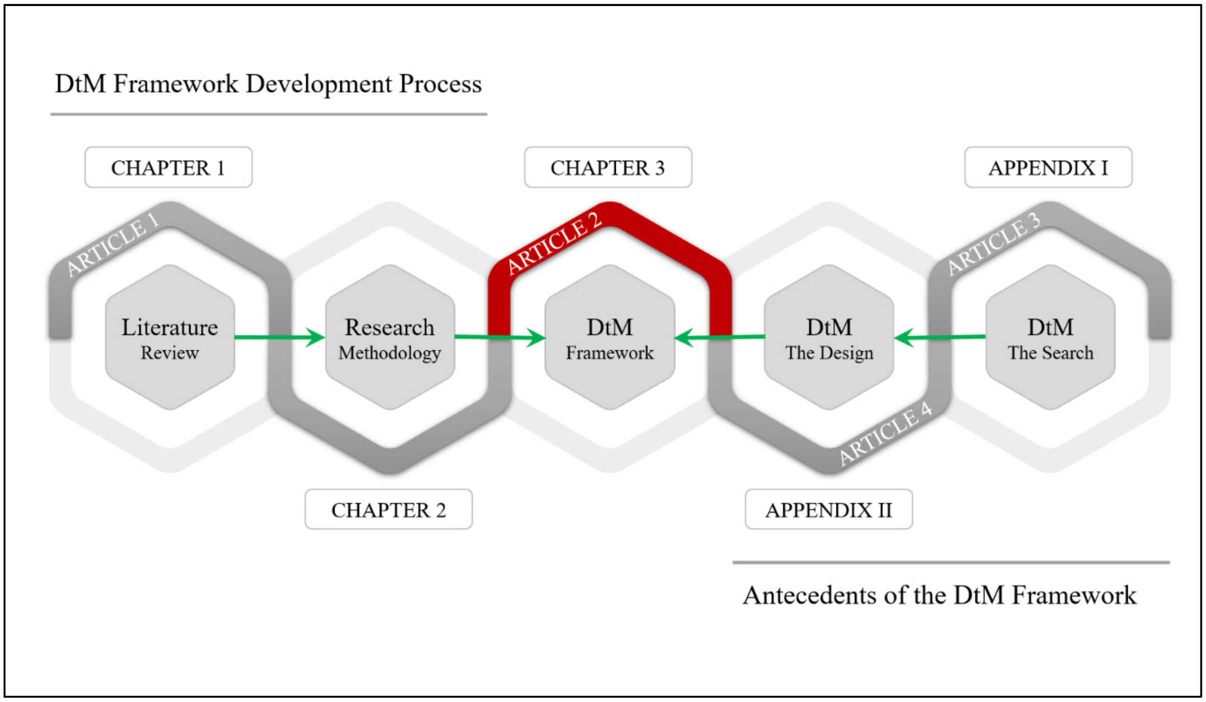

Figure 0.2 The structure of the article-based thesis

The main objective of the DtM framework is to extend the design process by incorporating the execution of a robotic program within integrated technological environments. Once integrated, the routines can be operated by the robot alongside the design phase. Therefore, this research contributes to knowledge by proposing a workflow for integrating the BIM-RM dyad. In addition, the DtM approach enhances the Design for Manufacturing (DfM) method; it is not limited to considering manufacturing requirements and instead programs, simulates and operationalizes industrial robots for construction. Finally, this research provides new approaches using existing and common technological tools in the AEC industry.

CHAPTER 1

BIM AND ROBOTIC MANUFACTURING TECHNOLOGICAL INTEROPERABILITY IN CONSTRUCTION – A CYCLIC SYSTEMATIC LITERATURE REVIEW

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1.1 Abstract

The Architectural Engineering and Construction (AEC) industry is undergoing a digital transformation that progressively improves its performance, productivity, and competitiveness. This digital shift is accelerated through Building Information Modeling (BIM) that facilitates technological integrations. BIM has significantly contributed to digitizing design and management activities. However, it has not yet sufficiently demonstrated its interoperability with digital manufacturing processes, such as Robotic Manufacturing (RM). It is from this perspective that this work will review the current literature's stance on the technological interoperability of BIM and RM tools through the Systematic Literature Review (SLR) method. This literature review aims to identify research avenues to operationalize RM through BIM tools in construction. The study conducted in this research is progressive; it builds on the identified research gaps and investigates potential research avenues to be undertaken. The results revealed that Computational Design (CD) could serve as a bridge between BIM and RM. They also revealed that RM is operationalizable in Off-Site Construction (OSC) through BIM and CD.

Keywords: Interoperability, BIM; Robotic manufacturing; Computational design; Off-site construction

1.2 Introduction

The construction industry is experiencing significant challenges due to low productivity and a shortage of skilled labor (Agarwal, Chandrasekaran et Sridhar, 2016 ; Chen, García de Soto et Adey, 2018). Digital transformation offers a promising alternative to overcome these challenges, mainly through digitizing design and manufacturing workflows (Correa, 2020). Indeed, digitization transforms the way stakeholders generate and consume information. It allows for information production, management and materialization in construction projects. This digital shift is the basis of a new revolution in construction known as Construction 4.0 (Wang *et al.*, 2022 ; Forcael *et al.*, 2020). The driving force of this revolution relies on the convergence of technologies, enabling the effective management of relevant data in a collaborative manner, which is then materialized through cyber-physical systems (Ammar et Nassereddine, 2022). In this context, Building Information Modeling (BIM) and Robotic Manufacturing (RM) are two fundamental systems in Construction 4.0.

The philosophy behind BIM is that all collaborators involved in design and construction use centralized information in a digital model that is relatively accessible throughout all stages of a construction project (Race, 2019). This system is mainly focused on highly informed modeling, management, and collaboration. On the other hand, the quest for automation in construction has often resulted in research involving RM (Siciliano et Khatib, 2016 ; Willmann *et al.*, 2019). Indeed, *automation* in construction is defined as implementing industrial automation principles in the built environment practices (Cousineau et Miura, 1998 ; Dachs, Fu et Jäger, 2022 ; Sawhney, Riley et Irizarry, 2020). At the manufacturing level, these principles are often translated through industrial robots. However, as BIM and robotics are increasingly studied in construction, this review identified two research questions on the joint use of BIM and RM:

- Q1: How can technological integration between BIM and RM be achieved?
- Q2: Currently, which construction system is technologically suitable to put into practice the BIM-RM integration?

This work aims to *provide potential solutions to these questions as documented in the literature and pave the way for exploring new perspectives in research*. In order to identify possible ways to converge these two distinct systems for their use in a shared environment, this literature review focuses on the technological interoperability of these two systems. Originally, *interoperability* was defined as: ‘‘the ability of two or more systems or components to exchange information and use the information exchanged’’ (IEEE, 1990). This definition was initially limited to data transfer and thus to the technological aspect of interoperability among systems. Interoperability terminology in research then evolved to incorporate different dimensions defined by Poirier, Forgues et Staub-French (2014) as ‘‘technological, organizational, procedural, and contextual’’ interoperability. However, due to the broad scope of each dimension, this literature review only focuses on the technological aspect of BIM-RM interoperability.

This research uses the Systematic Literature Review (SLR) methodology through two cycles. The first cycle starts with an in-depth bibliometric study on the BIM-RM technological interoperability. This investigation showed that BIM and RM are evolving in parallel, and there is not much work that brings them together. For this reason, the authors directed this literature review toward possible solutions for bridging BIM and RM through an in-depth analysis of the SLR results. This investigation concluded that BIM and RM could be bridged through Computational Design (CD) tools.

This finding initiated the second SLR cycle, which suggests a construction system that is technologically interoperable with BIM-CD-RM triad. This study revealed that Off-Site Construction (OSC) is appropriate for such an application. The present article is divided into two sections. The first section is dedicated to studying BIM-RM technological interoperability and concludes with the CD perspective of enabling this dyad. The second section is reserved for the potential of OSC for linking BIM, CD, and RM. It is divided into three dyads: BIM-OSC, CD-OSC, and RM-OSC. Finally, this article concludes with a discussion and a conclusion.

1.3 The Systematic Literature Review (SLR) methodology

The objective of this article is to synthesize the existing body of knowledge on the joint use of BIM and RM through the SLR method. It is a five-step cyclic approach adapted from Kitchenham (2004) ; Van Eck and Waltman (2010) ; Moher et al. (2015) that involves identification of the research, bibliographic research, eligibility assessment, bibliometric analysis, and finally, data-synthesis and research hypothesis.

Following the research questions presented in the introduction, bibliographic research is initiated. In this study, the databases chosen were Scopus and Dimensions. They encompass a broader range of Engineering research compared to other databases such as Web of Science or PubMed (Mongeon et Paul-Hus, 2016 ; Singh *et al.*, 2021 ; van Eck et Waltman, 2014a). Therefore, the bibliographic research was conducted using keywords that quantifies the publications available through these databases. After collection, these publications underwent an eligibility assessment by reviewing their title, abstract, keywords, figures, and conclusions. This investigation reduced the number of publications on hand and permitted the start of the bibliometric analysis. This step was based on a qualitative analysis of the various publications collected. It was managed by investigating keyword co-occurrence networks generated through VosViewer software (van Eck et Waltman, 2014b ; Waltman et van Eck, 2012 ; Waltman, van Eck et Noyons, 2010). The results of this analysis were finally synthesized; they led to identifying research avenues and hypotheses. Figure 1.1 shows the steps of the SLR methodology, which the present study used through two cycles.

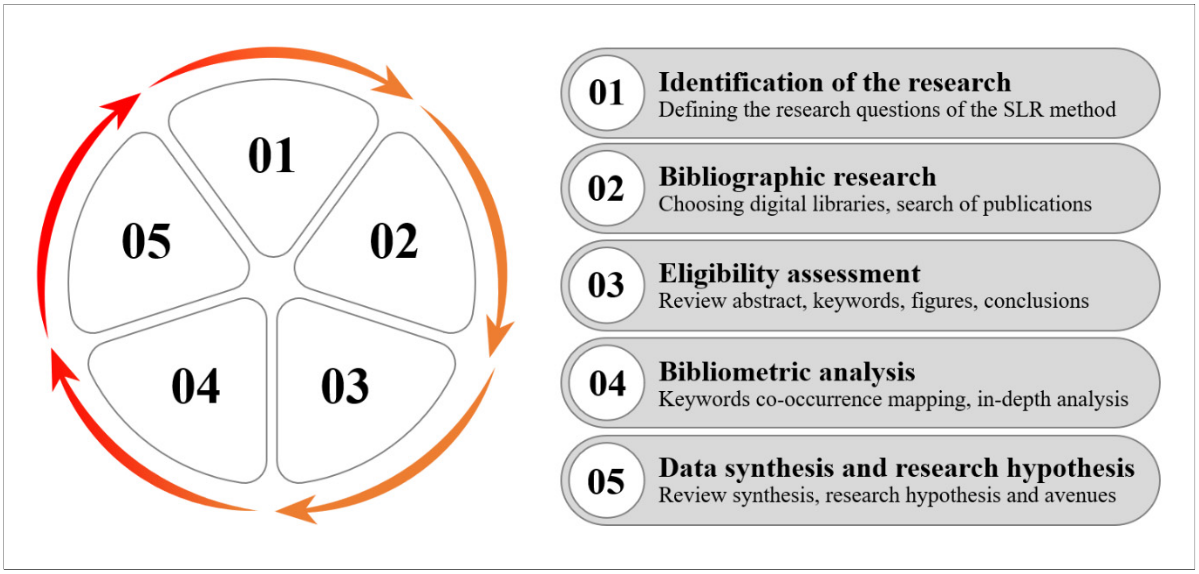

Figure 1.1 Systematic Literature Review (SLR) methodology conducted through two cycles

In engineering, the time before scientific publications become outdated is often debated. Depending on the field, this period is either five or three years (Al-Emran et Shaalan, 2021). BIM, CD, RM, and OSC are widely developed separately and attract further research interest. However, their dyadic relationship is not similarly studied in the literature; some are highly investigated, others much less so. As a result, two types of dyads are qualitatively identified in this review; *dyads with interconnected technological evolution* and *dyads with parallel technological evolution*. In this context, this review is based on publications from the last five years (between 2018 and 2022), given that three years are not enough for technologies to mature. Their qualitative evaluation is based on the number of articles published, their extensive deployment in research, and their use of industrial case studies. This categorization allowed the authors to evaluate the different dyads in their latest evolution state. Therefore, it simplified identifying research hypotheses and avenues.

The present study conducted SLR cycles according to search tags in the articles' titles, abstracts, or keywords. These studies are reproducible since all search tags and the filtering results are communicated in Appendix III. In order to allow an extensive evaluation of the different dyads, SLRs were supported by ‘‘backward and forward snowballing.’’ This technique uses ‘‘forward snowballing’’ to identify where the studied article was cited and ‘‘backward snowballing’’ to see on which citations this article was based (Wohlin, 2014 ; Felizardo *et al.*, 2016 ; Wohlin *et al.*, 2022). This support stops after reaching the cap of 30 documents; it implies that the investigated dyad is extensively studied in research. In this context, VosViewer visualizations are limited to the Scopus base in case of extensive literature. However, these visualizations are based on both databases in case of a lack of documentation. This choice was made to improve the consistency of the keyword clusters in the VosViewer mappings. In addition, to approximate the different clusters related to the systems involved, the keywords generated are color coded and variable in size. The colors are light blue for BIM, dark blue for CD, grey for RM and green for OSC. The larger they are represented, the more they are co-occurring.

1.4 BIM-RM technological interoperability (2018-2022): First SLR cycle

The first SLR cycle was intended to answer the first research question (Q1), *how can technological integration between BIM and RM be achieved?* Therefore, this section reviewed BIM-RM technological interoperability in the literature. It studied the different approaches of researchers and evaluated the best technological way to integrate BIM and RM. This section concludes with research avenues and hypotheses that led to the investigation of the second research question.

1.4.1 BIM-RM bibliographic review and eligibility assessment

BIM is defined as interacting processes and technologies that provide a digital framework for designing and managing construction projects (Shepherd, 2019 ; Poirier *et al.*, 2018). It is a mature system that touches various construction aspects, making it a facilitator of complex workflows. Furthermore, BIM is acknowledged for its potential to improve the productivity of construction processes, a capability it shares with RM (Rogers, 2018 ; Simpson *et al.*, 2019 ; García de Soto *et al.*, 2018 ; Gurgul, 2018). Indeed, since robots were introduced to production lines, RM has improved productivity and relieved workers of significant workloads (Liu *et al.*, 2022). Robotic equipment plays a central role in industrial automation by bringing a cyber-physical basis for manufacturing processes. Their success in this context has given rise to the concept of *industrial robots*.

According to ISO 8373:2021 (International Organization for Standardization, 2021), ‘‘an *industrial robot* is an automatically controlled, reprogrammable, multi-purpose manipulator, programmable in three or more axes, that can be either fixed in place or attached to a mobile platform for use in automation applications in an industrial environment.’’ Based on this definition, programmable machines such as 3D printers or laser cutters are not considered industrial robots since they are not multi-purpose. Instead, this definition is often linked to robotic arms, the most widely used robot for industrial automation (Aldinhas Ferreira et Fletcher, 2022 ; Dachs, Fu et Jäger, 2022). Therefore, to narrow the breadth of this research, the present work is focused on the technological interoperability between BIM and RM using robotic arms.

The bibliographic review initiating the first SLR cycle resulted in 10 documents in Scopus and seven in Dimensions. After deleting the duplicates, the number of articles amounted to 16 documents, initiating the eligibility evaluation. This step only included publications with *sufficient* BIM and RM content. In this context, *sufficient* coverage of both systems was not limited to the act of mentioning or defining them. Publications were eligible if they included a study with minimal comprehensive coverage of the combined use of BIM and RM. Therefore, following a thorough investigation of the literature, 14 articles were retained. In order to have a more exhaustive bibliographic process, the ‘‘snowballing’’ method was used to identify more articles related to this research topic. This approach raised the documents found to 18; they are listed in Appendix IV.

1.4.2 BIM-RM bibliometric analysis

The list of articles showed that this research topic has been gaining interest over the years, although containing only a few articles. However, many publications do not demonstrate BIM-

RM technological interoperability through real-world case studies. They are often limited to the prospect of coupling these systems in the construction industry. Indeed, research projects are often unfinished or are in the process of using BIM for basic modeling. In addition, the joint use of BIM and RM varies between authors, generating ambiguity regarding the best approach to adopt. This variation is noticeable through the BIM-RM technological interoperability keyword network, illustrated in Figure 1.2.

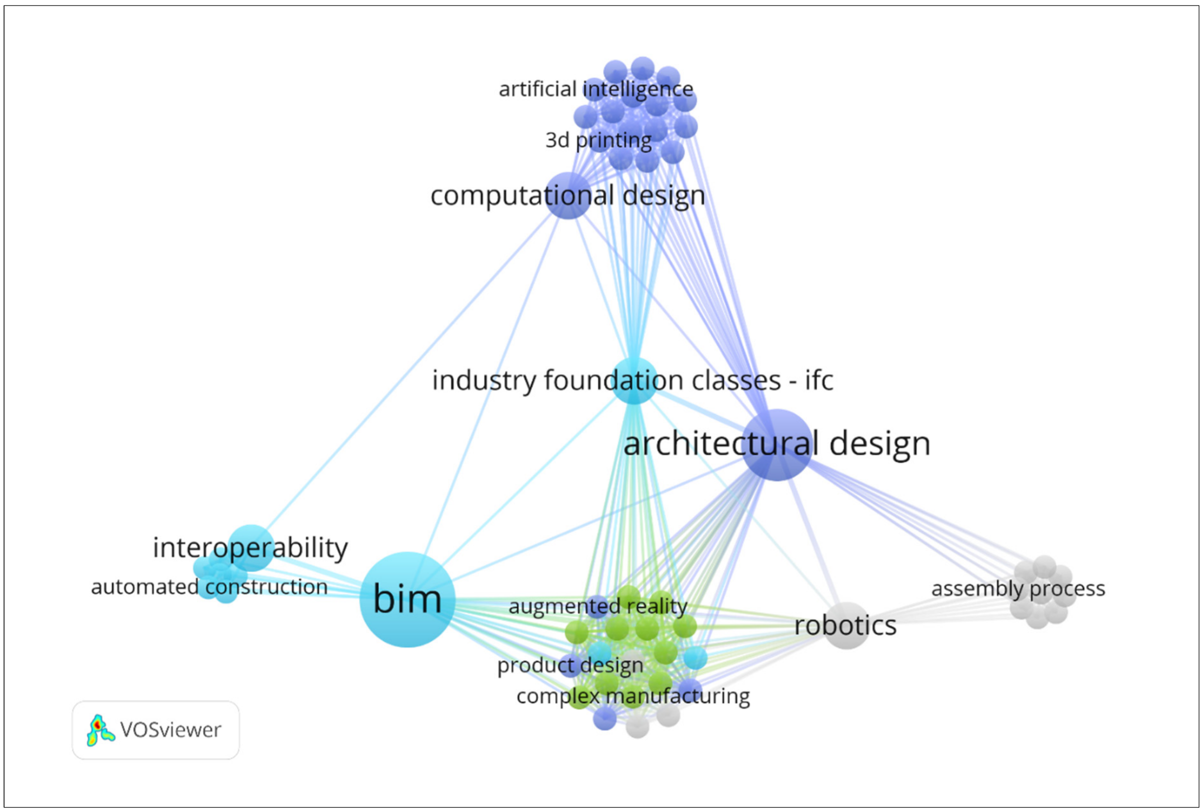

Figure 1.2 Keywords co-occurrence network of BIM-RM technological interoperability within the literature (2018-2022)

Despite the lack of research on the BIM-RM dyad, this bibliometric mapping allowed us to assume that there is a potential common ground for these systems in the construction industry. Indeed, throughout the different publications, BIM-RM data exchange can follow three paths: either through transfer of file formats (e.g. IFC), Computational Design (CD), or both. Therefore, the different approaches combining BIM and RM were classified according to

Janssen (2015), who reported that coupling with BIM software involves a *loosely coupled or a tightly coupled approach*. A *loosely coupled approach* involves the exchange of models through file transfer. A *tightly coupled approach* involves the exchange of models through the modeling software's application programming interface (API). These definitions were customized for this research context since the third case of BIM-RM technological coupling can be achieved alternatively through APIs and exchange of file formats. This workflow is named a *moderately coupled approach*. The three approaches are discussed in the following sections.

1.4.2.1 Loosely coupled approach

The loosely coupled approach illustrated in Figure 1.3 is the most commonly used approach for bridging BIM and RM (Slepicka, Vilgertshofer et Borrmann, 2021 ; Davtalab, Kazemian et Khoshnevis, 2018). This approach is usually the easiest since it involves a simple export, import, or conversion of file formats. However, it is the least efficient approach in terms of technological interoperability. Indeed, BIM file format exchange is often based on IFC. On the other hand, RM formats are often based on STL, STEP, or OBJ. This disparity in data communication tools leads to data structure conflicts between proprietary software, resulting in information loss during data exchange. For example, the most used BIM software in the available literature is Revit. Currently, this software does not support the import/export formats STL, STEP, and OBJ. Therefore, researchers tend to develop new extensions or use external converters to circumvent this problem (He *et al.*, 2021).

Even with such solutions, exporting data disrupts BIM workflows. RM software remains disjointed from the design and management processes, reducing the value of using BIM. In these contexts, the model is often iteratively modified without real-time insight into its manufacturability. Indeed, the design parameters of the model are lost at export, and will have to be reworked in the case of manufacturing programming failure. These limitations of *the loosely coupled approach* demonstrate that the undertaken research in BIM-RM technological interoperability is ambitious but not yet effective.

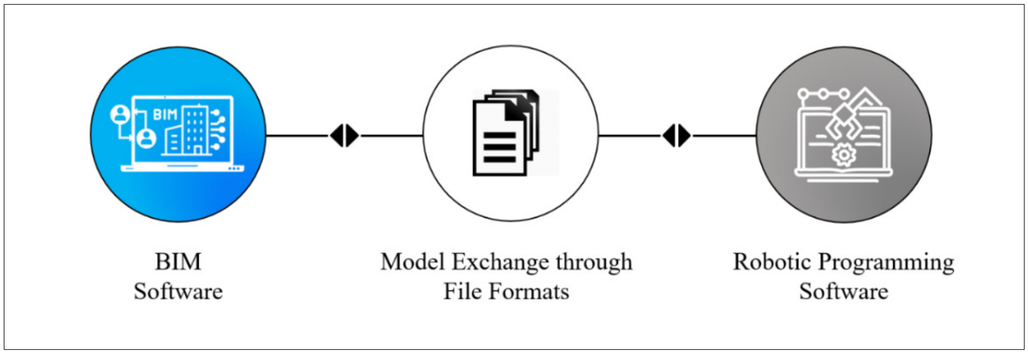

Figure 1.3 Loosely coupled approach for exchanging data between BIM and Robotic Manufacturing (RM) tools

1.4.2.2 Moderately coupled approach

The moderately coupled approach is a step towards data integration. From this perspective, researchers use software APIs to perform either a BIM workflow or robotic programming. What dissociates these two workflows is the modeling environment. In the work by Wong Chong et al. (2022), the modeling is initially performed in BIM software. Next, this model is included in a simulation environment by adapting the IFC format to the robotic context. Finally, it is automatically redesigned and programmed for manufacturing. Momeni et al. (2022) perform a similar experiment but slightly differ in managing BIM data. They manually extracted the manufacturing information and developed a specific plugin for a simulator. Such an approach is tedious and requires a significant amount of manual effort for punctual automation.

Nevertheless, *the moderately coupled approach* is more efficient than *the loosely coupled approach*; it allows minimum responsiveness between the modeling and manufacturing workflows. It also reduces the range of software used and gives a clearer perspective of BIM-RM interoperability. However, the disjunction between BIM and RM environments is still prevalent. This limitation minimizes the feedback capability between design and manufacturing processes. This approach is illustrated in Figure 1.4, where the modeling environment is taken as the source and enables either an integrated BIM workflow or an integrated RM workflow.

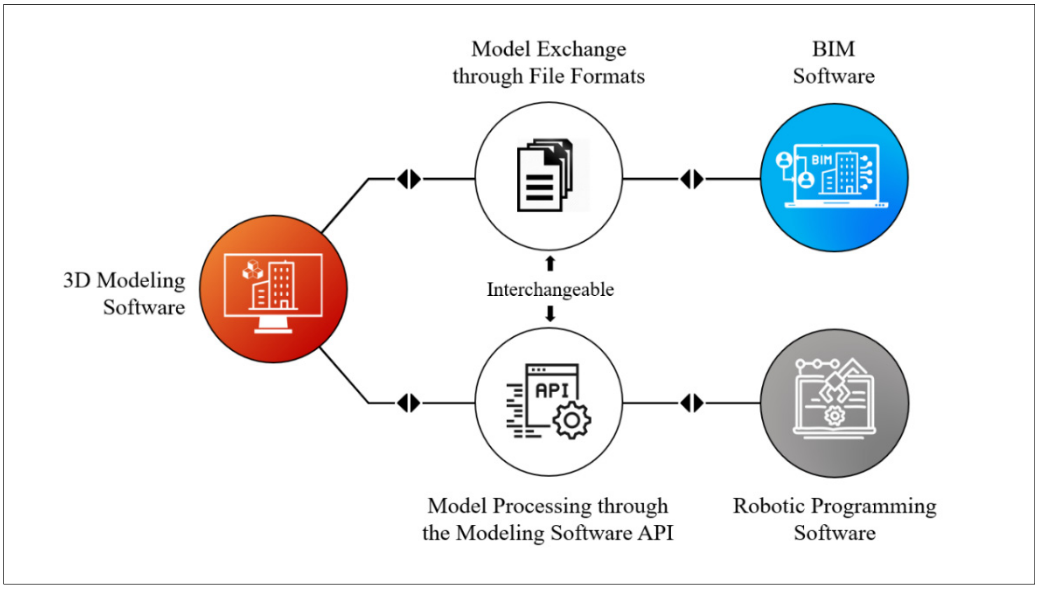

Figure 1.4 Moderately coupled approach for exchanging data between BIM and Robotic Manufacturing (RM) tools

1.4.2.3 Tightly coupled approach

Illustrated in Figure 1.5, the last approach identified in this SLR is *the tightly coupled approach*. This approach is equivalent to integration or interdependent coupling through the APIs of the software used. It is also format-agnostic, meaning that no proprietary file formats are used in the workflow. As a result, this approach offers the most consistent BIM-RM technological interoperability compared to previous approaches. Indeed, *the tightly coupled approach* provides reciprocal access to the different functions of the coupled software, offering the possibility of their technological integration.

In the case of interdependent coupling (e.g., through Representational State Transfer (REST) APIs), model exchange is processed using a connecting plugin. Unlike export and import, this method preserves the native characteristics of the models and overcomes data structure incompatibilities. Moreover, in the case of environment integration, this same model is no longer transferred but processed for manufacturing in the same technological environment. This technological interoperability provides significant resource savings as the information is native and the workflows are centralized. Therefore, it enables a feedback loop between design, BIM workflows, and robotic manufacturing processes. However, *the tightly coupled approach* is the least used in the current context of BIM-RM interoperability. Nevertheless, two publications have applied this approach: Forcael et al. (2021) and Ali, Lee et Song (2021); both of which used *computational design tools*.

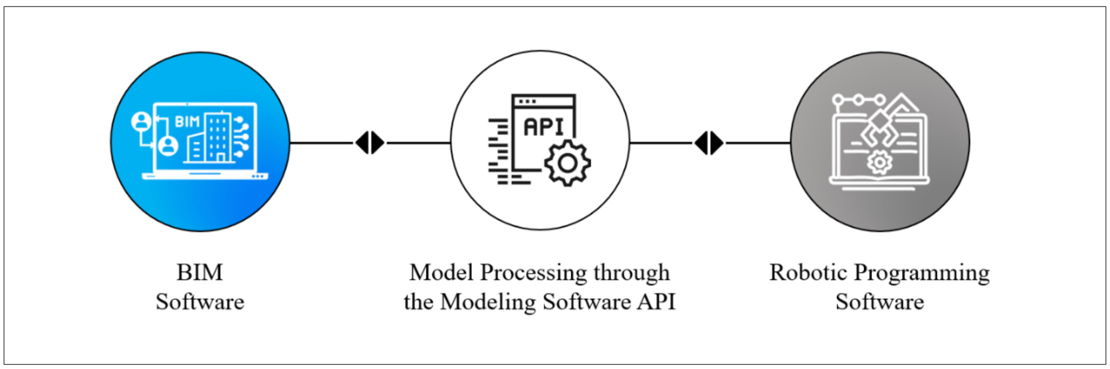

Figure 1.5 Tightly coupled approach for exchanging data between BIM and Robotic Manufacturing (RM) tools

This bibliometric review highlighted the BIM-RM interoperability gap and the inconsistency of most publications available. Indeed, the limited number of articles collected on the topic presented limited results in terms of technological interoperability. The information flow is fragmented, and the use of both systems is mainly loosely coupled. This analysis allows the authors to assume *that BIM and RM are in a parallel technological evolution*.

Nevertheless, this review has given rise to a potential enabler for BIM-RM technological integration that is still little explored: *Computational Design* (CD). Indeed, CD tools were used in *the tightly coupled approach* for integrating BIM and RM; CD also appeared as a potential bridge in Figure 1.2. For these reasons, the bibliometric analysis was supported by a specific review of the CD taxonomy. It is followed by CD perspectives for bridging BIM and RM.

1.4.3 Computational design taxonomy

In the AEC industry, CD systems are progressively developing, especially in architecture and design (Leach et Yuan, 2017). Design professionals and researchers have adopted different terminologies to designate and differentiate these systems, but this has generated ambiguity in their use due to their intrinsic nature. The taxonomy used is generally associated with the nature of the information flow. For example, we can name Parametric Design (PD), Generative Design (GD), Evolutionary Design (ED), and Algorithms-Aided Design (AAD). Aside from their differences, they are all subsystems of CD (Caetano, Santos et Leitão, 2020). To understand this taxonomy, it is necessary to start by comprehending the difference between CD and Computer-Aided Design (CAD).

Menges et Ahlquist (2011) explain, computation is understood by distinguishing it from computerization. Computation improves information content and accuracy, enhance typical workflows and creates new features. On the other hand, computerization only retains the initial amount of information and groups it into functionalities. Therefore, CD is conducted with versatile tools and CAD with static functions. However, some confusion occurs between CD subsystems, especially between PD and GD. This confusion is understandable since, after modifying parameters, a new shape is ‘‘generated.’’ Yet, modifying parameters does not necessarily justify using generative terminology. Indeed, GD could be considered parametric, but PD is not generative (Wortmann et Tunçer, 2017 ; Chaszar et Joyce, 2016). This distinction is made because GD is based on algorithms that can be coupled with parameters to generate designs. However, PD does not use specific algorithms to generate design concepts. It is for this reason that these two terms should be differentiated.

Due to the redundant use of algorithms in the design workflow, terms such as AAD and ED are also confused with GD (Bi et Li, 2018 ; Anon, 2014). These two are subsystems of GD; however, they are distinct. Indeed, AAD is a CD subsystem that uses GD concepts and keeps a correlation between the input data and the obtained design result. Therefore, AAD is distinguished by its ability to trace the factors giving the result (Caetano, Santos et Leitão, 2020). On the other hand, ED uses algorithms and parameters to create various iterations collected from different genomes to satisfy one or more specific fitness criteria (Rutten, 2010 ; Showkatbakhsh, Kaviani et Weinstock, 2021). Therefore, ED is a system that also uses the principles of GD but does not necessarily keep a correlation between the output obtained and the input conditions and rules. As a result, ED is not necessarily associated with AAD.

Figure 1.6 illustrates the distinction between these different concepts. It should be noted that the name of these systems, once used, are irreversible. It is not logical to use the denomination of GD when using a particular style such as AAD, as this makes the design process lose all specificity. This figure is color-coded; each design system has its color. Initially, CD (in grey) is divided into two subsystems: PD (in light blue) and GD (in dark blue). These two concepts are fundamentally distinct by the resulting workflow in design; one uses parameters, the other algorithms. Second, AAD (in yellow) and ED (in orange) are presented together as subsystems of GD but not of PD. All these subsystems are interconnected, meaning they can support each other. However, these subsystems are only depending on the system that embodies them. This figure shows that CD is the basis of all the mentioned design subsystems. PD is a potential driver for GD, AAD, and ED systems, but these can still be parameter agnostic. It also defines ED and AAD as subsystems of GD but shows that GD does not depend on AAD, ED, or PD.

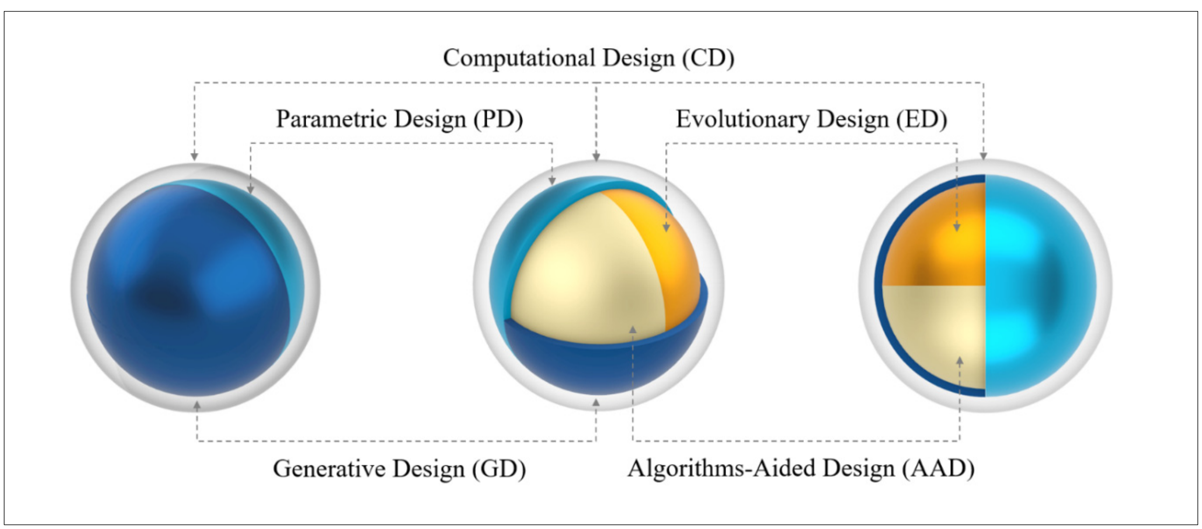

Figure 1.6 Computational Design (CD) taxonomy

1.4.4 CD for technologically bridging BIM-RM dyad

From a technological perspective, BIM and RM are based on computation. Therefore, by transposing their interoperability to the design context, it is theoretically possible to bridge these two systems through CD. However, such an assessment needs to be supported by additional literature investigation. Thus, this section evaluates if the different dyads involved (BIM-CD and CD-RM) are in parallel or interconnected evolution in the literature.

This review was conducted by refining the bibliometric mapping presented in Figure 1.2. Indeed, to further synthesize the results of the first review cycle, emphasis was given to analyzing indexed keywords related to *the tightly coupled approach*. As a result, the new keyword network visualization is presented in Figure 1.7. It provides a clear illustration of the BIM-CD-RM triad. In addition, it gives an overview of the main concepts related to it.

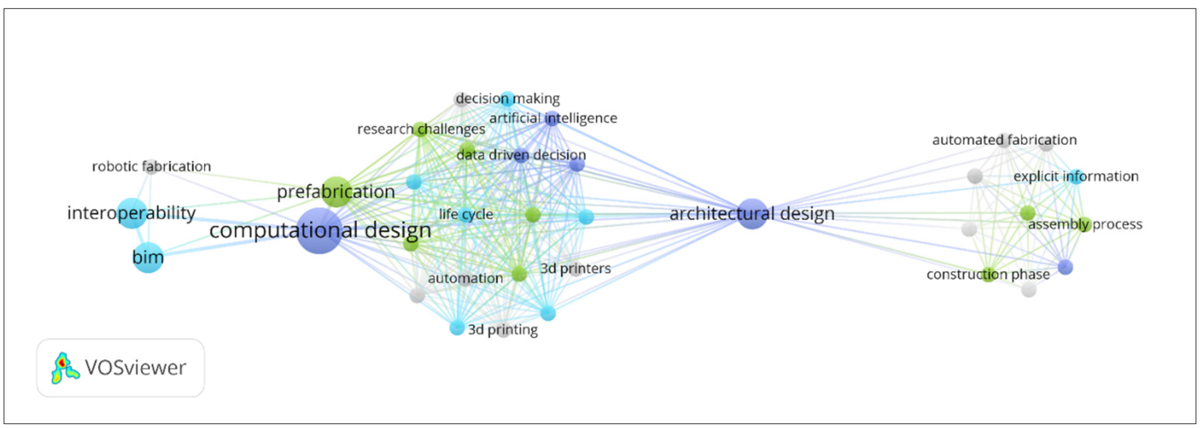

Figure 1.7 Refined keywords co-occurrence network of BIM-RM technological interoperability within the literature (2018-2022)

This bibliometric mapping was supported by an in-depth literature analysis regarding the technological interoperability driving BIM-CD and CD-RM dyads. For the first dyad, the bibliographic search initially yielded 127 documents in Scopus and 68 documents in Dimensions. Following a similar filtering process to the BIM-RM review, this study resulted in 103 eligible documents. This review was then supported by the snowballing method, increasing the number of eligible documents to more than 133. The keyword co-occurrence network is illustrated in Appendix V, Figure-A V-1; it reveals that BIM and CD are strongly linked.

BIM-CD technological interoperability is evident as BIM modeling is not only part of CAD systems; it is also related to CD and is mainly associated with PD (Eastman *et al.*, 2012 ; Dautremont *et al.*, 2019 ; Coenders, 2021). Indeed, BIM tools do not represent objects with fixed geometries and properties. Instead, they represent objects with editable parameters that control and define the geometry and attribute properties (Yuan, Sun et Wang, 2018 ; Akkoyunlu, 2018 ; Amoruso, Dietrich et Schuetze, 2018). Therefore, using BIM systems in computational workflows facilitates the adaptation of digital models. In addition, such approaches provide BIM with optimization and exploration capabilities that automate design procedures (Haghir *et al.*, 2021 ; Xiao et Bhola, 2022 ; Schwerdtfeger, 2018). With their joint technological potential, they are suitable to contribute to the automation of design-related processes, such as planning, management, and collaboration.

Furthermore, the BIM-CD technological dyad enable other digital processes such as reality visualizations, artificial intelligence, and more (Worawan, N. et Motamedi, A., 2019 ; Ouellette, 2019). In short, BIM-CD are not only tightly coupled; they are inherently embedded. Therefore, besides having numerous publications, the maturity of the research conducted on the BIM-CD dyad allows the authors to assume that *BIM and CD are in an interconnected technological evolution in research*. However, these two systems are distinct: BIM is not necessarily CD and vice versa.

For CD-RM technological interoperability, the search initially yielded 78 documents in Scopus and 32 in Dimensions. After an eligibility study and ‘‘snowballing’’ support, the total number of documents amounted to more than 106. CD-RM keywords co-occurrence mapping is illustrated in Appendix V, Figure-A V-2; it demonstrates the relationship between CD and RM systems. This second dyad is less commonly deployed in the literature compared to the BIM-CD dyad. Nevertheless, CD-RM interoperability is gaining momentum thanks to pioneering work such as that of Gramazio Kohler Research. Indeed, the research laboratory of architectural design and fabrication processes at ETH Zurich was the first to implement a robotic lab for construction in 2005. Many have followed suit, such as Vienna University of Technology (Austria) in 2006, Harvard Graduate School of Design (USA) in 2007, Royal Melbourne Institute of Technology (Australia) in 2007, University of Stuttgart (Germany) in 2010, Massachusetts Institute of Technology Media Lab (USA) in 2011, University College London (UK) in 2012, University Delft of Technology (Netherlands) in 2012, Institute for Advanced Architecture of Catalonia (Spain) in 2012, and the list continues to grow (Gramazio, Kohler et Willmann, 2014). These research laboratories use CD-RM workflows to materialize designs through robotic manipulations.

Compared to Computer-Aided Manufacturing (CAM) workflows, CD systems allow for an integrated parametric feedback loop between design and robotic programming (Knippers et Menges, 2020 ; Claypool *et al.*, 2019 ; Ercan Jenny *et al.*, 2020). Within the design process, these two distinct workflows can be tightly coupled and mutually inform each other. Indeed, this loop allows for identifying manufacturing limits (e.g. point of singularities, clashes) and facilitates the adaptation of the design to such limits (Braumann et Brell-Cokcan, 2011 ; Aggarwal, Urbanic et Aggarwal, 2014 ; Devadass, Stumm et Brell-Cokcan, 2019). This capacity gives a considerable advantage over CAM processes often restricted to programming separately from modeling. Furthermore, using CD enables integrated design and post-processing that, once coupled with the generic nature of robotic hardware, will connect the digital and physical interfaces. Such a workflow will therefore allow the development of new manufacturing processes and facilitate designers' access to robotic programming (Garcia del Castillo Lopez, 2019 ; Schwinn et Krieg, 2017 ; Gramazio et Kohler, 2014). A sample of CD-RM technological interoperability results is shown in Figure 1.8; they illustrate CD's potential for robotic programming in the construction context. These projects were completed between 2018 and 2022 and were sourced from Gramazio et Kohler (2022) and Menges et Knippers (2022).

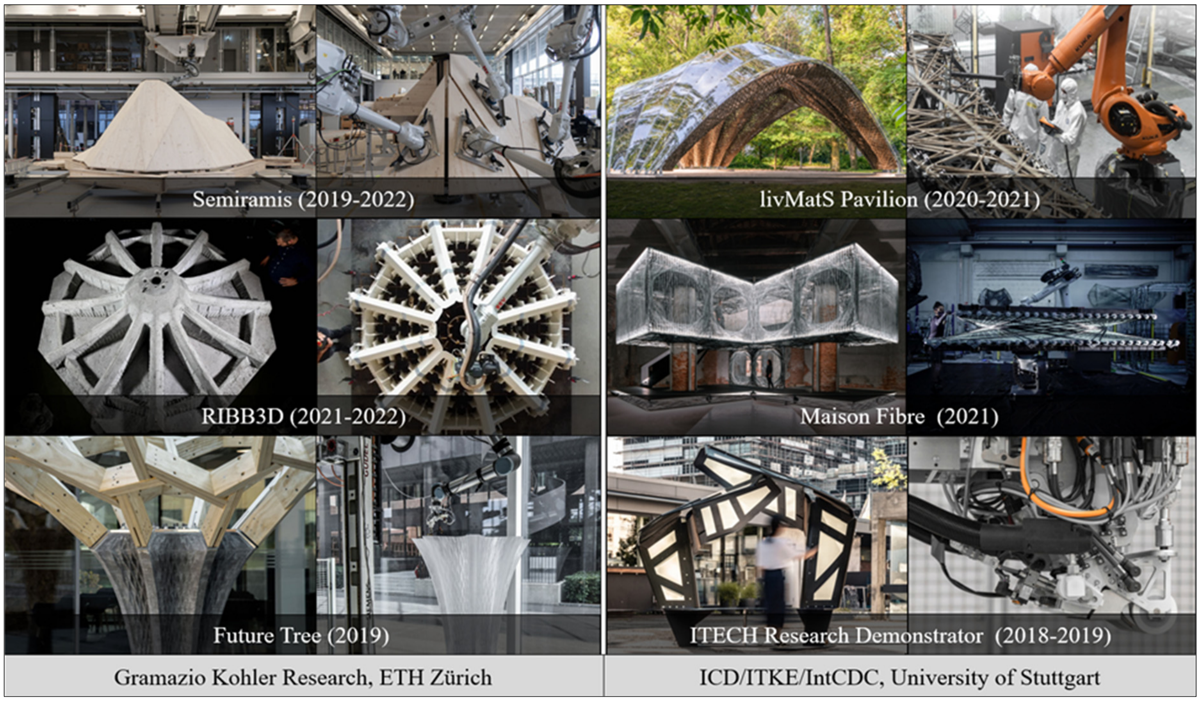

Figure 1.8 Projects involving CD-RM technological interoperability
Adapted from Gramazio and Kohler (2022) ; Menges and Knippers (2022)

These research outcomes illustrate the materialization of multi-manufacturing processes realized by a single workflow, the use of CD for RM. The widespread use across numerous universities and the abundant literature addressing such a workflow allow the authors to assume that *CD and RM are in an interconnected technological evolution in research*. However, the major criticism is that these research projects neglect BIM dimensions. While they focus on highly informed models, few publications are dedicated to the management and collaborative technologies involved in full-scale, standard, and multi-actor construction systems. Furthermore, these projects are often restricted to prototypes; they use complex computational processes that drastically change construction practices. This disparity limits their implementation in industry, requiring standardized and collaborative digital systems, such as BIM. Through the bibliometric analysis performed on BIM-CD-RM technological interoperability, the potential of CD to bridge BIM and RM was clarified. This observation led to the research hypothesis.

1.4.5 Data-synthesis and research hypothesis

The first SLR cycle revealed numerous publications citing BIM and RM as keywords throughout this review. However, these articles did not contain sufficient content addressing BIM-RM technological interoperability. The latest trends in this area are primarily proofs of concept involving additive manufacturing or robotic assembly. These topics are not yet mature enough in the literature; they are still in the early stages of development. Therefore, this SLR review concluded *that BIM and RM are in a technological parallel evolution in research.* Nevertheless, the synthesis of the results revealed attractive perspectives and potential avenues of research, such as the use of CD for bridging BIM and RM. Indeed, CD proved to be in an interconnected evolution, with BIM on one side and RM on the other. This avenue revealed the first research hypothesis (H1) illustrated in Figure 1.9: *CD is a medium for BIM-RM technological interoperability*.

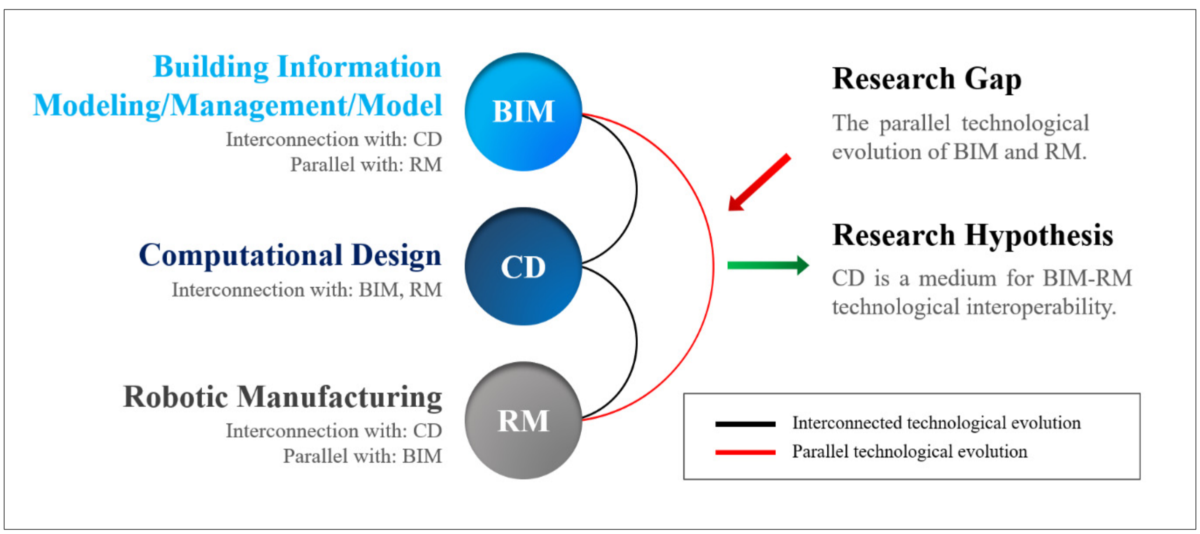

Figure 1.9 BIM-RM technological interoperability –
Research gap and research hypothesis

In the SLR context, this research hypothesis contributed to answering Q1: *How can the technological integration between BIM and RM be achieved?* The central conclusion was that instead of forcing a direct transition between BIM and RM, research efforts should potentially turn to CD tools. Indeed, instead of developing new tools or converting and adapting file formats, it is possible to use CD tools that are already well developed through *the tightly coupled approach*. Moreover, there is great potential for technological integration through such workflows. They have proven their potential with the BIM-CD and CD-RM dyads. This avenue of research can include Artificial Intelligence (AI) services (e.g. machine learning, deep learning) and other computational approaches that aim at automating and integrating design and manufacturing workflows.

The research avenues have not been limited to computational advances; they have also involved the potential construction system of this research. Indeed, looking at Figure 1.7, CD is not the only element linking BIM and RM; prefabrication is also a linking element. This interpretation is logical since the off-site setting provides a controlled environment suitable for implementing RM technologies. Indeed, this interpretation would not yet hold for on-site construction since its nature is unpredictable and compounds many challenges for industrial robots (e.g., safety, transportation). This observation led to the second research question (Q2): *Currently, which construction system is technologically suitable to put into practice the BIM-RM integration?* This question engaged the second cycle of SLR.

1.5 Off-Site Construction (OSC) as a construction system: Second SLR cycle

OSC is commonly defined according to two subsystems: *prefabrication* and *modular construction* (Ginigaddara *et al.*, 2022). *Prefabrication* can be used for structural elements, panelized constructions, and building or infrastructure components (Goodier et Ashley, 2006 ; Li, Shen et Xue, 2014), whereas *modular construction* refers to volumetric modules, pre-finished units, or functional pods (Hairstans *et al.*, 2014 ; Modular Building Institute, 2020). It is essential to note that modular construction can be considered prefabrication. However, not all prefabricated construction can be considered modular.

This section discusses the study of OSC as a potential construction system for using the BIM-RM dyad through CD. This avenue was studied with a second SLR cycle that emerged from the findings of the first cycle. However, the second cycle was less in-depth since the objective was focused on simply identifying the technological suitability of OSC. Therefore, this SLR answered Q2 by examining OSC when paired individually with BIM, CD, and RM.

1.5.1 BIM-OSC technological interoperability (2018-2022)

BIM and OSC are increasingly being implemented in industry and research, either separately or in combination (Wang *et al.*, 2020 ; Zhang *et al.*, 2021). Indeed, research efforts are extensive in addressing these two systems since they closely reflect the digital shift's potential for enhancing construction productivity (Jang *et al.*, 2021 ; Sabet et Chong, 2019). Moreover, these systems are acknowledged for being critical drivers for construction industrialization (Wallance, 2021 ; Han *et al.*, 2020 ; Xu, Wang et Rao, 2020); they foster automation of design and manufacturing operations. The bibliographic review addressing the joint use of BIM and OSC resulted in 182 documents in Scopus and 193 in Dimensions. Once the duplicates were merged, the total number of documents found was 275. In the context of the second SLR cycle, the eligibility study was similar to the BIM-RM dyad. The criterion for inclusion was the comprehensive coverage of using OSC systems through technological workflows. Therefore, it was not sufficient to study the potential of OSC for the construction industry to be eligible for this review. Included studies had to involve technological evidence and not be limited to perspectives. After the eligibility assessment and the ‘‘snowballing’’ support, the total number of documents retained in this search was more than 227. Figure 1.10 shows the co-occurrence keywords network generated from the collected publications.

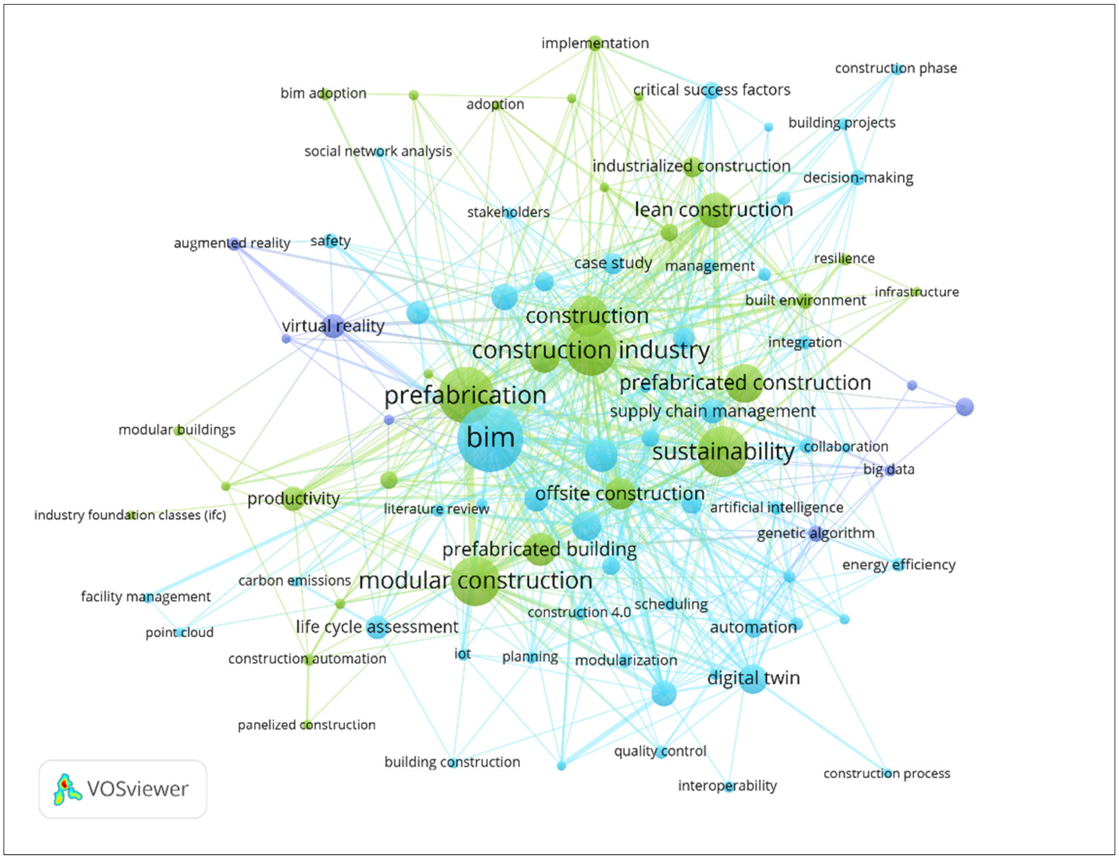

Figure 1.10 Keywords co-occurrence network of BIM-OSC technological interoperability within the literature (2018-2022)

The keywords co-occurrence network shows that BIM shares an extensive technological body of research with OSC. In these studies, BIM is often used in Design for X (DfX) (Li *et al.*, 2019 ; Marinelli, 2022), especially for Design for Manufacturing and Assembly (DfMA) (Gbadamosi *et al.*, 2020 ; Kalemi *et al.*, 2020 ; Zadeh *et al.*, 2018). Indeed, these design processes are supported by the standardization and collaborative technological workflows provided by BIM tools. In addition, BIM-OSC technological dyad is also used for implementing technologies such as digital twins (Rausch *et al.*, 2021) and internet of things (IoT) (Han et Ye, 2018 ; Zhao, Liu et Mbachu, 2019). Finally, this dyad often aims to ensure sustainability by using lean processes to construct prefabricated or modular components (Santana-Sosa et Riola-Parada, 2018 ; McHugh, Dave et Craig, 2019 ; Hussein *et al.*, 2021).

This bibliometric analysis provides evidence for *BIM-OSC interconnected technological evolution*. This dyad is widely studied in the literature and is not limited to the technological dimension of interoperability; it also considers the procedural, organizational, and contextual dimensions. However, this study did not yield concepts like CD or RM. This research gap is reflected in the literature by the SLR conducted by Yin et al. (2019), who proposed RM for OSC as a research direction. It is also reflected by the research of Yuan, Sun et Wang (2018), who suggested that computational processes (such as PD or GD) involved in BIM-OSC workflows should be further investigated. This review highlights the need for computational systems in OSC, leading to the second dyad, that of CD-OSC.

1.5.2 CD-OSC technological interoperability (2018-2022)

Following the BIM-OSC technological interoperability assessment, it should be mentioned that their interconnected evolution did not lead to any findings for the CD-OSC dyad. Indeed, while BIM is extensively used in OSC, this does not necessarily imply extensive use of PD in OSC, even less so for CD. As a result, this review initially yielded 23 documents in Scopus and 24 documents in Dimensions by orienting the second SLR cycle to the CD-OSC dyad. After filtering and performing an eligibility assessment similar to the BIM-OSC dyad, the total number of retained articles was reduced to 18. Considering the limited literature this research had yielded, this search was supported by the ‘‘snowballing’’ method. This additional investigation increased the number of documents to 27, engaging the bibliometric analysis based on the co-occurrence keyword mapping illustrated in Figure 1.11.

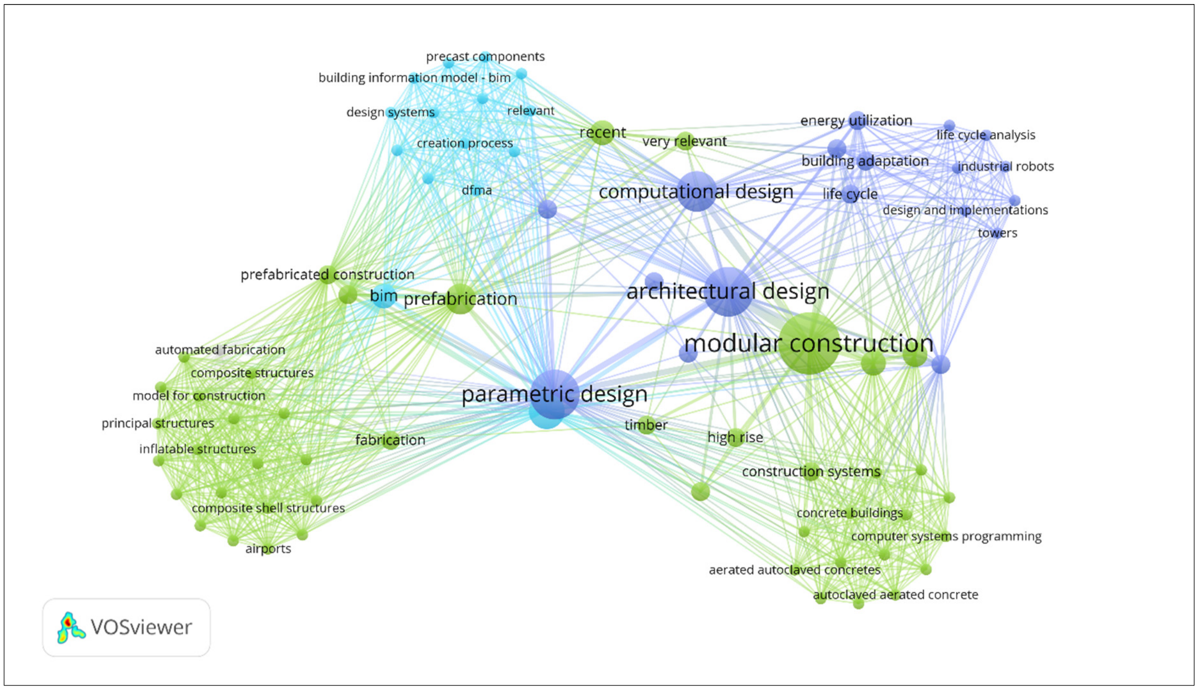

Figure 1.11 Keywords co-occurrence network of CD-OSC technological interoperability within the literature (2018-2022)

When analyzing this bibliometric mapping, the first observation was that PD is the most used CD subsystem in OSC. This finding is consistent with the BIM-OSC technological interoperability review. Indeed, BIM tools are largely used in OSC. However, by interpolating this visualization to the number of documents collected, the disparity between resources allows the authors to assume that BIM systems are primarily used in computerized workflows, not computational ones. In fact, through the review of the documentation available, the main observation was that OSC-related literature is heavily focused on standard CAD-based design procedures (Doe, 2018 ; Hou *et al.*, 2020). In addition, OSC involves specific construction techniques that require high-level detailing, especially for manufacturing and assembly (Hyun, Kim et Kim, 2022 ; Ehwi *et al.*, 2022). For such reasons, designers are inclined to use conventional CAD processes rather than disruptive computational systems for addressing prefabricated or modular designs. Considering the lack of literature on the CD-OSC dyad and the insufficient maturity of their joint research in industrial implementations, the authors assessed that *CD and OSC are technologically evolving in parallel in research*. However, distinguishable technological approaches were found for using CD in OSC systems. These approaches are mainly related to the research conducted in the Bartlett School of Architecture (UCL).

Through the research of Carpo (2019), Retsin (2019a), and Claypool (2019a), CD is performed in OSC design through *discrete architecture*. ‘‘Discreteness’’ in architecture refers to building components that are singular and distinct (Retsin, 2019b). This approach correlates with OSC since it is based on construction entities produced through modular aggregations. Furthermore, this architectural approach is intrinsically linked to CD since it is based on GD (Rossi et Tessmann, 2019 ; Tessmann et Rossi, 2019). Indeed, discrete architecture requires the modules’ definition, connections, and aggregation rules to produce combinable modular design iterations algorithmically. Therefore, this approach is highly valued for its potential to enrich the design scope in prefabricated systems through mass customization (Sanchez, 2019). Figure 1.12 illustrates some results of using discrete architecture in prefabrication (Retsin, 2022).

Figure 1.12 Examples of projects involving CD-OSC technological interoperability through discrete architecture
Adapted from Retsin (2022)

Although discrete architecture has excellent potential for adaptability in prefabrication, this approach is limited to modular prototypes distinct from the OSC status quo. It is a design approach that is drastically different from conventional DfX processes. Furthermore, it is delicate to adapt to real contexts where it must deal with structural or MEP inputs, a dimension well suited for BIM but remains little investigated by the pioneers of discrete architecture. This disparity reflects the technological parallel evolution of CD-OSC; even if the design approaches are very innovative, they are not yet mature for their application on full-scale projects. As shown in Figure 1.12, discrete architecture also linked CD to RM, giving rise to discrete automation terminology (Claypool *et al.*, 2020). Indeed, using the feedback loop of the CD-RM dyad, different discrete modules can be assembled using robotics as a medium between digital data and reality. This finding led to the last dyad investigated in the second SLR cycle: RM-OSC.

1.5.3 RM-OSC technological interoperability (2018-2022)

In the industrialized context, the AEC industry is on an avid quest for a faster production process with ever-increasing shape complexity (Taylor, 2020 ; Brissi *et al.*, 2022). Such insights are fostered through the use of RM in OSC. However, numerous technological considerations are involved in using automation tools within a highly variable-demand industry (Bowmaster et Rankin, 2019). This bibliographic review initially yielded 15 documents in Scopus and 14 in Dimensions. These documents were filtered and underwent an eligibility assessment based on the inclusion criteria of the second SLR cycle. This step led to the selection of 15 documents, and engaged the ‘‘snowballing’’ support. At the end of this exhaustive review process, the number of documents amounted to 22. These have been loaded into VosViewer for the generation of the co-occurrence keyword network related to RM-OSC technological interoperability. This mapping is presented in Figure 1.13.

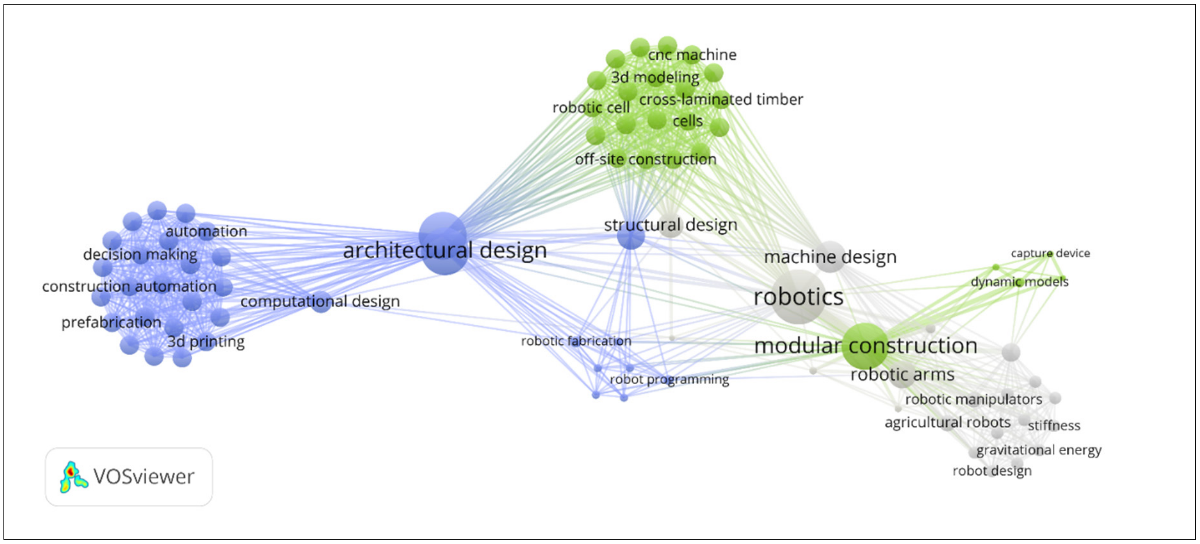

Figure 1.13 Keywords co-occurrence network of RM-OSC technological interoperability within the literature (2018-2022)

The keywords network generation of the RM-OSC dyad has given rise to CD as a third cluster. This observation was consistent with the CD-RM analysis as this dyad is in an interconnected evolution in the literature. However, despite the promising results of this dyad, little research was dedicated to full-scale OSC studies involving real contexts and systems. Furthermore, no trace of BIM was apparent in the network visualization. This observation was consistent with the parallel evolution of BIM-RM; BIM is often neglected in CD-RM workflows. In the literature, the RM-OSC dyad is still limited to laboratory studies without actual implementation in industrial systems. This lack of investigation is understandable since RM technologies are resource-intensive (Davila Delgado *et al.*, 2019). Moreover, RM is a system that implies drastic changes in prefabrication processes (Pan *et al.*, 2020), which further limits its adoption in the industry. These limitations provide insight into the lack of investigation of BIM. In fact, BIM can be overlooked for occasional prototypes such as columns, walls, pavilions, or other. However, industrial implementation of RM will not be limited to using CD tools. Additional workflows are to be considered, including OSC digital planning and management activities that are inherently facilitated through BIM tools.

Given these observations and the lack of documentation on the RM-OSC dyad, the authors assess that *RM and OSC are technologically evolving in parallel in research*. However, it is worth mentioning that significant advances are in line with the prospect of this dyad. In this context, the research carried out by ICD/ITKE led by Achim Menges and Jan Knippers (already mentioned in the CD-RM dyad) is distinguished by its involvement in full-scale OSC projects. Indeed, results such as the BUGA Fibre Pavilion and BUGA Wood Pavilion projects represent evidence for the potential of RM in OSC (Bechert, Sonntag, *et al.*, 2021 ; Wagner, Alvarez, Groenewolt, *et al.*, 2020 ; Gil Pérez *et al.*, 2020). Snapshots of these projects and their manufacturing processes are illustrated in Figure 1.14 (Menges et Knippers, 2022).

Figure 1.14 Example of projects involving RM-OSC technological interoperability: ICD/ITKE BUGA Pavillions
Adapted from Menges and Knippers (2022)

The results of this research are evidence for the development of CD-RM technological interoperability. They are supported by recent publications that clearly outline an operational link with OSC systems (e.g., Co-design (Bechert, Aldinger, *et al.*, 2021), Maison Fibre (Gil

Pérez *et al.*, 2022)). However, despite their large scale, these results are often restricted to punctual projects (e.g. pavilions). They do not yet thoroughly address RM implementation in full-scale OSC systems. Indeed, this pioneering research is still at the stage of prototyping and laboratory experiments. They constitute unique in-house laboratory developments, and their outcomes are not yet implemented in industrialized OSC environments. Therefore, even if Figure 14 presents evidence of the potential of RM in OSC, it is inconsistent to evaluate that the RM-OSC dyad is in an interconnected technological evolution in research. This review has reflected the potential of the CD-RM-OSC triad for the industrialization of construction. However, although developed on the CD-RM dyad, this triad still requires further research on the CD-OSC and RM-OSC dyads. Moreover, more case studies involving industrialized construction systems should be considered in such contexts. This evaluation of the final dyad enables the step of data synthesis and research hypothesis.

1.5.4 Data-synthesis and research hypothesis

The second SLR cycle was initiated by the findings of the first cycle. Interestingly, it brought further attention to the technological interoperability potential of BIM, CD, RM and OSC. This review revealed two dyads that are technologically evolving in parallel in the literature: CD-OSC and RM-OSC. For the CD-OSC dyad, its review has revealed great potential in terms of modular and prefabricated design. However, this dyad remains limited in its application in DfX and collaborative industrial systems. Indeed, CD is not sufficient to address all aspects of OSC systems. For its implementation, it has to play with other technological workflows to enable collaboration and management of construction projects. From this perspective, BIM has the potential to play the role of a technological facilitator for the use of CD in OSC. This insight is supported by the interconnected evolution of research on BIM-CD and BIM-OSC dyads. Therefore, the research second hypothesis (H2) is that *BIM is a medium for CD-OSC technological interoperability.* Figure 1.15 illustrates the research gap and hypothesis identified through the study of CD-OSC technological dyad.

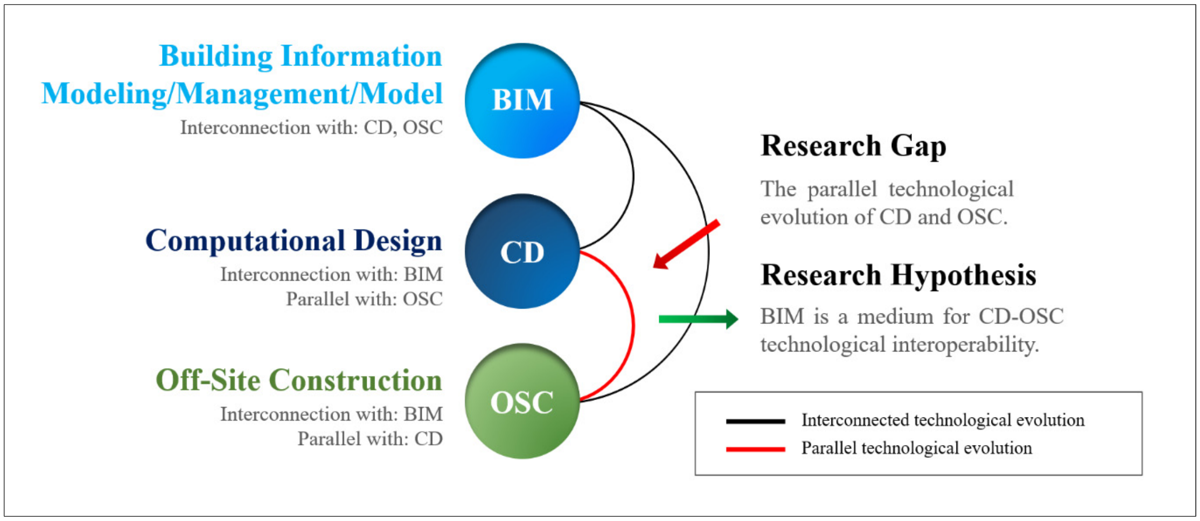

Figure 1.15 CD-OSC technological interoperability – Research gap and hypothesis

For the RM-OSC dyad, its review has demonstrated remarkable potential for architectural and technological innovation in the construction industry. It is a dyad that relies heavily on the CD-RM coupling; it uses CD for design and robotic programming. This workflow creates an integrated approach for merging design and manufacturing. However, it does not yet provide a significant body of research on information management in collaborative technological processes. Indeed, CD tools are exclusively developed for design and programming, they are not yet effective for the digital management of construction processes. Therefore, on the one hand, RM-OSC research is technologically slowed down by the parallel evolution of the CD-OSC dyad, which BIM potentially facilitates. And on the other hand, BIM is in parallel evolution with RM and is likely facilitated by CD. This alternating relationship between parallelism and interconnections gave rise to the third research hypothesis (H3), *the BIM-CD-RM technological triad has the potential to operationalize RM in OSC*. The interrelation based on technological interoperability between these different dyads is illustrated in Figure 1.16.

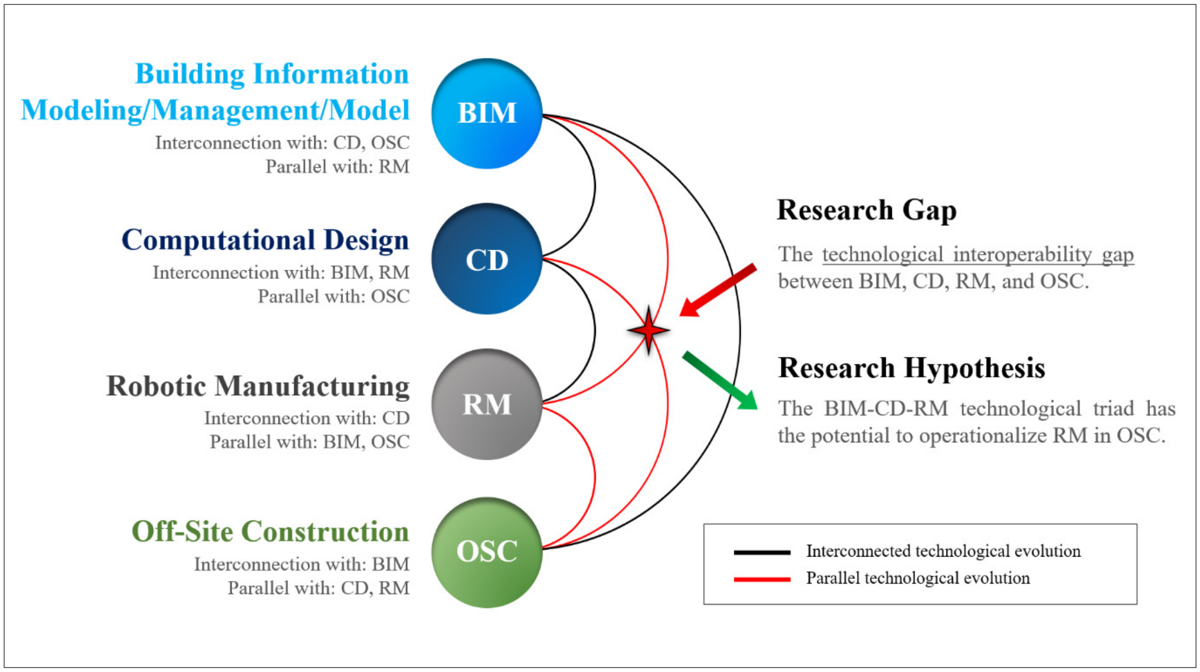

Figure 1.16 RM-OSC technological interoperability –
Research gap and hypothesis

With these additional research hypotheses, the second cycle of the SLR addressed Q2 by identifying the construction system that is currently technologically suitable for using the BIM-RM integration. Through the different reviews involving BIM-OSC, CD-OSC, and RM-OSC dyads. OSC has proved to be a possible enabling system for the industrialization of construction. It offers distinctive products through RM and is in an interconnected evolution with BIM. Therefore, it is possible to assume that OSC is technologically suitable for BIM-RM integration. This finding confirms the research avenues outlined in the first SLR cycle and extends the research avenues towards the different identified parallelisms.

1.6 Discussion

This literature review was conducted through two SLR cycles, based on 533 documents. It investigated the BIM, CD, RM, and OSC dyads. Their joint technological evolution in research was qualitatively evaluated according to the number of articles published, their extensive deployment in research, and their use of industrial case studies. This review resulted in the following categorization:

- Dyads in an interconnected technological evolution: BIM-CD / CD-RM / BIM-OSC
- Dyads in a parallel technological evolution: BIM-RM / CD-OSC / RM-OSC

When investigating these different dyads, it was possible to generate three research hypotheses. These assumptions are intended to address the different research gaps identified and contribute to the above-mentioned objective of this article. Q1 is related to the parallel BIM-RM dyad. This question has been addressed through the first SLR cycle that led to the hypothesis *that CD is a medium for BIM-RM technological interoperability* (H1). Indeed, this review revealed that CD provides one-to-one integration with both systems (BIM-CD and CD-RM). Therefore, this finding implies the need for further research validating the interoperability of the BIM-CD-RM technological triad.

Regarding Q2, the second SLR cycle has expanded on the first and demonstrated that OSC systems are potentially suitable for BIM-RM integration. Indeed, this study revealed that BIM-OSC are in an interconnected technological evolution. Based on the previously established interconnection of BIM-CD, this review has identified the second research hypothesis (H2) that *BIM is a medium for CD-OSC technological interoperability.* By involving RM, this study revealed the last research hypothesis (H3) that *the BIM-CD-RM technological triad has the potential to operationalize RM in OSC.* Indeed, the use of RM in construction is strongly linked to CD, which is in turn supported by BIM for its use in OSC. An overview of this systematic literature review is presented in Table 1.1. The answers to the research questions are found by addressing the identified parallel technological dyads. This objective can be achieved through the interconnected dyads, such eventuality is represented through the research hypotheses.

Table 1.1 Overview of the systematic literature review

Research Questions	Parallel Dyads Identified	Proposed Solution through the Interconnected Dyads	Research Hypotheses
Q1	BIM-RM	BIM-CD → CD-RM	H1
Q2	CD-OSC	CD-BIM → BIM-OSC	H2
	RM-OSC	RM-CD → CD-BIM → BIM-OSC	H3 = (H1+H2)

Through the analysis of these results, it appears that BIM, CD, RM, and OSC are inherently interrelated. On the technological dimension, their dyadic evolution varies from one pair to another, but their convergence has the potential to offer a means of operationalizing RM in OSC. This perspective can be enabled through the performance of CD-RM dyad for design and robotic programming, enhanced by BIM for information management and collaborative technological workflows, and framed by OSC as an execution system. Such workflow is digital from design to execution; its ability can be visualized in Figures 1.8, 1.12, and 1.14. This digital nature provides the opportunity to integrate other technological innovations related to the Construction 4.0 paradigm. However, the analysis of the technological interoperability of these four concepts is not sufficient to drive the industrialization of construction. The investigation of their interoperability must also cover their organizational, procedural, and contextual dimensions.

These concepts may overlap in cyber-physical systems and may encounter the same limitations identified in this study. Indeed, even if this study covered two major databases such as Scopus or Dimensions, the body of research encompassing the different dyads is difficult to frame or quantify. In addition, despite the search tags provided in Appendix III, VosViewer's visualizations may be difficult to reproduce because of redundant or irrelevant keywords that have been removed. These inherent limitations of the SLR methodology carry the risk of biasing results. However, this bias has been minimized as much as possible with the ‘‘snowballing’’ support, and the extensive bibliometric analyses. The next step in this research is the development of a framework based on Design Science Research (DSR) methodology to integrate the BIM-CD-RM technological triad and use it in OSC systems.

1.7 Conclusion

This literature review initially began with the investigation of BIM-RM technological interoperability. It then evolved into new perspectives involving CD and OSC, with the objective of providing potential solutions to their joint technological integration. The presented study demonstrated the value of converging processes in construction technologies. Its main conclusion is that technological tools should not be forced to perform tasks they are not designed to do. Forcing BIM tools to perform RM is unnecessary when it is enough to combine it with already existing tools and workflows. Likewise, forcing RM into OSC with computerized processes for manufacturing a unique product is a hard automation as opposed to a flexible one. Finally, forcing CD tools to manage all construction phases can be pointless. In short, the intensive focus on technological developments without studying their interoperability can be resource-intensive.

These notes reflect the barrier established by the fragmented nature of the construction industry. However, when used together, these technologies can mutually reinforce each other. Indeed, this review has reflected the inherent relationship between the different dyads studied. It provides a basis for the investigation of BIM-RM integration through CD, and thus studying the BIM-CD-RM technological triad and its potential to operationalize RM in OSC.

1.8 Acknowledgements

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Graphic charts: Supported by PresentationGo and Canvas.

1.9 Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The Bibliography section is presented at the very end of the thesis.

CHAPTER 2

RESEARCH METHODOLOGY

2.1 Introduction

Initially, this research began in an exploratory context for investigating BIM-RM technological interoperability. It then evolved into research to develop a framework for integrating BIM-CD-RM technological triad in OSC based on the Design Science Research (DSR) methodology. Therefore, this chapter begins with a definition of the research methodology used. It is then structured according to the different stages of DSR, from identifying the research problem to the design cycle of the framework. Finally, this chapter is concluded with the communication structure and contributions of this research.

2.2 Design Science Research (DSR) methodology

Artificial science is designed to study and develop artificial subjects for solving existing problems (De Sordi, 2021). These developments often lead to human-creations that are generically called artifacts (Simon, 1996). In terms of philosophy of science, the DSR methodology originated from the science of the artificial. In fact, it is a methodology that is based on the development of an artifact for the resolution of a real problem in research or industry (Hevner *et al.*, 2004).

This research methodology has been explored by various researchers, but the definition that has been most widely reported is that of Peffers, Tuunanen, Rothenberger, and Chatterjee (2007). Typically, it is defined in 6 steps: Motivation and problem identification; The definition of the objectives for a solution; The design and development of the artifact; Demonstration; Evaluation; and Communication. Figure 2.1 shows the main steps of the DSR methodology.

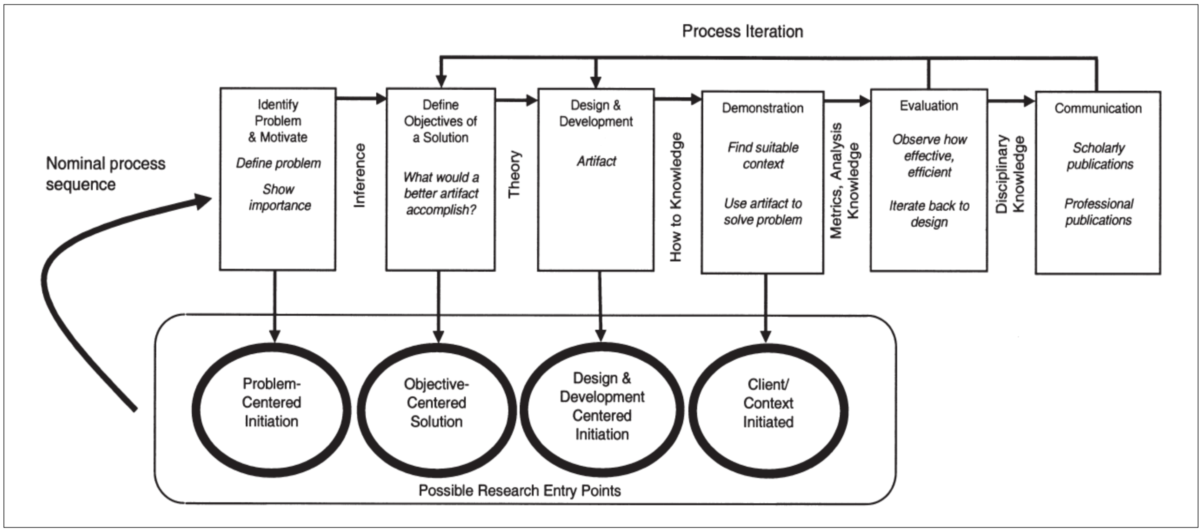

Figure 2.1 Design Science Research (DSR) methodology process
Taken from Peffers et al. (2007, p.11)

In this chapter, the different steps of the DSR methodology are explained in the context of this research. This methodology resulted in an artifact that manifests as a framework allowing the integration of the four investigated systems: BIM, CD, RM and OSC. The data flow involving these systems can be defined as BIM-driven computational design for robotic manufacturing in off-site construction. This finding revealed that these four concepts constitute a cyber-physical system that has the potential to integrate both design and manufacturing workflows. Indeed, design can be managed by BIM-CD technological dyad, robotic programming by CD-RM, and the materialization of the whole workflow through RM-OSC. As a result, this research gave rise to an integrated Design-to-Manufacturing (DtM) framework. The DtM approach is different from DfM. Indeed, the DtM approach allows design and manufacturing programming through integrated UIs. However, the DfM approach only includes design in a modeling software that does not support manufacturing programming.

2.2.1 Research motivation

From a theoretical perspective, the construction industry is witnessing a second digital transformation, which, through the introduction of the robot, has the potential to materialize its digital processes (Gramazio, Kohler et Willmann, 2014). Indeed, digital design in the AEC industry is highly developed in terms of tools, processes, and organization. However, its automated materialization has been more coveted than realized (Bademosi et Issa, 2021). This disparity reflects the technological interoperability gap between digital design technologies and robotics in the construction industry. It is this lack of interoperability that motivated this research and enabled a deeper investigation of the BIM, CD, RM, and OSC systems.

From a practical perspective, this research was initially motivated by the industrial and academic need to operationalize industrial robotics in construction. More specifically, it was primarily driven by the parallel technological evolution of the BIM-RM dyad. As presented in the literature review, this research gap led to the need to investigate the BIM-CD-RM technological triad in OSC. Indeed, developing a framework that integrates design and manufacturing technological processes would have a significant practical impact. As a result, this research was motivated by the need to operationalize industrial robots in construction through an integrated Design-to-Manufacturing (DtM) approach.

2.2.2 Problem statement, research questions and hypotheses

The problem statement of this research was determined through a gradual emergence of different sub-problems identified in the literature review. Initially motivated by the parallel technological evolution of BIM-RM in construction, the research encountered two additional parallel technological dyads: CD-OSC and RM-OSC. Therefore, these three research gaps are grouped under the problem statement of this research: *The research gap involving the technological interoperability of BIM, CD, RM, and OSC.*

This problem is discussed through the research questions introduced in Chapter 1. The findings of the SLR and the motivations driving this research raised a third inquiry. Therefore, the research questions investigated in this study are the following:

- Q1: How can technological integration between BIM and RM be achieved?

- Q2: Currently, which construction system is technologically suitable to put into practice the BIM-RM integration?
- Q3: How can BIM, CD, RM and OSC technological integration enable a Design-to-Manufacturing (DtM) approach?

In this study, these research questions are addressed through validating the three research hypotheses identified in the SLR:

- H1: CD is a medium for BIM-RM technological interoperability;
- H2: BIM is a medium for CD-OSC technological interoperability;
- H3: The BIM-CD-RM technological triad has the potential to operationalize RM in OSC.

The statement of the problem, research questions and hypotheses, leads to the second step of the DSR, the setting of the research objectives.

2.2.3 Research objectives

The critical observations of the literature review revealed a significant ambiguity regarding BIM-RM technological interoperability. Therefore, the primary objective of this research was to clarify this ambiguity by defining the technological nexus of the BIM-RM dyad with CD. Once this nexus was specified, adding OSC as a construction system implied the rise of the DtM approach. As a result, this approach aims to extend the design process by incorporating the execution of a robotic program. In other words, this research seeks to *define a framework integrating BIM and CD for using RM in OSC, enabling an integrated DtM workflow.*

2.2.4 Artifact development

2.2.4.1 The Ex Ante and Ex Post contexts in Design Science Research (DSR)

According to the research methodology used, the development of the artifact follows two primary contexts, the *Ex Ante* and the *Ex Post* contexts (Peffers, Rothenberger et Kuechler, 2012). The *Ex Ante* context is used to demonstrate and evaluate the artifact as a ‘‘design’’; the artifact is in its first form. The *Ex Post* context is used to demonstrate and evaluate the artifact as a ‘‘construct’’; the artifact is in its advanced form. Evaluating an artifact in its *Ex Ante* context is part of the ‘‘design research’’ phase of the DSR methodology. It is a phase that transforms into ‘‘design science’’ only after an *Ex Post* evaluation (Pries-Heje, Baskerville et Venable, 2008). Therefore, ‘‘design science’’ incorporates ‘‘design research’’, but ‘‘design research’’ is not ‘‘design science.’’

This distinction between the research contexts used is essential to situate the maturity of the artifact developed. Indeed, artifacts in their ‘‘design’’ representation are often not mature enough to be applied in a natural context. However, ‘‘constructs’’ are often mature enough to be tested in these real contexts. The DSR phases are outlined and contextualized in Figure 2.2.

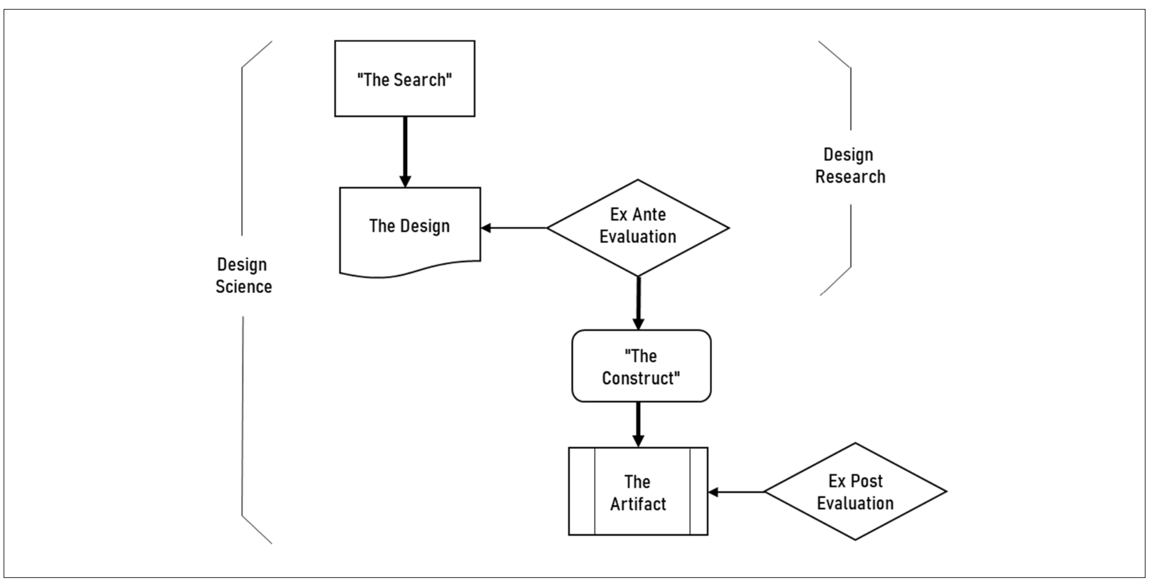

Figure 2.2 Ex Ante versus Ex Post in Design Science Research (DSR) methodology
Taken from Pries-Heje et al. (2008, p.8)

Research is evolutive, implying that any artifact developed is in constant evolution (Carpo, 2017). Indeed, the DSR methodology is iterative; it evolves between the *Ex Ante* and *Ex Post* contexts. These iterations are called the ‘‘design cycle’’ of the artifact.

2.2.4.2 The design cycle

In the DSR methodology, the first step is to define the research problem. Once identified, the ‘‘design cycle’’ of the artifact is engaged. According to Sonnenberg and vom Brocke (2012), this cycle initially situates the research in the *Ex Ante* context. Then, the artifact is demonstrated and evaluated in its ‘‘design’’ form. After the *Ex Ante* evaluations, the research reaches the ‘‘design science’’ phase through the manifestation of the artifact in its ‘‘construct’’ form. The artifact is then sufficiently advanced to be demonstrated and evaluated in the *Ex Post* context. This step implies using the artifact according to the purpose for which it was developed. This use raises new problems, often defined as the limits of the artifact and avenues for future research. These limitations rewind the design cycle of the artifact, and a new research cycle is initiated. Figure 2.3 illustrates the design cycle in the DSR methodology.

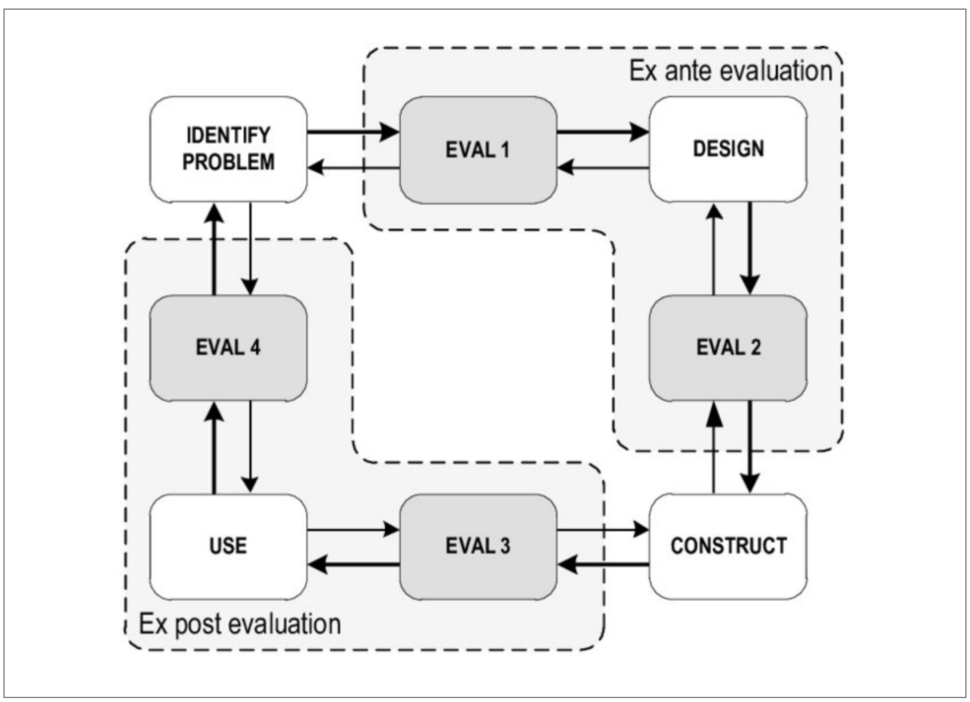

Figure 2.3 ‘‘Design cycle’’ in the DSR process
Taken from Sonnenberg & vom Brocke (2012, p.13)

In this thesis, the ‘‘design cycle’’ resulted in the DtM framework, demonstrated and evaluated in both the *Ex Ante* and the *Ex Post* contexts. The methodology underlying these demonstrations and evaluations is explained in the following sections.

2.2.5 Demonstration

In qualitative research, the demonstration phase is often confused with the evaluation phase (Baskerville, Kaul et Storey, 2015). This confusion is due to the intrinsic nature of these two phases. Indeed, a demonstration inherently leads to an evaluation, and an evaluation is usually associated to a demonstration. This section clarifies the notion of demonstration and its distinction from an evaluation.

In the DSR methodology, the objective of the demonstration is to provide evidence of the results of a developed artifact (De Sordi, 2021). This step is iterative and is carried out to support the rigor of the research conducted. As explained in section 1.2.5.1, the demonstrations are always performed either in the *Ex Ante* context or the *Ex Post* context. In these contexts, they are conducted in two different natures, the naturalistic nature and the artificial nature. According to Venable, Pries-Heje, and Baskerville (2012), a naturalistic demonstration involves its evaluation with a real system, real users, and real problems. In contrast, an artificial demonstration involves its evaluation with unreal systems, unreal users, and unreal problems. These contexts create the matrix of evaluation strategies of the DSR methodology presented in Figure 2.4. This matrix is used to determine the context and the nature of the demonstrations.

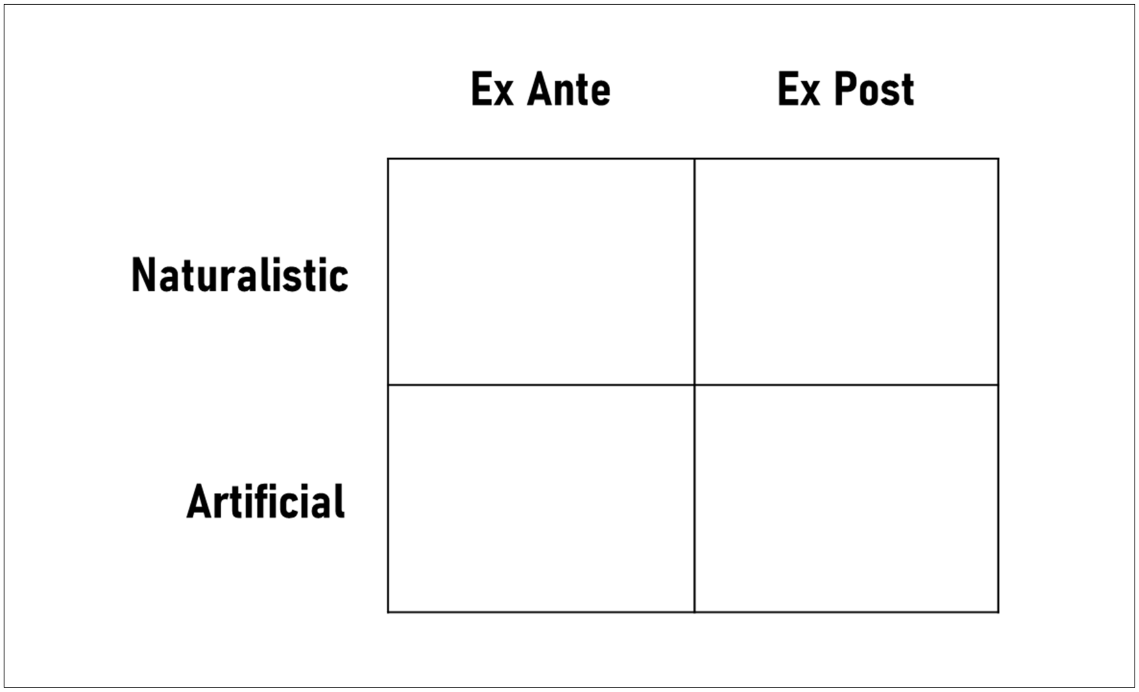

Figure 2.4 DSR evaluation strategies matrix
Taken from Venable et al. (2012, p.440)

The strategic choice of demonstrations depends on the available resources and the evaluation to be performed. For example, naturalistic evaluations may involve long evaluation times, high costs, and challenges in accessing organizations. On the other hand, artificial evaluations may involve rigor challenges, unrealistic results, and purely technical results. Thus, naturalistic demonstrations are often characterized by solid validity, while artificial demonstrations are only characterized by internal validity. For choosing the demonstration strategy to adopt, this research is based on the framework presented by Venable et al. (2012). This framework is illustrated in Figure 2.5; it presents the different demonstration methods to be adopted according to the matrix of evaluation strategies of the DSR methodology.

DSR Evaluation Method Selection Framework	Ex Ante	Ex Post
Naturalistic	• Action Research • Focus Group	• Action Research • Case Study • Focus Group • Participant Observation • Ethnography • Phenomenology • Survey (qualitative or quantitative)
Artificial	• Mathematical or Logical Proof • Criteria-Based Evaluation • Lab Experiment • Computer Simulation	• Mathematical or Logical Proof • Lab Experiment • Role Playing Simulation • Computer Simulation • Field Experiment

Figure 2.5 DSR evaluation (and demonstration) method selection framework
Taken from Venable et al. (2012, p444)

The objective of the DtM framework is to facilitate and operationalize RM in OSC. However, this manufacturing technology is resource-intensive and disrupts production processes. Moreover, our local partners' experience in using robotic arms in construction is still limited; they are not yet inclined towards a robotized production implementation. For such reasons, this research emphasizes artificial demonstrations in the *Ex Ante* context. These artificial demonstrations are then supported and evaluated in a naturalistic *Ex Post* context.

The development of the DtM framework is initially conducted with two evaluation episodes involving artificial *Ex Ante* demonstrations. The first episode involves two demonstrations using computer simulations. The second episode involves three other demonstrations using laboratory experiments. Then, the DtM framework is evaluated in a naturalistic *Ex Post* context through individual interviews concluded by qualitative evaluation surveys.

2.2.6 Evaluation

2.2.6.1 The evaluation strategy

This thesis's evaluation phase is conducted according to the *Technical Risk & Efficacy* strategy of the Framework for Evaluation in Design Science Research (FEDS) (Venable, Pries-Heje et Baskerville, 2016). Compared to the remaining approaches (i.e. Quick & Simple, Human Risk & Effectiveness, Purely Technical Artefact), the selected approach is the most suitable for this research project since it relies heavily on artificial demonstrations, and holds an avenue for naturalistic demonstrations. Moreover, this approach is designed for projects that are prohibitively expensive to evaluate with real users and real systems in real settings, which further justifies its selection in our research context.

The *Technical Risk & Efficacy* approach iteratively performs ''formative'' artificial evaluations initially and progressively evolves to ''summative'' artificial evaluations. The distinction between ''formative'' and ''summative'' approaches is understood by the distinction in their functional purpose. ''Formative'' evaluations help improve the results of the evaluation process. ''Summative'' evaluations assess the extent to which the results meet expectations. Therefore, towards the ''formative'' end, evaluations must provide a basis for successful action. On the other hand, towards the ''summative'' end, the evaluations must provide a research validation.

By interpolating this evaluation method to this research, this framework justifies the gradual evolution from artificial *Ex Ante* evaluations to naturalistic *Ex Post* evaluations. *Ex Ante* demonstrations improve the performance of the artifact, and *Ex Post* demonstrations ensure that the results meet the evaluators' expectations. Figure 2.6 shows the *Technical Risk & Efficacy* evaluation strategy selected from the FEDS framework.

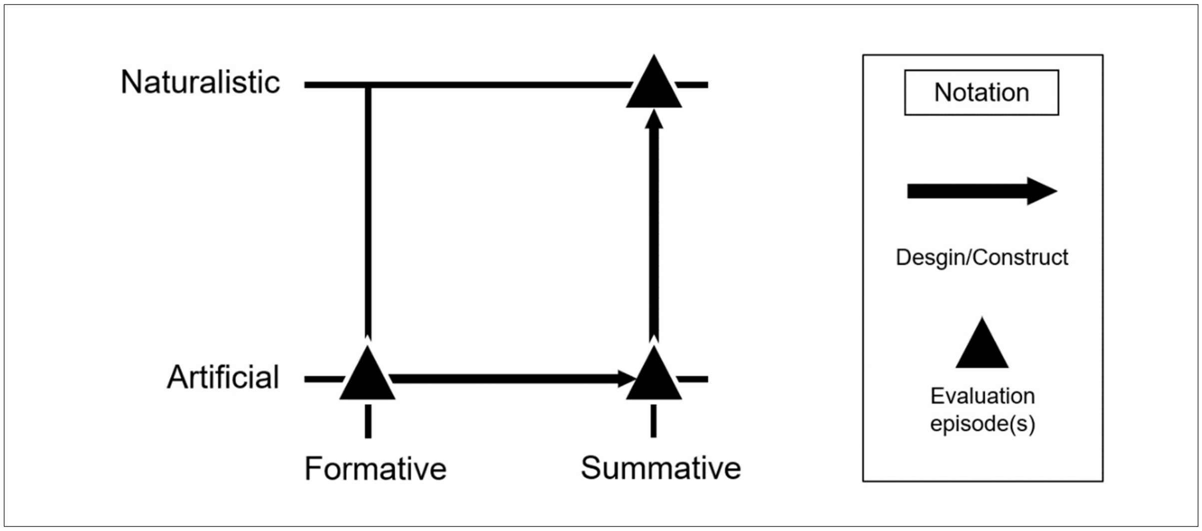

Figure 2.6 Technical Risk & Efficacy evaluation strategy
Reproduced and adapted with the permission of Venable et al. (2016, p.4)

2.2.6.2 Evaluators' involvement in this research through the DSR methodology

In this research, the *Ex Ante* evaluations are conducted to examine the feasibility and improve the artifact's ''design.'' This evaluation context is little at risk of conflict of interest; it is to the developer's advantage to discover the artifact's weaknesses and areas of improvement (Venable, Pries-Heje et Baskerville, 2016). From this perspective, the artificial demonstrations are internally evaluated through this thesis. This step leads to the artifact's ''construct.''

Through this research's ''design cycle'', the ''construct'' is evaluated in the *Ex Post* context. However, unlike the *Ex Ante* context, *Ex Post* evaluations are highly prone to conflicts of interest because they provide validation and contribute to the research publication (Venable, Pries-Heje et Baskerville, 2016). For this reason, this research is based on a naturalistic evaluation involving 16 evaluators. These evaluators engaged in one-on-one interviews and assessed the DtM framework according to a survey-based criteria grid.

2.2.6.3 Evaluation criteria

Evaluation in DSR consists of assessing the conducted demonstrations according to a grid of specific criteria. These criteria have been adapted from the *Technical Risk & Efficacy* evaluation strategy, which are often based on the ones established by (Hevner et Chatterjee, 2010): *Utility, Quality and Effectiveness*.

In this research, these criteria were used to evaluate the DtM framework according to the following definitions:

- *Utility* is the usefulness of the framework concerning the stated problem;
- *Quality* of the framework encompasses clarity, ease of use, functionality, performance, reliability, consistency and completeness;
- *Effectiveness* is the degree of success of the framework in producing a desired result.

These evaluation criteria are essential in conducting the ‘‘design cycle’’ of this research methodology. Indeed, they allow the rigorous resolution of the ‘‘design’’ and ‘‘construct’’ of the DtM framework.

2.2.7 Research communication

Communication of the research is the final step in the DSR methodology. According to De Sordi (2021), this step must consider two groups of readers; professionals and researchers. For this reason, this thesis has been structured as a series of publications. These articles have been submitted or published in scientific journals and conference proceedings. They are briefly introduced in this section, thus concluding the second chapter of the thesis.

2.2.8 Article 01: BIM and robotic manufacturing technological interoperability in construction – A cyclic systematic literature review (journal publication)

This article initiated this research by addressing the first step of the DSR methodology. It presented a cyclic SLR through Chapter 01 and provided the different research hypotheses that motivated the present study.

Article 01 investigated the most recent publications (between 2018 and 2022) covering the BIM, CD, RM, and OSC dyads. It enabled to categorize their joint technological evolution according to the number of articles published, their wide deployment in research and their use of industrial cases. This work aimed to provide potential solutions for the first two research questions (Q1 and Q2) and initiated the study conducted in Chapter 03. Article 01 was submitted to the *Journal of Digital Manufacturing Technology.*

2.2.9 Article 02: BIM-driven computational design for robotic manufacturing in off-site construction: a design-to-manufacturing approach (journal publication)

This article is the core communication of the thesis. It is featured in Chapter 03 and introduced the ‘‘construct’’ – the DtM framework. The study conducted in this research summarized Appendix I and II. It also presented the second *Ex Ante* episode and the *Ex Post* evaluation.

Article 02 covered all the outlined evaluation episodes of the DtM framework. Indeed, this study presented two computer simulation demonstrations and three laboratory experiments. These demonstrations were then assessed by a naturalistic *Ex Post* evaluation involving 16 evaluators through one-on-one interviews and surveys. As a result, this study addressed the last research question (Q3) by demonstrating how the technological integration of BIM, CD, RM, and OSC enables a DtM approach. Through this research, the interconnection of dyads in parallel technological evolution is supported by the BIM-CD, CD-RM, BIM-OSC dyads.

Furthermore, this study used the BIM-CD-RM technological triad in OSC systems to demonstrate the utility, quality, and effectiveness of the DtM framework. These demonstrations have been positively evaluated and further validated the research hypotheses presented. Article 02 was submitted to the *Journal of Automation in Construction.*

2.2.10 Article 03: The use of BIM for robotic 3d concrete printing (conference proceeding)

This article was involved in the first evaluation episode of this research and addressed robotic 3D Concrete Printing (3DCP). The work carried out in this section relates to prefabricated construction. It is presented in Appendix I and is synthesized in Chapter 03 as an artificial *Ex Ante* demonstration.

Article 03 studied the BIM-RM technological interoperability, a dyad that was thoroughly studied in the context of 3DCP. The results of this communication confirmed the findings of the first SLR cycle; it was concluded by the suggestion of using CD tools for bridging the BIM-RM technological dyad. Therefore, this investigation focused on addressing the first research question (Q1). It contributed to validating the first hypothesis (H1) and suggested further investigations of the BIM-CD-RM technological triad in OSC systems. This article was published in the *Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021* and won the *Third Best Paper Award*.

2.2.11 Article 04: Modular robotic prefabrication of discrete aggregations driven by BIM and computational design (conference journal publication)

This article concluded the first evaluation episode of this research. It used the discrete architecture approach and covered wood manufacturing and assembly in modular systems. Appendix II presents this work; its synthesis is discussed in the Chapter 03 as an artificial *Ex Ante* demonstration.

Article 04 investigated the BIM-CD-RM technological triad in OSC. Within this study, the workflow of BIM-driven computational design for robotic manufacturing in off-site construction emerged, giving insight into the DtM approach. Indeed, this research was based on bridging the BIM-RM dyad through CD to highlight the suitability of OSC for driving this triad. Moreover, it has emphasized the added value of BIM-OSC dyad in discrete architecture to enable the CD-OSC technological interoperability.

The study performed in this communication was supported by the research conducted in Appendix I, and resulted in the ‘‘design’’ of the DtM framework. Therefore, this study addressed Q1 and Q2 by contributing to the validation of the research hypotheses. This article was published in the *Procedia Computer Science special issue* and was presented at the *3rd International Conference on Industry 4.0 and Smart Manufacturing*

CHAPTER 3

BIM-DRIVEN COMPUTATIONAL DESIGN FOR ROBOTIC MANUFACTURING IN OFF-SITE CONSTRUCTION: A DESIGN-TO-MANUFACTURING APPROACH

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3.1 Abstract

Technological interoperability is a driver for seamless data and information exchange between project team members in the architecture, engineering, and construction (AEC) industry. It is defined as the ability of different systems to exchange information with minimum loss. Therefore, interoperability lack is often a barrier in modern construction applications, such as robotics. Construction and robotics, seen from their respective areas, are highly divergent in context, organization, procedures, and technologies. However, both paradigms use computation, which gives computational systems the potential to enable construction robotics. This article employs Computational Design (CD) driven by Building Information Modeling (BIM) for Robotic Manufacturing (RM) and evaluates it within Off-Site Construction (OSC) systems. This research uses the method of Design Science Research (DSR) and aims to develop a framework for operationalizing RM in OSC. Results indicate an approach for bridging the BIM-CD-RM triad in OSC, through a Design-to-Manufacturing (DtM) integration framework.

Keywords: Design-to-manufacturing; BIM; Computational design; Robotic manufacturing; Off-site construction; Interoperability

3.2 Introduction

Computational Design (CD) enables complex geometries and improves design thinking (Leach et Yuan, 2017). The taxonomy used for CD is generally associated with the nature of the data flow, namely: parametric design, generative design, evolutionary design, and algorithms-aided design (Caetano, Santos et Leitão, 2020). This design system is distinct from Computer-Aided Design (CAD). As Menges et Ahlquist (2011) explain, computation is understood by distinguishing between computation and computerization. Computation drives CD; it improves information content and accuracy and enhances typical workflows by creating new features. On the other hand, computerization drives CAD; it only retains the initial amount of information and groups it into functionalities. This difference highlights the added value of CD compared to CAD; the first relates to dynamic information while the later, static information.

In this sense, Building Information Modeling (BIM) is more than a CAD system. It relates to CD, mainly to parametric design (Janssen, 2015). Also, the concept of BIM is not limited to design, it encompasses the processes of a construction project from X to Y. Therefore, BIM is a system that is able to change a building's shape, function, and construction process (Eastman *et al.*, 2012). BIM and CD are part of the ''second digital turn'' (Carpo, 2017), a shift involving design and management processes and manufacturing and construction operations that have enabled automation.

In construction, automation is defined as implementing industrial robots (also known as robotic arms) in built environments (Cousineau et Miura, 1998 ; Dachs, Fu et Jäger, 2022). The use of this technology is often associated with controlled environments. This association correlates with a specific construction system, Off-Site Construction (OSC). Indeed, OSC is the manufacturing of components or building systems in a factory plant to be transported and assembled on-site. This construction system encompasses two main subsystems, prefabrication and modular construction (Wallance, 2021 ; Smith et Quale, 2017). It favors implementing automation solutions such as Robotic Manufacturing (RM), a long-standing research objective (Yin *et al.*, 2019).

Despite the apparent synergistic potential, robotics and construction technological tools are disparate. This study will address the research gaps we found in the literature regarding the technological interoperability of BIM, CD, RM, and OSC systems. Our research is consistently presented in the following data flow order: The BIM model is the data source, it is supported and converted through CD tools into a program for a robotic arm, which in turn transforms this program into an operation for OSC. This data flow stands for BIM-driven computational design for robotic manufacturing in off-site construction. It gives rise to a *Design-to-Manufacturing (DtM)* approach that encompasses the Design for Manufacturing (DfM) process. Indeed, DfM involves design with manufacturing considerations (Wakil, 2019), while DtM integrates design and manufacturing programming. In sum, this research seeks to answer the following research question: *How can BIM, CD, RM and OSC technological integration enable a Design-to-Manufacturing (DtM) approach?*

This article begins by presenting a literature review and the methodology used. It then introduces the DtM framework using BIM-driven computational design for robotic manufacturing in off-site construction. Finally, this framework is put into operation through demonstrations and laboratory experiments to be evaluated by several practitioners, the results of which are presented in the discussion and conclusion.

3.3 Literature review

The present research study was initiated with the Systematic Literature Review (SLR) method and addressed the technological interoperability between BIM, CD, RM, and OSC dyads. The restriction to the binary settings is because there are rarely, if ever, more than two systems studied in a single article. This investigation involved the most recent publications, published between 2018 and 2022. It was conducted through five steps adapted from Kitchenham (2004) ; Van Eck and Waltman (2010) ; Moher et al. (2015): research identification, bibliographic review, eligibility assessment, bibliometric analysis, and finally, data synthesis and research hypothesis. The findings of this SLR are summarized in this section.

The dyads studied were categorized as systems in either an interconnected or parallel technological evolution in research. This qualitative categorization was based on the number of articles published (indexed in Scopus or Dimensions databases), extensive research deployment, and involvement of industrial case studies. In other words, *dyads in an interconnected technological evolution* are defined by joint research or implementation that has reached maturity in research or industry. In contrast, *dyads in a technological parallel evolution* are defined as having joint research that is still in the preliminary stage or non-existent. The findings of this categorization are as follows:

- Dyads in an interconnected technological evolution: BIM-CD / CD-RM / BIM-OSC.
- Dyads in a parallel technological evolution: BIM-RM / CD-OSC / RM-OSC.

Regarding the BIM-CD interconnected evolution, more than 133 eligible documents were identified. These publications reflected the added value of this technological dyad through its various functionalities, the data management it enables, and the design versatility it provides within full-scale projects (Akkoyunlu, 2018 ; Xhafa, Patnaik et Tavana, 2020 ; Amoruso, Dietrich et Schuetze, 2018). This dyad is inherently connected through parametric design (Dautremont *et al.*, 2019 ; Coenders, 2021). It is widely used by the world's most successful architectural and engineering firms (Schwerdtfeger, 2018 ; May, Pynn et Hill, 2018 ; Gehry, Lloyd et Shelden, 2020). In the case of the CD-RM dyad, the eligible documents found amounted to more than 106. This dyad is experiencing significant expansion within research laboratories specialized in digital manufacturing. Indeed, it has revealed its potential through iconic projects such as those conducted at the Gramazio & Kohler laboratory (ETH) (Gramazio, Kohler et Willmann, 2014 ; Lloret-Fritschi *et al.*, 2020 ; Hack *et al.*, 2020 ; Thoma *et al.*, 2019), the ICD/ITKE/IntCDC (University of Stuttgart) (Menges et Knippers, 2020 ; Bodea *et al.*, 2021 ; Wagner, Alvarez, Kyjanek, *et al.*, 2020 ; Gil Pérez *et al.*, 2020), and the Bartlett School of Architecture (UCL) (Claypool *et al.*, 2019 ; Claypool, 2019b ; Retsin *et al.*, 2020). Finally, for the BIM-OSC interconnected dyad, more than 227 eligible documents were identified. Research and industrial case studies have proven the productivity improvement of OSC through BIM tools (Li *et al.*, 2019 ; Jang *et al.*, 2021 ; Sabet et Chong, 2019 ; Jang et Lee, 2018). It is a widely used dyad in Design for X (DfX) approaches, especially in Design for Manufacturing and Assembly (DfMA) (Zadeh *et al.*, 2018 ; Gbadamosi *et al.*, 2020 ; Kalemi *et al.*, 2020).

On the other hand, research is rare for parallel dyads. For example, BIM-RM only generated 18 eligible documents. These publications revealed an ambiguity in regard to choosing an approach to adopt, the disparity in the tools used, and insufficient validation (Sepasgozar *et al.*, 2020 ; Lee *et al.*, 2021). Interestingly, CD is interconnected with both systems of this dyad. This observation raised the first research hypothesis (H1): *CD is a medium for BIM-RM technological interoperability*. The same case applies to the CD-OSC dyad (Wallance, 2021 ; Retsin, 2019c), which generated 27 eligible documents. This dyad is also limited by the disparity of the technological tools used since OSC design is currently heavily based on CAD, suitable for BIM tools but not CD. This observation generates the second research hypothesis (H2): *BIM is a medium for CD-OSC technological interoperability*. The last parallel dyad is RM-OSC, which involved 22 eligible documents. This dyad is seldom implemented due to, among other reasons, the challenge of adapting robotic programming to ever-changing building products (Verboeket et Krikke, 2019 ; Davila Delgado *et al.*, 2019). By merging the dyads categorized, it was possible to yield the final research hypothesis (H3): *the BIM-CD-RM technological triad has the potential to operationalize RM in OSC*.

Figure 3.1 clarifies the different dyads identified among the concepts investigated. Black links define an interconnected technological evolution, while red links define a parallel technological evolution. Finally, the research gap involving the conjunction of the four systems is explicitly identified.

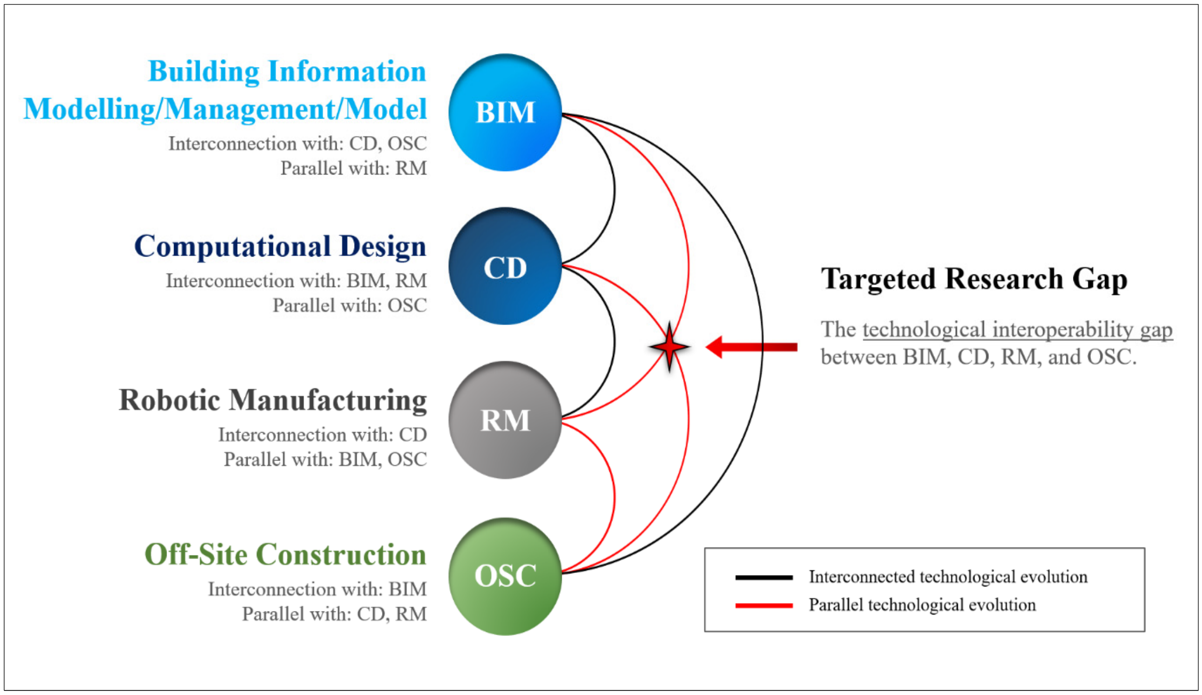


Figure 3.1 Interconnected and parallel dyads of the different systems identified through the Systematic Literature Review (SLR)

This SLR is supported by other such studies in the literature that explicitly cite the need for research that joins BIM-CD-RM or BIM-RM-OSC (Wang *et al.*, 2020 ; Yin *et al.*, 2019 ; Vähä *et al.*, 2013). However, these approaches should not be addressed in a discrete way but rather in an integrated manner since they are intrinsically linked. For this reason, this research investigates BIM-driven computational design for robotic manufacturing in off-site construction. BIM-CD are technologically coupled for design, management and collaboration, CD-RM for robotic programming, and OSC as the system bringing these approaches together.

3.4 Research methodology

Following the identification of research gaps in the literature, the need for a framework addressing the use of industrial robots in construction is highlighted. Therefore, the Design Science Research (DSR) methodology was adopted to tackle this topic. This methodology is described in six phases by De Sordi (2021): motivation and problem identification, the definition of objectives for solutions, design and development of an artifact, demonstration, evaluation, and finally, communication. By interpolating these different stages to the research discussed in this article, this research was primarily motivated by the industrial and academic need to operationalize industrial robotics in construction. The identified problem is illustrated in Figure 3.1; it consists of *the research gap involving the technological interoperability between BIM, CD, RM and OSC*. This problem covers the three sub-problems: *BIM-RM, CD-OSC, and RM-OSC parallel dyads*.

This research aims at developing an artifact that manifests as a framework for addressing the research question mentioned in the introduction. Specifically, it seeks to *define a framework integrating BIM and CD for using RM in OSC, enabling an integrated DtM workflow*. The framework is developed in this workflow's two main stages: the design and manufacturing stages. It is essential to acknowledge that our local industrial partners do not yet support the implementation of RM in their internal processes. Nevertheless, they manifested their interest in this research by participating in the qualitative evaluations of the framework through individual interviews and surveys. The *Technical Risk & Efficacy* evaluation strategy is used in evaluating the developed framework. As Venable et al. (2016) described, this approach focuses on iterative artificial strategies initially in the process and progressively evolves to naturalistic strategies. Artificial strategies involve ‘‘unreal systems, unreal users, and unreal problems.’’ On the other hand, naturalistic strategies involve ‘‘real systems, real users, and real problems.’’ These strategies are materialized in the *Ex Ante* and *Ex Post* contexts. The *Ex Ante* context is for evaluating the ‘‘design’’; the artifact in its preliminary phase. The *Ex Post* context is for evaluating the ‘‘construct’’; the artifact in its advanced phase (Pries-Heje, Baskerville et Venable, 2008). Naturally, the evaluation process of an artifact is constantly iterative. Therefore, the *Ex Ante* and *Ex Post* contexts drive the artifact design cycle (Sonnenberg et vom Brocke, 2012).

This study starts with two artificial *Ex Ante* demonstrations using computer simulations. These demonstrations enabled the ‘‘design’’ of the framework. They are then supported by an additional *Ex Ante* demonstration using laboratory experiments, resulting in the ‘‘construct’’ of the framework. This step engages the naturalistic strategy for the validation of the research. Indeed, this study concludes with a naturalistic *Ex Post* evaluation conducted through individual interviews involving 16 evaluators.

This article presents the DtM approach within two OSC systems. The first is for prefabricated components, and the second is for modular construction. These two systems were selected because they represent the main paradigms of OSC. Regarding the selected robotic technology, this article specifically addresses robotic arms as it is the most widely used technology in industrial manufacturing (Dachs, Fu et Jäger, 2022 ; Aldinhas Ferreira et Fletcher, 2022 ; Gurgul, 2018). The framework presented was evaluated for utility, quality, and effectiveness. According to Hevner and Chatterjee (2010), utility refers to the artifact's usefulness in the context in which it is used. Quality encompasses clarity, ease of use, functionality, performance, reliability, consistency, and completeness of the framework. Finally, effectiveness is the degree of success in producing the desired result. This evaluation will lead to the communication of the research.

In order to synthesize and validate the results of this study, only the advanced framework (the ‘‘construct’’) is presented. Thus, the discussion section of this article will focus on the *Ex Post* naturalistic evaluations, i.e., the individual interviews and surveys. Figure 3.2 illustrates the steps of the research methodology.

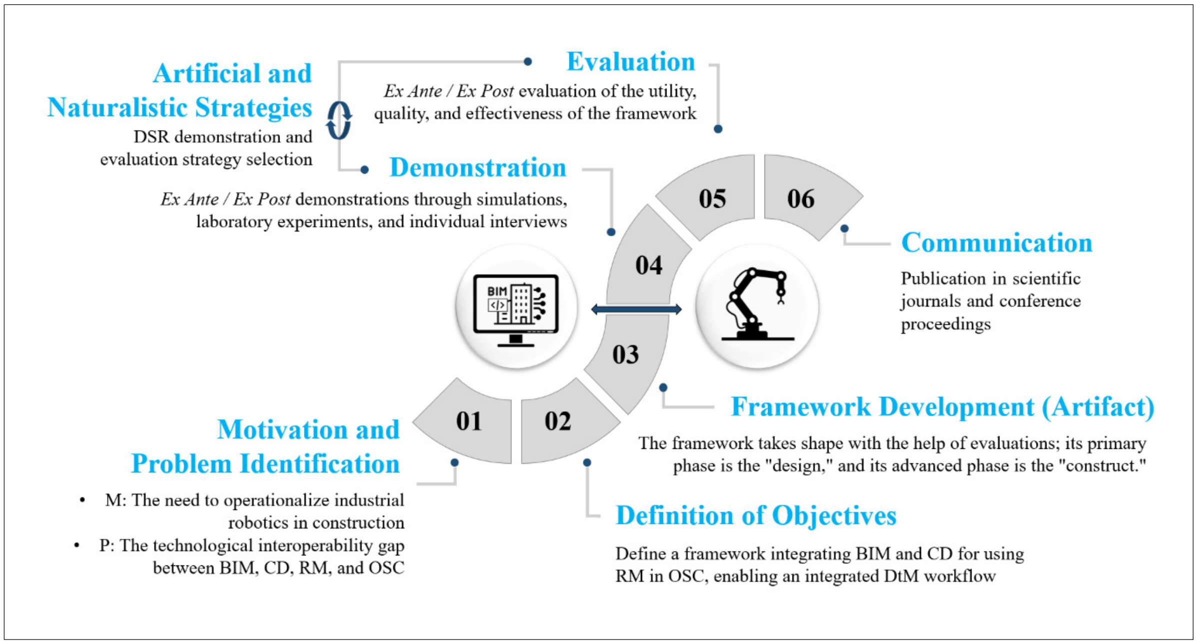


Figure 3.2 Steps of the Design Science Research (DSR) methodology used in this research

3.5 BIM-driven computational design for robotic manufacturing in off-site construction: The Design-to-Manufacturing (DtM) approach

This section addresses the research question; it presents steps three and four of the research methodology illustrated in Figure 3.2. First, the role of BIM-CD technological dyad for robotic programming is clarified. Then, the framework in its ‘‘construct’’ state is introduced, followed by the demonstrations that led to its development. These demonstrations are conducted through two different projects using computer simulations. Three laboratory experiments subsequently support them to demonstrate the functionality of the workflow proposed, leading to the evaluation of the framework.

3.5.1 The role of BIM-driven computational design in robotic arms programming

This research involves robotic arms since they enable manufacturing processes to be customized for specific construction applications. Indeed, robotic arms are multifunctional because they can be equipped with a wide range of end effectors. They can integrate several tools at the robot flange (varying from extruders, grippers, screwdrivers, and more), thus granting a different application each time. In addition, robotic arms can be coupled with a technological environment (such as sensors, conveyors, and safety equipment) through analogue or digital signals. However, the construction industry has frequently reconfigured its operations due to unpredictable design changes. For this reason, the conventional manual programming of robotic arms is unsuitable for the AEC industry (Rodrigues *et al.*, 2021 ; Bock et Linner, 2015 ; Brell-Çokcan et Braumann, 2013). Therefore, computerized processes such as Computer-Aided Manufacturing (CAM) are insufficient for enabling robotic arm programming for construction workflows.

Robotic arm programming is a set of instructions that aims to define the subsequent path and manipulations of the tool used. This path is established using a key element called the tool center point (TCP), which crosses the different targets defining the toolpath. Therefore, the robotic arm will adjust to the positioning of its TCP by generating its joints' rotations, exhibiting a process of inverse kinematics (Renaud, 2000). Programmed instructions are then visualized in a simulator to ensure the proper functioning of the intended operation. This process is the main workflow that defines typical offline programming designed to prevent malfunctions related to robotic arms (Devadass, Stumm et Brell-Cokcan, 2019 ; García del Castillo y López, 2019). Once these steps are complete, the user can transfer the operational commands to the robot to test simulations in a natural context. However, these steps must be manually redefined when modifying the workpiece design in computerized programming. This lack of flexibility reduces the capacity of robotic arms in a multi-product industry like construction. Therefore, the use of a BIM-driven computational design approach for robotic programming is proposed.

In this approach, robotic programming is enabled by CD. First, as shown in Figure 3.3, the inputs are informed models (e.g., robotic arm, tool, workpiece). These inputs are then transformed into a simulated robotic program through an algorithms-aided process. This transformation eliminates the need to go back and forth between modeling and robotic programming software. Furthermore, it transforms file-formats exchange into an integrated process. Indeed, this approach gives flexibility to RM by providing the ability to modify design and programming within integrated User Interfaces (UIs). In addition, the robot arm-specific commands (i.e. Rapid Code for ABB, KRL for Kuka) are generated automatically. Finally, this robotic program is processed within the BIM environment for management and collaboration in the production process through CD tools. This process gives a perspective on the DtM approach, where design and manufacturing programming are instantly responsive.

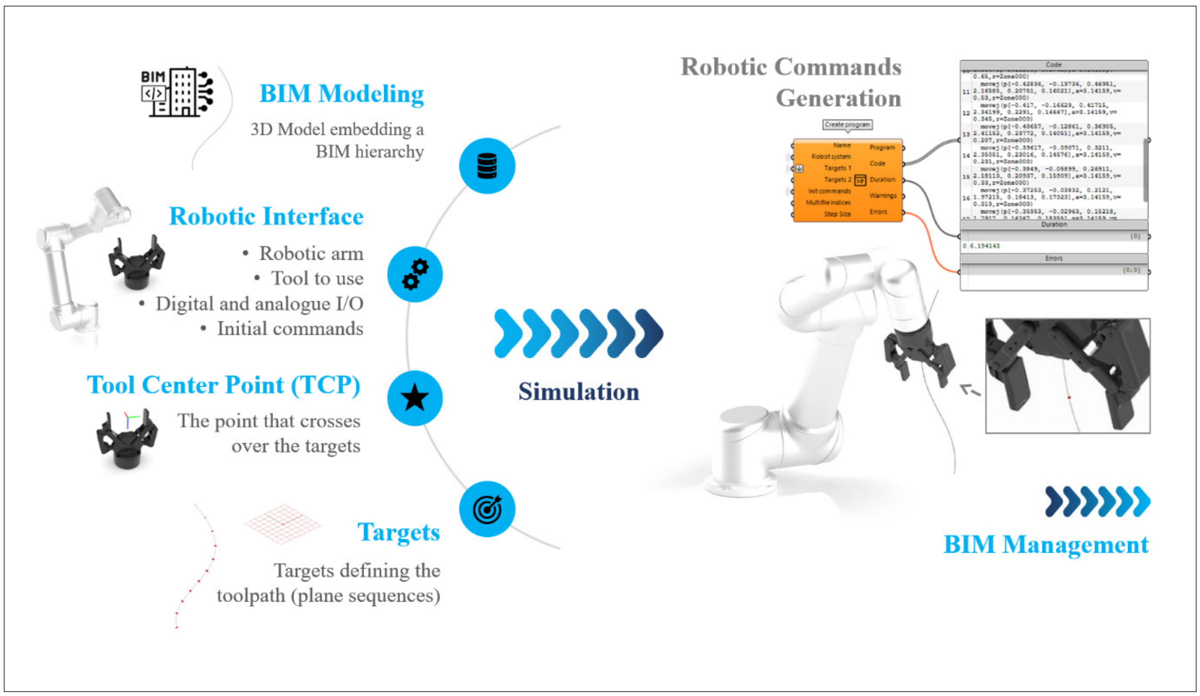


Figure 3.3 Inverse kinematics process through the BIM-driven computational design approach

3.5.2 Proposed framework for using BIM-driven computational design for robotic manufacturing in off-site construction – The DtM framework

This section introduces the proposed framework, first presenting the different sections of its skeleton and streamlining them in the ‘‘construct.’’ In this perspective, the skeleton is presented in Figure 3.4. This illustration describes the different workflows employed and uses black dotted lines if they are not covered in this article. In the framework, and for technological interoperability purposes, integration is the best configuration of software. This integration is translated into the framework by representing the CD environment within a BIM environment. For instance, this integration system is explicated by Anane, Iordanova and Ouellet-Plamondon (2023) ; Anane, Iordanova and Ouellet-Plamondon (2022) in terms of a tightly coupled approach. This approach is defined by Janssen (2015) as having two systems associated through the modeling software's application programming interface (API). This integration system eliminates the export and import of file formats, minimizing the risk of losing model data and keeping the information flow centralized around a BIM model. In this framework, the main stages are clustered into four sections. Section λ is for BIM-driven computational design, section ω for algorithms-aided robotic programming, section δ for cloud-based collaboration, and section η for OSC. This symbolic designation avoids understanding the sections in sequence since the design and manufacturing programming process is integrated and iterative. The following is a clarification of each section:

Section λ: This section addresses the modeling process and is framed within a BIM-driven computational design workflow, meaning that the models created are supported by a BIM hierarchy (i.e., a category, a family, a type, and an instance) and attributes. During this process, the model is designed for manufacturing and improved by the input of the different project stakeholders. This model is preliminarily validated over several iterations, leading to a BIM model. Section λ is intrinsically interrelated with sections ω and δ. Indeed, the design phase relies on manufacturability and cloud-based collaboration.

Section ω: This section addresses robotic programming. Once the manufacturing method is identified, the programming starts by selecting the robotic arm model, the tool, and the digital and analog I/O configuration. These settings enable the tool path creation for the BIM model manufacturing. The robotic arm programming is then generated and simulated using CD tools in the same modeling environment. Section ω depends on section λ since the manufacturing process requires a digital model for its execution. This section is similarly reinforced by section δ, as cloud based-collaboration enhances manufacturing monitoring.

Section δ: This section covers cloud-based collaboration and acts as a connecting element among the other framework sections. Indeed, the cloud platform is involved in model exchange among designers and is used for manufacturing control and adaptation. In addition, it is involved in the coordination and planning of construction operations. The cloud platform is on the edge of the integrated environments within the framework since it is the medium between the collaborators and the digital model.

Section η: This section addresses OSC. It is the final section of the developed framework and incorporates the various manufacturing techniques enabled by robotic arms. This section may result from the previous sections or may also drive the other sections in an iterative construction process.

This framework brings together various complex concepts evolving in parallel in research and industry, providing a nexus for their technological integration. Indeed, the framework leverages the dyads in an interconnected technological evolution to tackle the identified research gap. In Figure 3.4, the BIM-CD dyad materializes by combining the framework's sections λ and δ. CD-RM dyad is formalized in the framework through sections λ and ω. Finally, section η is connected to all the previous sections through an OSC system; in this sense, this framework reveals the convergent potential of the BIM-CD-RM technological triad. It also reveals that these three systems become technologically integrated when combined and result in the DtM approach.

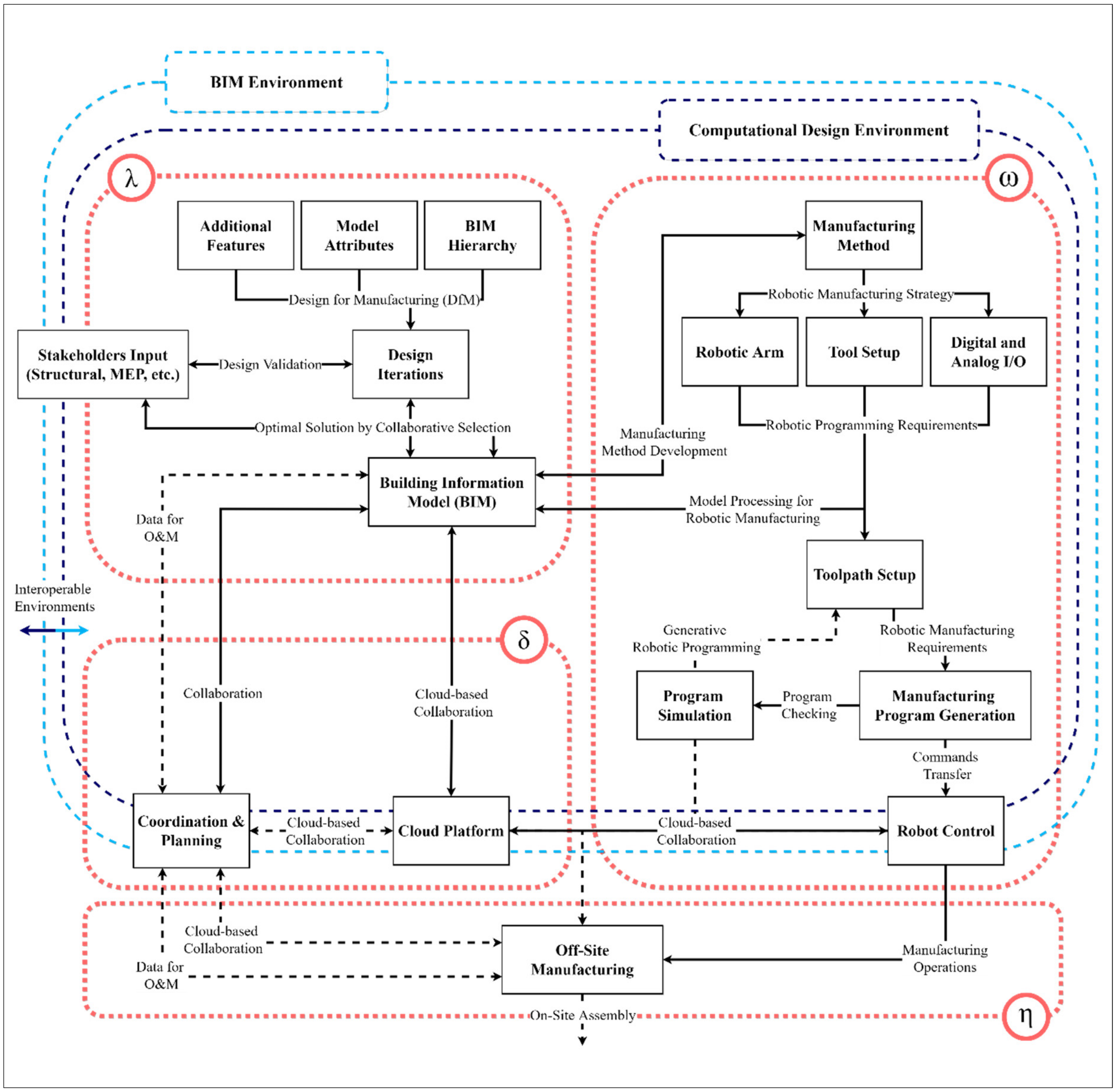


Figure 3.4 Framework skeleton of the Design-to-Manufacturing (DtM) approach enabled by BIM-driven computational design for robotic manufacturing in off-site construction

To facilitate the understanding of the framework skeleton, Figure 3.5 presents it in a streamlined form: the ‘‘construct.’’ The DtM approach is non-linear; it is a cyclic process based on technological environments’ integration. Therefore, the framework is represented in a circular form that frames the digital construction project. This framework is operational through the technological integration of BIM and CD environments. These two environments are the drivers around which the different sections revolve. These sections are represented by circular layers that are not sealed since each process will end after completing the construction project. Throughout this article, the DtM framework is adapted to different OSC systems, with an overview of the tools used in each system.

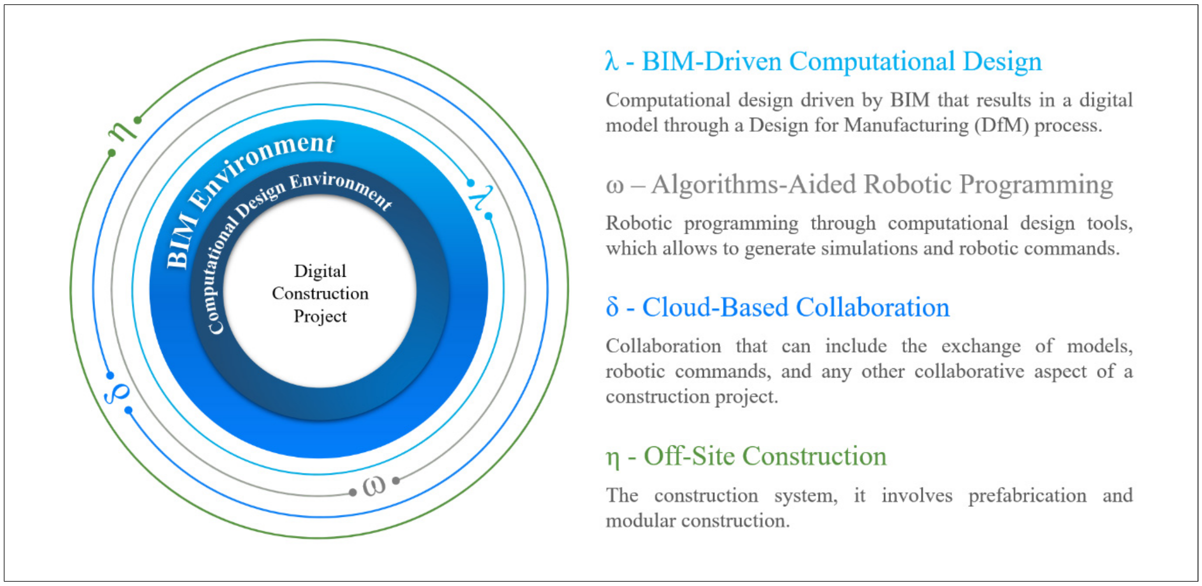


Figure 3.5 Framework supporting the Design-to-Manufacturing (DtM) approach enabled by BIM-driven computational design for robotic manufacturing in off-site construction

The following sections of the article demonstrate the framework's utility, quality, and effectiveness. The selected artificial projects are defined according to the two main OSC systems; prefabricated and modular construction. In the first system, the DtM framework will demonstrate its capacity to integrate freeform design and robotic programming while providing access to cloud-based collaboration. In the second system, the framework will demonstrate its productive ability to generate BIM-driven modular designs integrated with RM programming. *Ex Ante* laboratory experiments will then support the results of these demonstrations. These steps define the artificial *Ex Ante* context of this research, which evaluations will be covered in the discussion section of this article.

3.5.3 Demonstration of the DtM framework in the Ex Ante artificial context

3.5.3.1 Ex Ante demonstration of the DtM approach in prefabricated construction

Prefabrication is a manufacturing process usually conducted in a controlled environment; it involves assembling various materials to produce a part of a final installation (Ginigaddara *et al.*, 2022). Free forms are a coveted goal for OSC designers. However, they are difficult to achieve with conventional design and manufacturing (i.e., CAD/CAM processes, using standard molds) (Zuk et Asce, 1972). Herein lies the need for CD since it facilitates such architectures' access through form-finding capability (Schumacher, 2009). Therefore, the developed framework provides accessibility to the design and manufacture of free forms by relying on the CD and RM interconnection. However, successful innovations and design methodologies will not be exploited to their full potential if collaboration and management are lacking within a team.

In this context, digital design communication systems are in progressive development, especially through BIM cloud-based technologies (Alreshidi, Mourshed et Rezgui, 2018). Computation is inherent in this technology; it enables configurable resources to be sourced and deployed with minimal management effort or services (Mell et Grance, 2009). Using a BIM schema, the digital prefabricated products incorporate data (e.g., production line, manufacturing duration, materials quantities) that allow accurate cost estimation and production planning. This context justifies the need for integrating BIM and CD environments; they enable a fledged DtM process.

This section deploys the DtM framework through the integrated use of BIM and CD environments for robotic 3D Concrete Printing (3DCP) (Anane *et al.*, 2023). Figure 3.6 illustrates the tools used (but not limited to) in each section of the framework for this artificial project.

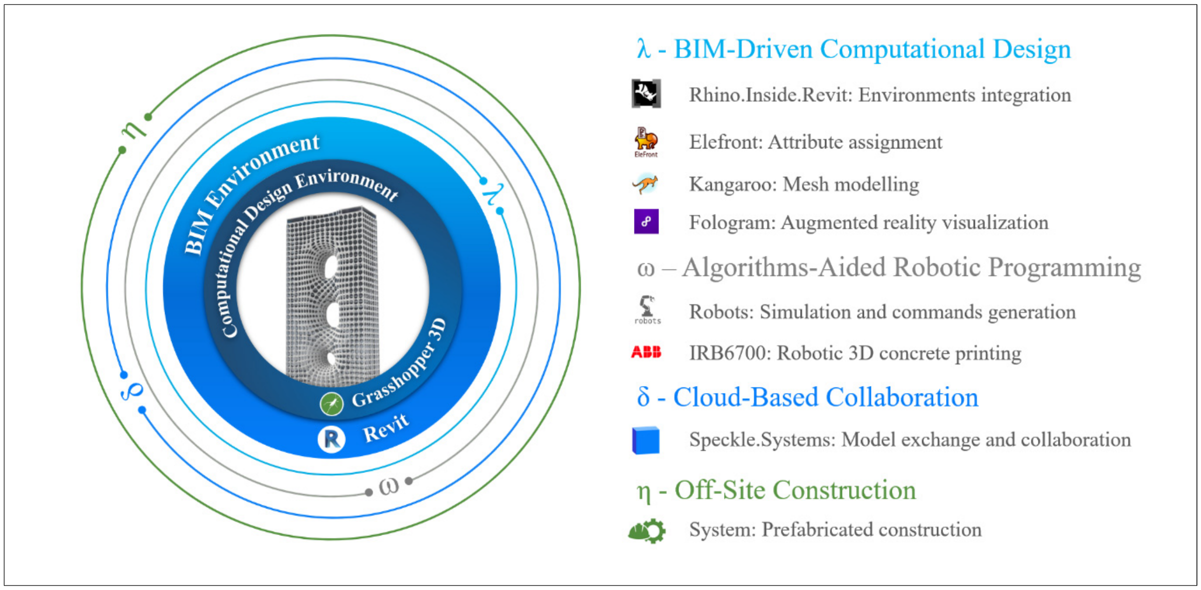


Figure 3.6 Framework deployment in the first Ex Ante demonstration – The DtM approach in prefabricated construction, tools and functions used

This artificial project uses the DtM approach to design and simulate the prefabrication of a freeform envelope assembled on a contemporary-styled building. This building is inspired by the Morpheus hotel located in Macau and designed by Zaha Hadid Architects (Anon, 2018 ; Piermarini *et al.*, 2018). The building's selection was determined by the duality of its mystical design and its real-world context. In this project, the parameters and properties that drive the DtM process are supported by Rhino.Inside.Revit (R.I.R), which is a tool that uses Revit's memory space to run Rhinoceros 3D and Grasshopper 3D. In section λ, the parametric capacity is coupled with attributes and other data through Elefront and the BIM hierarchy that R.I.R offers. From the early stages of the design process, attributes are inputted in parallel with the modeling activity involving mesh manipulations with Kangaroo. This process results in a BIM model, which is the central element of this system. Section ω uses the resulting BIM model to determine the manufacturing method. This step initiates the algorithms-aided robotic programming process, which requires the different inputs illustrated in Figure 3.3. After programming the toolpath, the Robots plugin generates the commands for the robotic arm and simultaneously simulates its operations and manufacturing data. These operations can be monitored on the cloud, reflecting the importance of the collaborative section. In section δ, cloud-based collaboration can be performed with the Speckle.Systems data platform. With REST APIs, it is possible to exchange models and robotic commands almost in real-time through the DtM process (Poinet, Stefanescu et Papadonikolaki, 2020). In addition, it allows for increased tracking of different versions and revisions of the BIM model. This cloud-based collaboration mechanism is not only limited to Speckle.Systems; it can involve any collaborative platform that is compatible with the software or formats used. Finally, in section η, collaboration on the cloud and robotic commands initiate the manufacturing process of the free form element. As an added feature enabled by this framework, this artificial project incorporates a demonstration of reality visualization. The models created can be visualized in Virtual/Augmented/Mixed Reality (VR/AR/MR) through Fologram, which offers real-time model synchronization with its digital representation in the real world. This application predicts the manufacturing process of the generated designs. It is important to note that the illustrated technological tools are not the only ones that allow such functionalities and are interchangeable with other software. As Anane et al. (2023) and Anane, Iordanova et Ouellet-Plamondon (2021) describe, the more data integration is required, the narrower the range of such software becomes.

As shown in Figure 3.7, this artificial demonstration results in a DtM approach that integrates design and robotic programming. This figure is represented in a matrix that combines the different processes with their use context. It illustrates that the proposed framework provides accessibility to BIM workflows, manufacturing simulations, cloud-based collaboration, and augmented reality. This approach is concluded by the program generated by the Robots plugin, which will be transferred to the robotic arm to transform the simulations into real-world manipulations. However, on-site assembly realism is not considered since it is not the scope of this demonstration. Figure 3.7 shows the simultaneous visualization of the developed model and the 3DCP simulation. This visualization is enabled through Grasshopper 3D. It is presented in Revit, Rhinoceros 3D, Speckle.Systems web viewer and in augmented reality by Fologram.

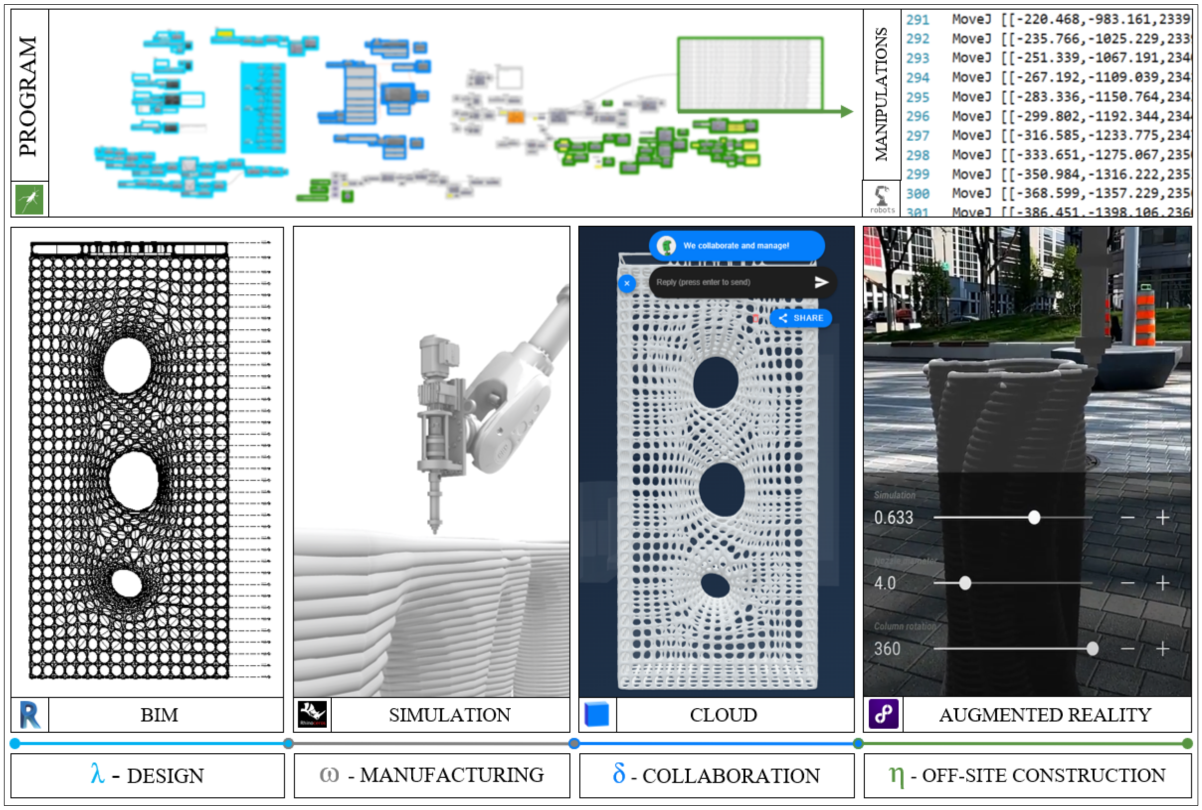


Figure 3.7 Simultaneous visualization of the artificial demonstration enabled by Grasshopper 3D and presented in Revit, Rhinoceros 3D, Speckle.Systems web viewer, and in augmented reality by Fologram

In this artificial project, the proposed framework reflected the strength of the DtM approach. Indeed, BIM-driven computational design provides integrated access to both freeform design and the robotic programming of its manufacturing. Furthermore, this capability is coupled with cloud-based collaboration between stakeholders for data visualization and exchange. This demonstration provides an example of the innovative potential of an approach based on the triad of BIM, CD, and RM. Finally, this triad is applied to prefabrication in OSC through the 3DCP process. This application gives an alternative to conventional prefabrication techniques and provides a framework for using RM in OSC.

3.5.3.2 Ex Ante demonstration of the DtM approach in modular construction

In this *Ex Ante* demonstration, the DtM approach is enabled by *discrete architecture*. *Discrete architecture* is a CD approach that uses algorithms to generate aggregations organized according to well-defined grammars (Retsin, 2019a ; Trotter, 2019). Discrete logic is deeply identified with the modular method in built environments. Indeed, modular construction is a method that involves three-dimensional or volumetric units that are manufactured and delivered to the construction site (Modular Building Institute, 2020 ; Goodier et Ashley, 2006). While this OSC subsystem favors robotic automation solutions, they are still seldom implemented in the modular industry.

In this section, the proposed framework is deployed through the artificial project conducted by Anane et al. (2022). This artificial demonstration involves the development of a modular residential building, in which modules are manufactured by robotic wood milling and assembly. As Figure 3.8 illustrates, the approach used was again based on Figure 3.5, thus demonstrating the framework's versatility. Similar to Figure 3.6, this figure shows the main steps and tools used in this project. In this instance, the choice was to keep the main BIM and CD environments to demonstrate the framework's reliability in different contexts.

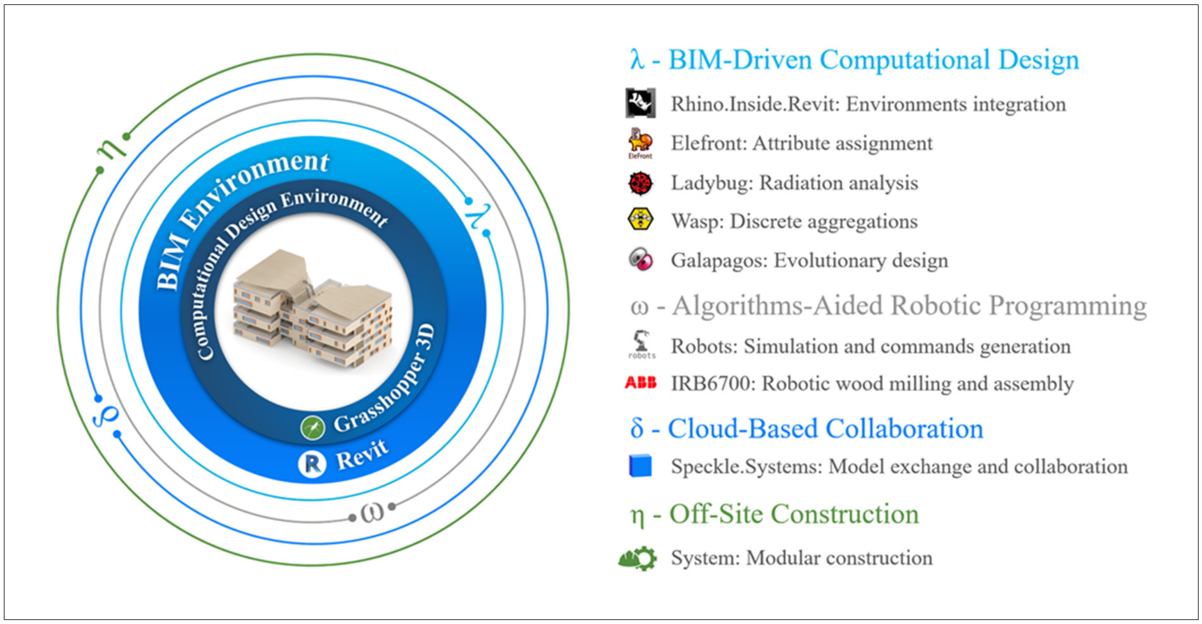


Figure 3.8 Framework deployment in the second Ex Ante artificial demonstration – The DtM approach in modular construction, tools and functions used

In this artificial project, the generation of modular aggregations is supported through the Wasp plugin of Grasshopper 3D (Rossi et Tessmann, 2019), integrated into Revit using R.I.R. As illustrated in Figure 3.9, the modules that are to be aggregated are initially divided into two categories. First, the main modules can include a kitchen, a living room, and a workspace. Second, the functional modules constitute either a bedroom, a bathroom with a corridor, or another type of use. These modules are structurally defined by their internal components (slab, columns, beams) and are natively identified in the BIM environment. To generate the aggregations, connections and combination rules must be defined. The connections are used to identify how the modules connect (e.g., from the right, left, top, and bottom). The combination rules are used to identify the possible coupling of modules (e.g., module A connects from the right to module B). These rules and connections allow aggregation iterations, providing designers with possible modular building configurations.

In order to illustrate the effectiveness of this approach, the aggregation rule is focused on the plumbing aspect throughout the modular project. A collaborator uses BIM tools to connect and root the plumbing devices of the modules. In this instance, the aggregation rule is that the modules for sanitary use are superimposed and connected to a central module on the kitchen side. In this sense, the assembly of modules results in a connected kitchen and sanitary modules throughout the building. This combination reduces the dispersion of pipes in the building floors and between the units within each apartment. Performing a radiation exposure study using the Ladybug tools is another functionality demonstrated in this project. Based on the analysis provided and evolutionary algorithms such as Galapagos, the width of windows and sunshades is adapted to the radiation conditions of the building. Finally, technical drawings and project dashboards are generated using BIM tools for the project's information management.

This demonstration has resulted in a workflow based on integrated data management through the environment's APIs. Figure 3.9 shows snapshots of this design process, which allowed the development of a functional modular design selected through effective iterations. In addition, this process has proven to be a clash avoidance technique. Indeed, the generated aggregations do not include clashes because they are algorithmically modeled instead of manually modeled. Finally, this approach results in a digitally documented project, allowing for future module recombinations according to the project context.

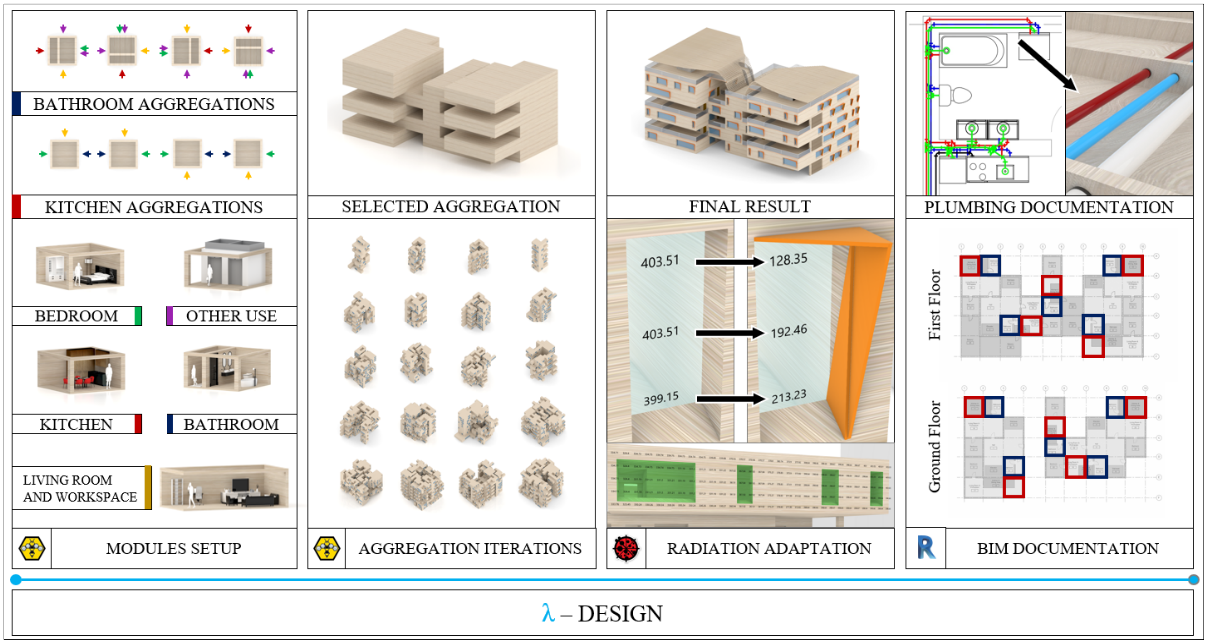


Figure 3.9 Overview of the DtM approach used in an artificial modular project driven by discrete architecture

Discrete architecture in modular construction driven by BIM addresses the research gap involving CD-OSC dyad. However, the DtM approach is not only limited to the modular design phase; it also involves the manufacturing phase. Indeed, by having a BIM hierarchy that identifies each construction module, the parts to be manufactured are robotically programmed along a production line. In the case of this artificial project, the elements integrating plumbing systems are grouped into families and manufactured by robotic cells. Thanks to Revit's plumbing model, these robotic arms prepare the piping locations by milling the wood pieces, and then assemble them using automatic screwdrivers. Indeed, the intersection of the architectural and plumbing elements defines the different targets of the robotic arms. These intersections are converted into a toolpath, allowing the TCP to reach each target. Since the design and robotic programming are performed in the same computational environment, the building elements that will incorporate the plumbing components are separately nested onto the conveyor of the digital robotic cell. This arrangement allows for the simulation of the manufacturing process and the generation of manufacturing commands for the robotic arms. As a result, a robotic program that considers the routing of the pipes based on the parameters (diameter, slope, grade) included in the BIM model is transferred to the robotic arm for operation. Figure 3.10 shows the DtM approach output in this artificial project.

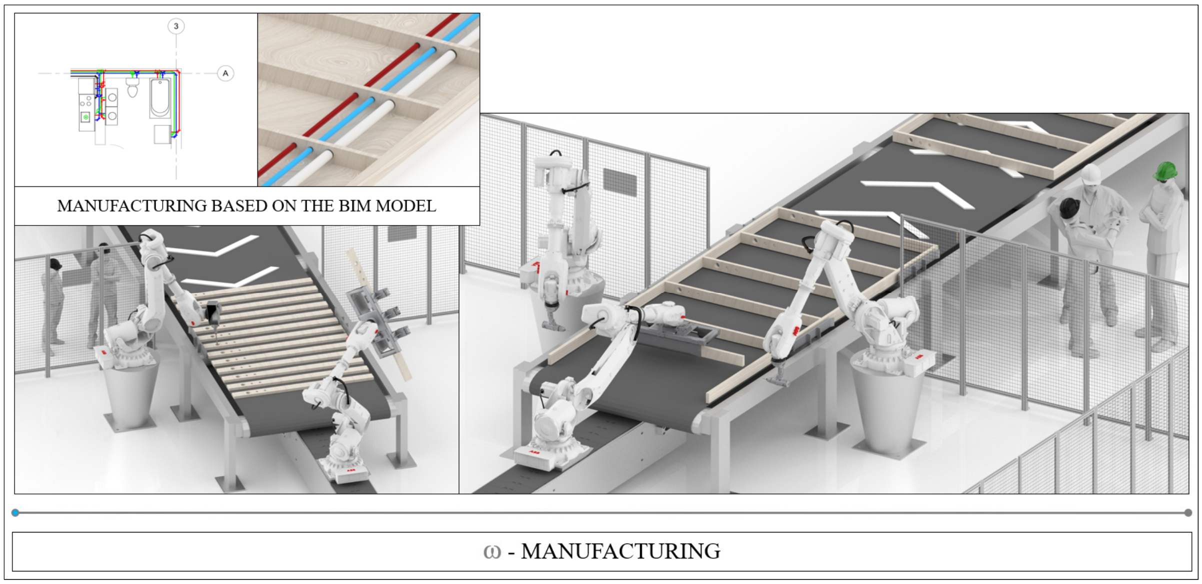


Figure 3.10 Robotic manufacturing and assembly simulation of a floor frame integrating plumbing based on the BIM model of the artificial modular project

Within the prospect of modular manufacturing automation, the DtM approach offers the capability to develop algorithmic-aided manufacturing strategies for modular constructions. According to the project discussed in this section, it is an approach that enables the generation of robotic cell programming using a native BIM model. This ability allows for a parametric feedback loop between design and manufacturing processes. Moreover, the proposed framework facilitates interdisciplinary collaboration through BIM. For instance, by modeling a module's plumbing, mass production by robotic cells is both programmable and visualizable. Furthermore, it provides modular construction designers with a form-finding process based on aggregation rules. As a result, it saves valuable resources in the modular design phase and subsequently in RM, demonstrating the effectiveness of the DtM approach.

The DtM framework has addressed the CD-OSC and RM-OSC parallel dyads using BIM-CD-RM technological triad in this artificial project. From this perspective, it has contributed to addressing the targeted research gap.

3.5.3.3 Ex Ante demonstrations of the DtM approach through laboratory experiments

In this section, the DtM framework is operationalized through *Ex Ante* laboratory experiments to support the performed *Ex Ante* simulations. These experiments were performed with two different robotic arms, performing two different functions to demonstrate the reliability of the framework regarding the generated robotic codes. The first robotic arm is a Universal Robots UR10, whose application is the assembly and reassembly through disassembly of wooden parts (Anane et Iordanova, 2021). The second robotic arm is an ABB IRB6700 identical to the one used in the artificial projects, whose application is 3D printing using mortar. Finally, the DtM framework was also tested in the case of other digital manufacturing tools such as 3D printers. These experiments were conducted within a BIM environment to demonstrate the technological interoperability of the BIM, CD, and RM triad.

In all laboratory demonstrations, the DtM framework enabled the design and programming of the toolpath the robots would follow. The approach has proven adaptability to changes in robotic targets due to design modifications. It also validated the data relative to the manipulations (e.g. manipulation duration, print volume, singularity points), hence the rigor of the artificial demonstrations. The use of 3D printers is not the scope of this research, but the results show that the framework developed extends beyond the use of robotic arms to other digital manufacturing techniques through G-code programming.

The first *Ex Ante* laboratory experiment is illustrated in Figure 3.11. In this demonstration, the UR10 robotic arm is driven by parametric design to reach its assigned targets in an ordered data structure. The toolpath is defined by an approach point, a grip or release point, and an exit point for each part to be manipulated. A transition point between the approach and exit points is also set to avoid singularities and collisions with the assembled parts. The computational aspect of the workflow makes it possible to assign this path to each part and integrate the necessary commands to operate the gripper. The process involved the assembly of 77 pieces of wood. With a travel speed set at 100 mm/s, the wall's construction took 26 minutes and 16 seconds, and that of the tower took 25 minutes and 23 seconds. This timing confirmed the duration prediction generated by the algorithms-aided process. In total, the robotic operation required 1902 lines of UR script. With the approach illustrated in Figure 3.3, these lines of code were automatically generated. Moreover, since design and programming are performed in an integrated environment, robotic commands are automatically adapted to design changes. Therefore, the DtM approach has demonstrated time and resource savings in the design and robotic programming processes.

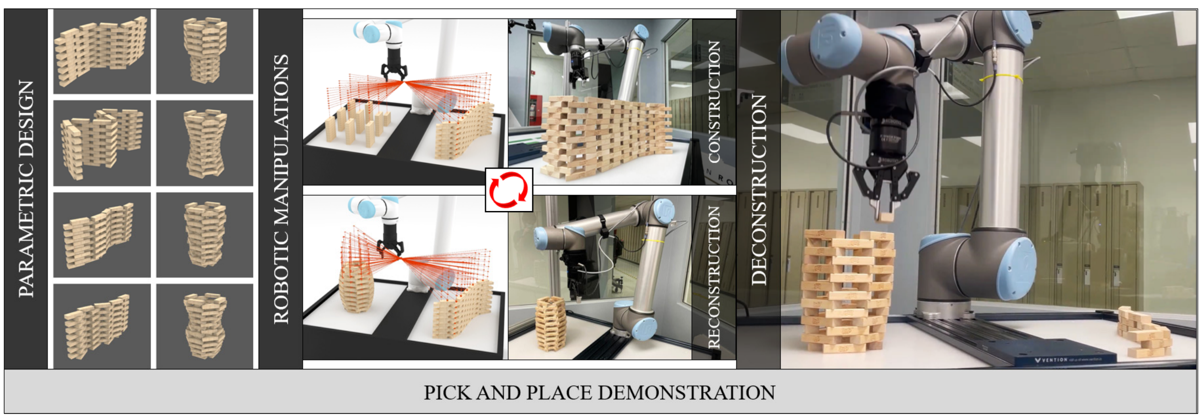


Figure 3.11 First Ex Ante laboratory results of the Design-to-Manufacturing (DtM) approach – Construction, deconstruction, and reconstruction of wooden parts
Taken from (Anane et Iordanova, 2021)

The remaining two *Ex Ante* laboratory experiments are displayed in Figure 3.12. In these demonstrations, the DtM framework proved its reliability by using a different manufacturing technique (3D printing) and different types of tools. Indeed, the second experiment involved a process of 3D printing in mortar operated by an ABB IRB6700. Despite this change of context, the DtM approach resulted in an operational robotic program that reveals, through configuration variations, the optimal extrusion speed and height for optimizing mortar consistency. Furthermore, even with the difference in programming language compared to the first approach (UR script for Universal Robots and Rapid Code for ABB), the use of the algorithms-aided robotic programming process allowed us to program both types of robotic arms. This technological interoperability overcomes the barrier of robotic language knowledge and facilitates access to RM for non-specialists. This accessibility is not limited to robotic arms programming. Indeed, the CD environment allowed the design of a parametric freeform that is 3D printed through G-code generations. In this last experiment, the 3D printing process took 4 hours and 44 minutes, used 8.11 m of filament, and was driven by 422,370 lines of G-code. Therefore, the DtM approach is not only limited to robotic arms programming; it extends to digital manufacturing. Figure 3.12 illustrates the results of these two experiments.

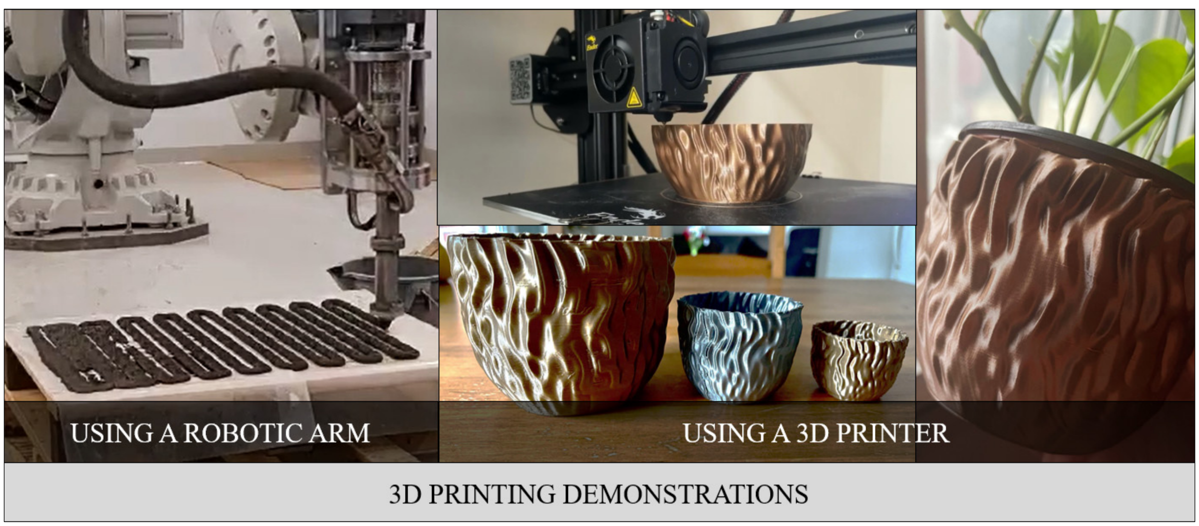


Figure 3.12 Second and third Ex Ante laboratory results of the Design-to-Manufacturing (DtM) approach – 3D printing using mortar with a robotic arm and 3D printing with PLA using a 3D printer

With these three experiments, the *Ex Ante* laboratory results proved the operability of the robotic programs presented through the previous *Ex Ante* computer simulations (Figure 3.7 and Figure 3.10). Therefore, the DtM framework will now be evaluated through a naturalistic *Ex Post* evaluation involving individual interviews and surveys.

3.6 Ex Post Evaluation

To validate the DtM framework presented in this research, an evaluation was completed by professionals in related domains. In addition, this approach is currently being taught in a BIM course in a reputable engineering school in Canada. Specifically, this course uses the BIM-CD-RM technological triad and introduces its potential in OSC. It is intended to allow students with no robotics background to be trained in algorithms-aided robotic programming. One-third of the class (five students) were selected to participate in the evaluation, four of whom are professionals. This evaluation also involved 11 other evaluators with professional experience ranging from 3 to 30 or more years. Thus, the evaluators were split into three occupations, i.e. students, educators, and professionals. Their areas of expertise range from architecture, structural engineering, building mechanics, software development, BIM, CD, automated systems, manufacturing technologies, and OSC. In addition, these evaluators were based in 6 different countries, namely Canada, the USA, Spain, France, India, and the UAE.

The evaluation process involved one-on-one interviews during which the problem, the research method, the framework, and the demonstrations were presented in detail and discussed. Once the interview was over, the evaluators submitted their evaluation through a 17-question survey divided into two sections (seven questions on the evaluator's information and background and ten questions on the evaluation of the DtM framework). The first section was dedicated to the evaluator's knowledge of the four systems mentioned, namely BIM, CD, RM, and OSC. It also included their perspective on using RM in OSC. In response to this question, 63% of the evaluators view it as forthcoming (in 5-10 years), while 31% stated it is a long-term horizon (10-20 years). Only one evaluator perceived it as a very long-term solution (20+ years), which is an interesting insight given that he is the CEO of a prefabrication company. However, no evaluator considered it a non-feasible solution, reflecting the evaluators' vision for this technology in OSC. The second section of the survey evaluated the research problem and whether the DtM framework addresses it globally. Three questions were devoted to evaluating the framework's usefulness, quality, and effectiveness. Finally, the survey concluded with critiques and suggestions for improving the framework.

In evaluating the targeted problem, the evaluators agreed on its realism and originality. They underlined the importance of technological interoperability in the built environment and robotics. However, some mentioned that the targeted systems are large and complex, which creates a difficult topic to grasp in the case of unfamiliarity with one or more of the systems. As for the second question, the evaluators agreed that the framework presented covers the problem in a comprehensive way. They underlined the coherence of the framework systems and their relationship to operating industrial robots in OSC. These assessments engage the evaluation of the utility, quality, and effectiveness of the DtM framework. The results of this evaluation are presented in percentages in Figure 3.13.

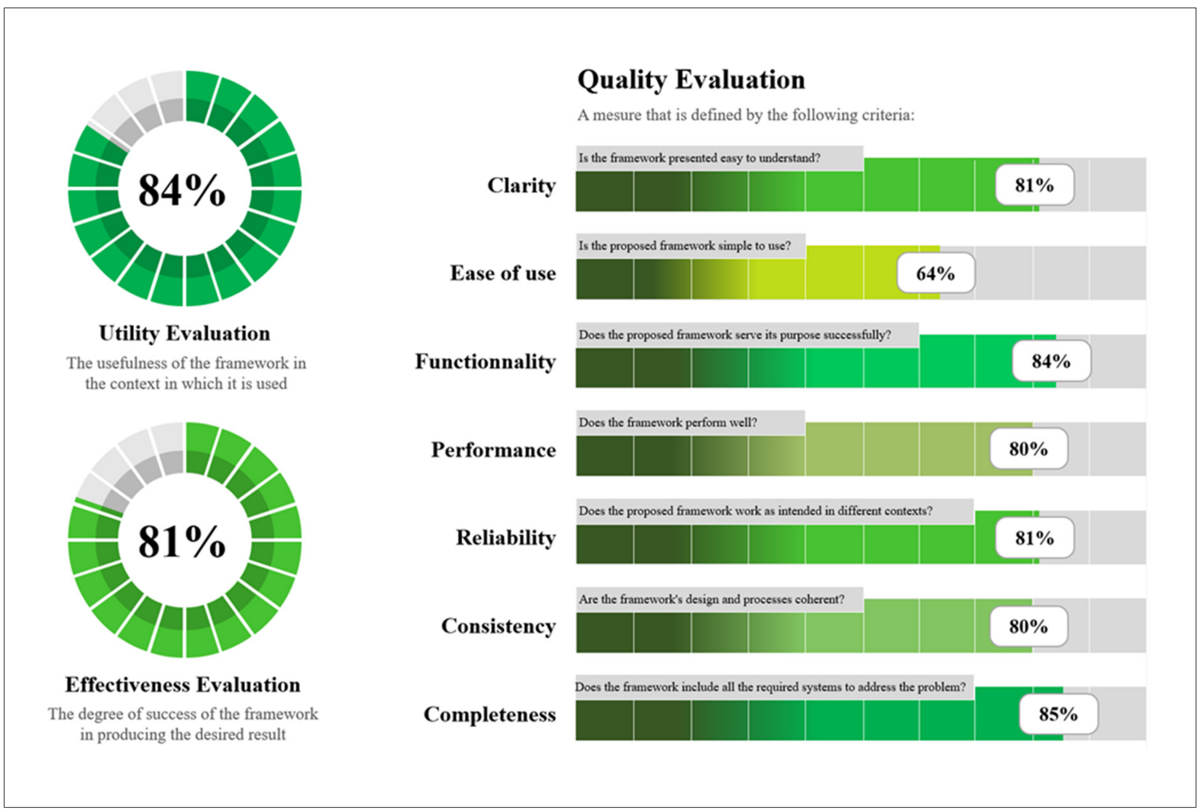


Figure 3.13 Design-to-Manufacturing (DtM) framework evaluation results

On a scale of 0 to 10, 0 being not useful and 10 being very useful, the usefulness of the DtM framework received an average score of 8.4. This score supports the framework's usefulness for operationalizing industrial robots in OSC. The evaluators stated that there is a relationship between BIM, CD, RM and OSC and that the presented framework is very useful in bridging these systems:

> Connecting all described phases in a 'common sense' way, where the objective is not to reinvent the entire way we work, but to just 'join the dots' between existing parts of our industry, using computational design as the common thread is a very powerful approach. It will provide the necessary customization and flexibility, without introducing a completely new way of working. (AEC Software Engineer)

For the quality criterion, the evaluation was based on a scale of 0 to 5. These evaluation results highlighted that the main barrier to the DtM framework is its limited ease of use. It involves disruptive concepts in the construction industry, and resistance to change could hinder its use. Regarding the framework clarity, a Senior Structural Engineer and CD expert mentioned that the DtM framework does not clearly represent its technological integration benefits. This evaluation is valid, but these benefits are difficult to represent due to their intrinsic nature. For example, these benefits are explicit when compared to the use of disjointed technological environments. Indeed, such workflows involve fragmented processes and induce mismatches in execution due to repetitive back and forth between design and manufacturing tools. Instead of using intensive exchanges of file formats like STL, STEP, or IFC for manufacturing post-processors, the DtM framework relies on a format-agnostic approach that natively uses models and programs manufacturing in an integrated way. In addition, the parameterization of the models is preserved during the robotic post-processing; it is not breached by exporting into a proprietary format. Finally, the framework performance was also discussed. Indeed, technological integration between environments that perform design and manufacturing simulations requires much computational power. The data used is native, but the performance of the DtM workflow is highly dependent on the computational capacity of the tools used. Despite these comments, the framework's quality was greatly appreciated, especially in clarity, functionality, reliability, consistency, and completeness.

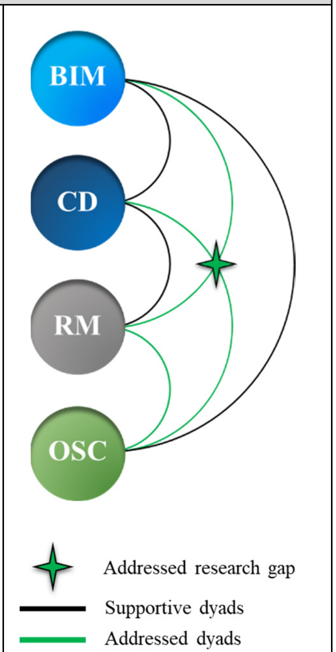
For the last evaluation criterion, effectiveness, the DtM framework received a score of 8.1 out of 10. The students especially perceived this effectiveness as they could operationalize their robotic commands in different scenarios. In addition, the artificial demonstration through simulation and proof of functionality attracted the professionals' interest. For example, an Automation Technician mentioned that the results concerning the use of CD reveal significant savings in programming times. Another Technical Director in robotic solutions mentioned, ‘‘this framework is complete since it encompasses all the necessary points for a successful robotic workflow, and with further robotics study, the effectiveness of this framework is almost guaranteed.’’ In addition, an OSC Specialist mentioned the contribution that this approach would have to change management, stating, ‘‘a direct impact on the industry would be the adaptability of the robotic programming concerning the incompatibility of prefabricated parts when used on site. Such adaptability would result in significant time and production costs savings.’’ Overall, all the evaluators expressed their enthusiasm for the DtM approach, confirming that the framework is theoretically effective for operationalizing industrial robots in OSC.

The evaluators provided additional feedback and suggested some improvements to conclude this evaluation. While they understand that robotics implementation is resource-intensive and unfeasible with local industrial partners, they said that the DtM framework should be evaluated in the future through an industrial case study. Indeed, the enthusiasm for the technological capabilities of the DtM framework has projected many of the evaluators into contextual industry applications. However, several professionals mentioned that the fragmented nature of the construction industry would be a barrier to implementing an integrated DtM approach. Thus, these evaluations have opened new avenues of research, pertaining to the contextual, procedural, and organizational interoperability of BIM, CD, RM, and OSC.

3.7 Discussion

The lack of technological interoperability is a barrier to stable information exchange between different systems. This barrier was perceived through the different parallel dyads identified in the literature review: BIM-RM, CD-OSC, and RM-OSC. Indeed, the parallel technological evolution of these dyads constituted the research sub-problems. They have been clustered under the targeted research gap concerning the technological interoperability between BIM, CD, RM, and OSC. The approach to addressing this problem was based on developing the DtM framework, which was demonstrated and evaluated through the DSR methodology. This research process is summarized in Table 3.1.

Table 3.1 Summary of the research presented in this article

Design-to-Manufacturing (DtM) Approach			Research Summary	Contributions	
	Ex Ante Demonstrations	Section 3.5.3.1	Prefabricated Systems • Data-driven freeform modeling • Robotic 3D concrete printing simulations • Cloud-based collaboration • Augmented reality visualization	Enabling BIM, CD, RM, and OSC technological interoperability	
		Section 3.5.3.2	Modular Systems • Data-driven discrete architecture • Environmental adaptation • Multidisciplinary collaboration • Robotic wood assembly simulations		
		Section 3.5.3.3	Laboratory Experiments • Design-to-Manufacturing (DtM) experiments • Multi-tool usage: robotic arms (ABB, UR), 3D printer • Multi-process accessibility: pick and place, 3D printing • Multi-material manufacturing: mortar, wood, PLA		
	Ex Post Evaluation	Section 3.6	Framework Evaluation • Performed through one-on-one interviews and surveys • Involved 16 evaluators based in 6 countries • Evaluated at 84% utility, 79% quality, 81% effectiveness		

This study was conducted in order to answer the research question: *How can BIM, CD, RM and OSC technological integration enable a Design-to-Manufacturing (DtM) approach?* This question was addressed through the summary illustrated in Table 3.1 and the confirmation of the three hypotheses presented in the literature review. Indeed, through the demonstrations shown, *CD is a medium for BIM-RM technological interoperability*; CD is integrated with BIM, allowing an algorithm-aided robotic programming process. Furthermore, *BIM is a medium for CD-OSC technological interoperability*. A construction project is not limited to design; it also involves information management, collaboration, and standardization. Finally, the demonstrations illustrated an integrated DtM workflow that is reliable for different OSC systems. These demonstrations were supported by the professionals' evaluation, confirming that *the BIM-CD-RM technological triad has the potential to operationalize RM in OSC*. Thus, this article has demonstrated how the technological integration of BIM, CD, RM and OSC can enable a Design-to-Manufacturing (DtM) approach.

The positive evaluation by 16 evaluators contributed to validating the DtM framework. It is a framework limited to technological interoperability and does not examine contextual, procedural, or organizational interoperability. The fact that the evaluators addressed immediate industry implementation assumptions revealed the suitability of the DtM framework for addressing the research gap identified. It is a framework that is part of an ''Exaptation'' context in its contribution to knowledge; it extends new solutions for low maturity applications (Gregor et Hevner, 2013). This article also gives an overview of all the tools used in this research, which is often not communicated in the literature. Regarding its contribution to technology, the DtM framework offers an integrated approach between design and manufacturing. This approach differs from many research efforts to bring together BIM and RM (Mechtcherine *et al.*, 2019 ; Ding *et al.*, 2020 ; Feringa et Krijnen, 2015 ; He *et al.*, 2021 ; Davtalab, Kazemian et Khoshnevis, 2018). Indeed, instead of strongly relying on file formats (such as IFC, STL, STEP and OBJ) and new plugins development, the DtM approach offers workflow integration through existing CD tools. This integration holds the potential for enabling innovative approaches since CD provides a basis for Artificial Intelligence (AI) services in design and manufacturing, such as machine learning and deep learning.

The DtM framework is not devoid of limitations. Managing design and manufacturing in the same environment requires significant computational power. Without proper data management, this workflow can be time-consuming. Moreover, it was perceived that the DtM framework could be challenging to use because it involves conjunctive systems implying extensive learning efforts. Future directions of this research will involve demonstrating DfMA accessibility, including a thorough technical demonstration of DfM, through the DtM framework. This demonstration will allow the implementation of this framework in an *Ex Post* naturalistic context involving a case study and industrial partners.

3.8 Conclusion

In the AEC industry, digital technologies have introduced a new data culture often perceived as drastically disruptive. It has changed the way projects are designed, managed, and built. In this context, the present research is supported by distinctive concepts contributing to this disruption, i.e., BIM, CD, and RM. This article integrates these approaches in a technological triad and reflects their shared potential in OSC systems. Therefore, this research gives rise to the Design-to-Manufacturing (DtM) approach.

Through this article, the DtM framework demonstrates:

- Design, management, and collaboration through the BIM-CD dyad;
- The integration of design and robotic programming through the CD-RM dyad;
- Its potential to operationalize RM in OSC systems through the BIM-CD-RM triad.

Therefore, the DtM approach improves the DfM method by integrating design and robotic programming for manufacturing. It provides insights into RM-OSC technological interoperability and gives BIM-CD technological integration a central role in enabling this dyad. It also reveals that the systems involved become technologically interoperable when combined. Therefore, this research goes beyond data integration and directs this need toward data management. It provides new avenues of research, including, but not limited to, the remaining interoperability dimensions (i.e. contextual, procedural, organizational) of the systems investigated, mass customization in OSC, and AI services for construction robotics.

3.9 Acknowledgements

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involvement of Vasilis Sergis in the robotic 3D printing project, and they thank all the evaluators for their valuable feedback and evaluations.

Graphic charts: Supported by PresentationGo and Canvas.

3.10 Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The Bibliography section is presented at the very end of the thesis.

CHAPTER 4

DISCUSSION

4.1 Introduction

Considering each article presented its respective discussion section, this chapter will include a detailed run-through of the thesis and a comprehensive review of the research project. This discussion presents the research design, findings, and contributions to knowledge and practice. In addition, the originality of this work and its future directions are also disclosed. Therefore, this section does not merely restate the results but presents the core insights of the thesis.

4.2 Discussion of the research design

The research design that drove this work was grounded in the DSR methodology; it started as exploratory research and led to the development of the DtM framework. This work progressively addressed the research questions presented in Section 2.2.2 and contributed to solving the identified problem: *The research gap involving the technological interoperability of BIM, CD, RM, and OSC*. The evaluation approach adopted throughout the different articles provided was the FEDS framework's *Technical Risk & Efficacy* strategy (see Figure 2.6) (Venable, Pries-Heje et Baskerville, 2016). This approach was employed to determine the type of evaluation to be used at each step of the DtM framework design cycle.

It is important to note that the ‘‘design’’ of the DtM framework has not been introduced in the body of the thesis. Instead, it is reported in Appendix II, Figure-A II-1. The ‘‘design’’ was derived from the different linear workflows of the first evaluation episode presented in Appendix I, Figure-A I-6. Such a format was adopted to streamline the body of this article-based thesis. Contrary to the ‘‘construct,’’ the evaluation of the ‘‘design’’ was done internally, as explained in Section 2.2.6.2. In brief, both versions of the framework incorporate the same workflows; their evolution is mainly linked to their representation style. Indeed, the ‘‘design’’ of the framework can be recognized in the skeleton of the ‘‘construct.’’ Their evaluation is intrinsically shared, and their main evolution is related to the clarity of the DtM framework. The design cycle illustrated in Figure 2.3 was reproduced in Figure 4.1 to provide a run-through of the various sections making up the thesis. It shows the research evaluation episodes and the corresponding sections in which they were addressed.

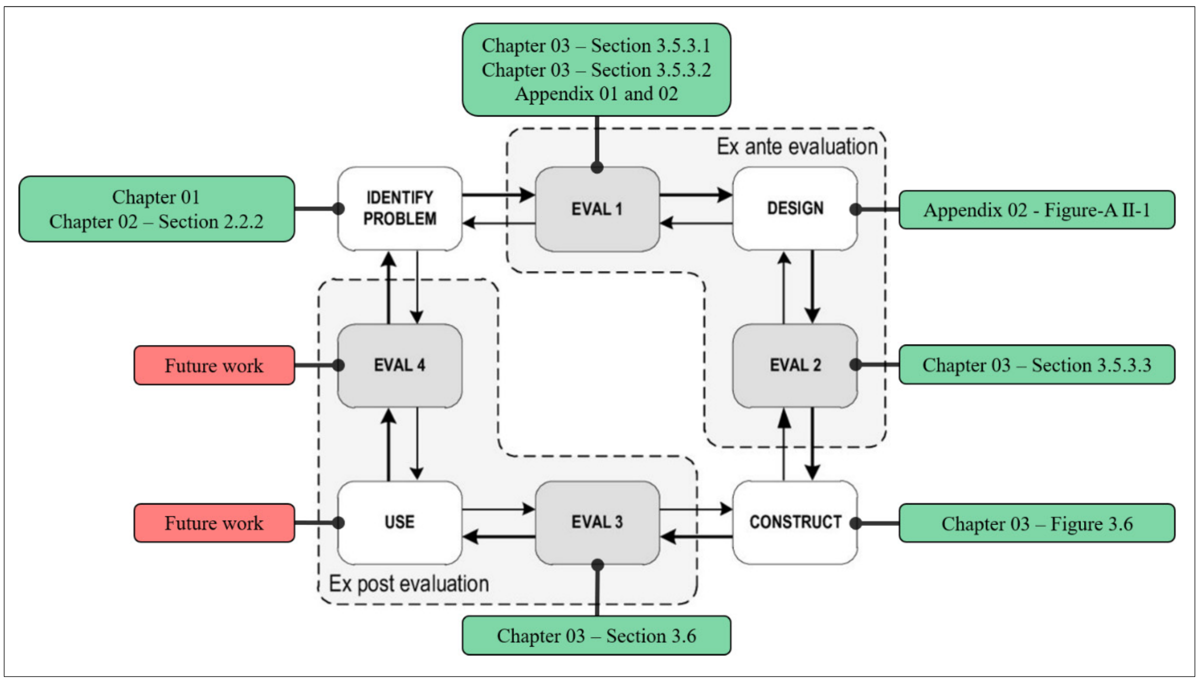

Figure 4.1 A run-through of the DtM design cycle

The DSR methodology, along with the *Technical Risk & Efficacy* evaluation strategy, greatly facilitated the research conducted in this thesis. This methodology allowed the selection of different demonstrations (section 2.2.5), clarified when to perform them (section 2.2.4), and how to evaluate them (section 2.2.6). However, this methodology did not indicate how often to perform them. This limitation is inherent to the DSR methodology since research evidence cannot be explicitly quantified. Such vagueness can generate difficulties for the researcher in deciding when to move from one episode to another, or when a framework can be qualified as a ‘‘design’’ or a ‘‘construct.’’ In the context of the present work, this limitation was addressed through several relatively in-depth evaluation episodes.

The comprehensive nature of the research process is reflected in the multiple iterations of each episode. To identify the research problem, the investigation process was carried out through the SLR presented in Chapter 1 and involved 533 scientific publications.

The first evaluation episode was conducted through two computer simulations involving:

- Different OSC systems: prefabricated / modular construction;
- Different RM processes: 3D printing / milling and assembly;
- Different construction materials: concrete / wood.

The second evaluation episode was carried out through three laboratory experiments involving:

- Different digital manufacturing tools: robotic arms / 3D printer;
- Different industrial robots: ABB IRB6700 / UR10;
- Different RM processes: pick and place / 3D printing;
- Different construction materials: concrete / wood / PLA.

The last evaluation episode involved 16 evaluators based in six countries and categorized into three occupations: students, educators, and professionals. The board of evaluators is presented in Appendix VI, with Table-A VI-1 outlining their organization and roles, and Table-A VI-2 their occupation, location, and expertise. The variety of demonstrations was intended to provide evidence for the validity of the DtM framework and thereby reinforce its status as a ‘‘construct.’’

Throughout this research, it was impossible to access robotized OSC contexts since they are costly and drastically disruptive to construction workflows. Indeed, the lack of adequate technological development within local industrial partners hindered the use of the DtM framework in naturalistic case studies, and thus prevented the execution of the last evaluation episode. For this reason, this thesis did not cover the entire research design. However, this obstacle is discussed in the last section of this chapter, addressing the work’s limitations and future directions.

4.3 Discussion of the findings

The research findings were initiated by the following research hypotheses:

- H1: CD is a medium for BIM-RM technological interoperability;
- H2: BIM is a medium for CD-OSC technological interoperability;
- H3: The BIM-CD-RM technological triad has the potential to operationalize RM in OSC.

They were raised by the SLR and have been supported by the evaluation episodes of the DSR methodology (see Chapter 3, Table 3.1). These findings can be displayed by interpolating the *Chasles*' *relations* on the different dyads investigated. Thus, the dyads in parallel evolution are bridged by those in technological interconnection. In this context, Table 4.1 presents the different research questions, the parallel dyads they entail, the proposed solutions, and their associated research findings.

Table 4.1 Overview of the research findings

Research Questions		Parallel Dyads Identified	Proposed Solution through the Interconnected Dyads	Research Findings	
Q3	Q1	BIM-RM	BIM-CD → CD-RM	F1	F4
	Q2	CD-OSC	CD-BIM → BIM-OSC	F2	
		RM-OSC	RM-CD → CD-BIM → BIM-OSC	F3	

The first research finding (F1) is that *CD is a medium for BIM-RM technological interoperability*; even more, CD *is a medium for BIM-RM technological integration*. The demonstrations were based on integrating the BIM-CD environments and enabled conjunctive informed modeling and algorithms-aided robotic programming. This integration reflected the full potential of the BIM-CD-RM triad, which created a multi-functional feedback loop between design and manufacturing. This first finding was thoroughly discussed in the body of the thesis; it validated H1, answered Q1, and implicitly contributed to answering Q3.

The second finding (F2) is that *BIM is a medium for CD-OSC technological interoperability.* This finding is supported explicitly by Section 3.5.3.2 and Appendix II, which reflected that CD has significant value for the design phase but is insufficient for fully enabling OSC. Indeed, OSC involves interdisciplinary collaboration and management and requires detailed construction documentation. This set of workflows is better managed with computerized BIM systems. Instead of striving to automate all OSC workflows through CD tools (i.e. Grasshopper 3D, Dynamo), it is currently more productive to use task-specific BIM tools. Moreover, the blended complexity generated by the unique use of CD in OSC (such as the use of discrete architecture) is drastically disruptive to current OSC practices. Unlike BIM systems, this design approach has not yet matured enough to interact with structural and other building aspects. Finally, considering the SLR results and the validation of H1, and by reinforcing the potential of the BIM-CD dyad in OSC, F2 has strengthened the evidence that OSC is a suitable building system for BIM-RM integration. As a result, the second finding contributed to the validation of H2 and Q2, and implicitly contributed to answering Q3.

The third research finding (F3) is that *the BIM-CD-RM technological triad has the potential to operationalize RM in OSC*. This finding is supported throughout all thesis sections, particularly by the practitioners' evaluation (see Section 3.6). Indeed, the positive evaluation by the board of evaluators has reflected the potential of the DtM framework. The evaluators perceived the BIM-CD-RM synergetic capacity and assumed the potential of this triad to operationalize the RM-OSC dyad. Moreover, through the provided demonstrations, this thesis has shown how the integration of BIM, CD, RM, and OSC could enable a DtM approach. In this sense, F3 validated all the research hypotheses, answered Q3, and reinforced the answers of Q1 and Q2.

The last research finding (F4) is *the DtM approach*. It combines all the preceding findings and all the systems involved. This central finding is that the technological fragmentation between

BIM, CD, RM, and OSC disappears when they are combined. Indeed, they are fragmented in the AEC industry when taken one by one. When they are taken in dyads, parallel dyads emerge. However, when combined, they complement each other to become completely integrated. This integration gives rise to BIM-driven computational design for robotic manufacturing in off-site construction, synthesized in the DtM approach. As a result, F4 includes all research findings. It demonstrates how integrating BIM, CD, RM, and OSC enables the DtM approach, thus answering Q3. This last finding leads to the discussion of this research's originality, validity, and contributions.

4.4 Discussion of the originality, validity, and contributions of the research

The purpose of this section is to discuss the strengths of this research project. The DtM framework is presented in regards to its originality, validity, and contributions to knowledge and technology.

4.4.1 Originality

This research project was built from the SLR presented in the first chapter of this thesis. It was initially motivated by the under-representation of research on the technological interoperability of the BIM-RM dyad. To date, only 18 scientific papers (published between 2018 and 2022) were identified and listed in Appendix IV, Table-A IV-1. Among these articles, much ambiguity regarding the approach to use for coupling BIM and RM was underlined and is discussed in section 1.4.2. In addition, the methodology behind these studies is often unclear; it is usually limited to computer simulations and overloaded with ad hoc scripts. Furthermore, no consideration is given to interoperability, and the focus is on the robotic manipulations, not data processing. This limited scope implies that these studies are technologically unreliable for a highly variable industrialized construction environment.

In contrast to the above-mentioned shortcomings, the present research is based on technological interoperability—a critical requirement that is often neglected in the literature—

and builds on this through the DSR methodology. This work involves computer simulations, laboratory experiments and an evaluation by practitioners. Each step had a unique time frame, and specific objectives, but a unified contribution to the DtM framework. Therefore, the first distinction of this work can be observed in its methodical approach.

The second distinction lies in the project's holistic nature. Instead of employing the tedious direct integration of the BIM-RM dyad by developing new plugins, the present work circumvents this challenge by using existing tools already deployed in the AEC industry. Furthermore, this approach broadens the scope of the research while allowing a streamlined workflow. Indeed, the present thesis covers:

- Multiple workflows (e.g. BIM-driven computational design, algorithms-aided robotic programming, cloud-based collaboration);
- Multiple CD subsystems (e.g. PD, AAD, ED);
- Multiple manufacturing processes, tools, and materials.

This varied accessibility proves the reliability of the DtM approach, reinforcing the originality of the proposed framework. Finally, the research project's validation process is another distinctive feature and it is presented in the next section.

4.4.2 Validity

Validity in DSR provides a rationale for the arguments and conclusions of a research study. This notion is often found in the quantitative/positivist paradigm and was originally analogous to evidence (Guba et Lincoln, 1989). However, there is little consensus over which methodologies and measures to adopt for assessing this requirement in qualitative research. According to Larsen et al. (2020), design science validity is defined as ''formalized procedures for justifying arguments and conclusions of a research study involving the design, development and/or evaluation of IT artifacts to solve identified problems.'' This notion is translated in this thesis through the 17 survey questions used in the *Ex Post* evaluation of the DtM framework. These questions were adapted from Hevner and Chatterjee (2010); they are mainly related to evaluating the utility, quality, and effectiveness of the DtM framework. The questionnaire used is provided in Appendix VII, Table-A VII-1, and its results are summarized in Figure 3.13.

With a score of 84% for usefulness, 79% for quality, and 81% for effectiveness, the evaluators' evaluation of the DtM framework supports this research's validity. These results are exclusively related to the framework, not to the tools used in the demonstrations. Indeed, the evaluators were already familiar with the tools used, but they were unaware of their potential once integrated through the DtM framework. In addition to the feedback mentioned in Section 3.6, many comments emphasized the framework's ability to address the research problem. Using the answers to question number eight (see Appendix VII, Table-A VII-1) as an example, a Computational Designer said he believes that through the use of the framework "there is technological interoperability between the four stated systems," and that it "allows for you to go back and change the building information and it will correct itself for the cloud-based collaboration and final fabrication." A BIM Technician mentioned that "one of the main problems that arise when developing processes involving different technological tools is interoperability," and that this approach "offers an interesting solution and a coherent process." Finally, an academic chairholder stated that the framework "covered clearly the interoperability of the systems; however, it is a very big framework and needs more research in order to be well validated."

The last statement was echoed by several reviewers. Indeed, the validation of a framework is more rigorous when done in a realistic industrial context. However, given the systems involved in this research and the current context of our industrial partners, it is not possible to conduct such an evaluation at this time. This limitation affects the validity of the DtM framework; it is discussed in the last section of this chapter.

4.4.3 Contributions

DSR contributions can be classified into two categories: contributions to knowledge and contributions to technology. In other words, the research conducted is expected to contribute to rapid technological improvements, while simultaneously generalizing these improvements into emerging design theories in an abstract form of models, methods, principles and rules (Baskerville *et al.*, 2018).

Based on this classification, the research contributions are mainly related to the research objectives. In addition to those already listed in section 3.7, the primary research contribution was related to *demystifying the BIM-RM dyad's technological integration*. Indeed, this integration is currently generating much ambiguity in the literature, and defining the optimal approach based on technological interoperability has been deemed to be of great use by practitioners. The contribution to technology encompasses the second research objective, *developing a framework integrating BIM and CD for using RM in OSC, enabling an integrated DtM framework.* This objective was reached through existing AEC digital tools, which relates this research to the computational shift:

> [..] just as the digital revolution of the 1990s (new machines, same old science) begot a new way of making, today's computational revolution (same machines, but a brand new science) is begetting a new way of thinking. (Carpo, 2017, p. 7)

By focusing on the technological interoperability of the different systems studied, it was possible to demonstrate a new form of dialogue between design and manufacturing. This dialogue is centralized in a digital BIM model, supported by a collaborative oversight on the Cloud and enabling automated materialization. Its dialect is based on integrated, deformable, dynamic information between thinking and making, and its resonance bridges the gap between construction practitioners and industrial robotics. Therefore, this research contributes to upgrading current technological routines within the AEC industry by repurposing existing tools and revealing their integrated potential.

Considering the initial fragmented context that initiated this research project (see Figure 0.1), the overall result of this thesis is illustrated in Figure 4.2. Through the DtM framework, BIM tools are integrated with industrial robots using CD tools, thus merging design and manufacturing operations into a single technological environment. As a result, this integration provides a full-fledged data environment for construction projects.

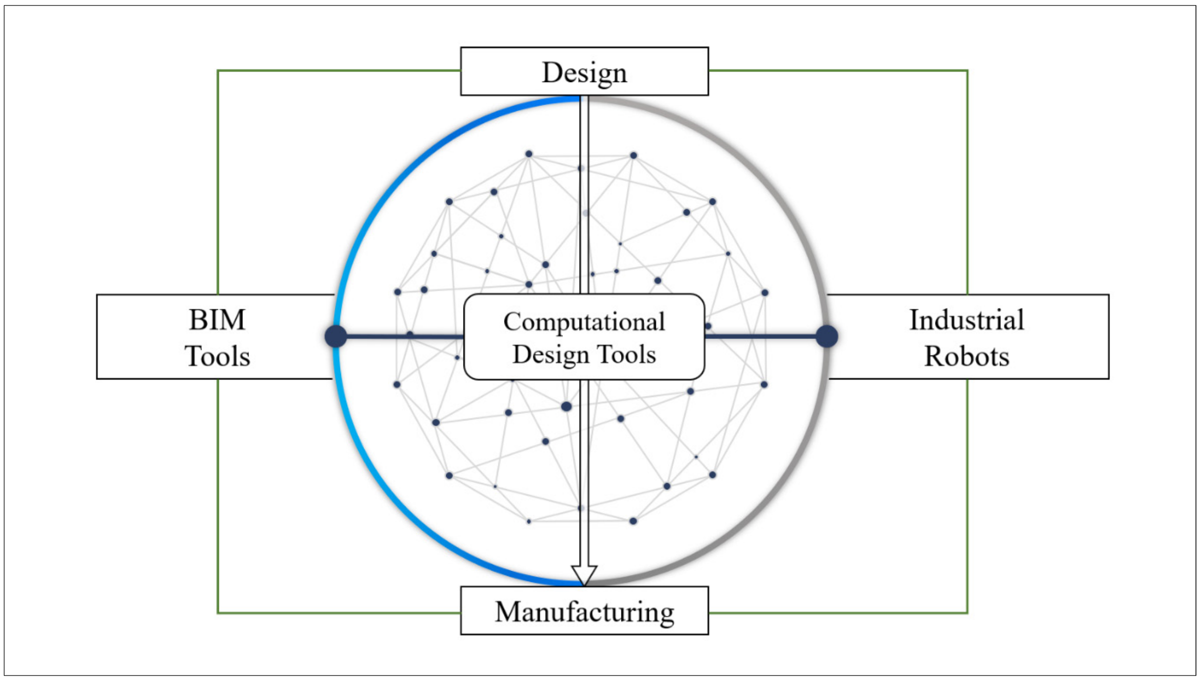

Figure 4.2 The overall output of the research project

The direct connection between design and manufacturing is prized in the AEC industry; it facilitates decision-making, reduces costs, and improves productivity. The work's contributions can also be perceived in the evaluator's feedback regarding the added value of the DtM approach. They are reflected in the following evidence:

> I think [that the DtM approach] is a very good attempt at finding an overall solution to link the four systems together. It does make a lot of sense, and it's an approach that I had not seen before. (AEC Software Engineer)

> I think the framework covers the relevant systems in a comprehensive manner. The approaches are well explained and even as a BIM practitioner, I understand the explanations of other systems very well. (BIM Designer)

> Connecting the four areas together (BIM, OSC, RM and CD) and the interoperability of data within these is the highlight of the framework. [The DtM approach] is very useful for someone who is using all these areas in their project, hence allowing them to use the data in a more efficient manner, thereby affecting the project delivery and outcome in a positive manner. (CEO of a Prefabrication Company)

> I believe this framework addresses the root cause of the difficulties experienced in implementing robotics in the construction world. The four different approaches are pretty mature on their own, but they need to be ''interconnected'' at first, which is what this framework is addressing. (Automation Technician)

> The demonstration [of the DtM framework] carried out is very powerful and relevant to the industry, however the framework seems unclear, and does not provide help in [visualizing the different steps of the DtM process]. (Senior Structural Engineer)

On this note, the discussion of the limitations of the work is presented along with future research directions.

4.5 Discussion of the limitations and future work

Any development involving digitization is, by definition, never finished nor stable and will forever be partly non-functioning, therefore requiring further updating (Carpo, 2017). Since the DtM framework is purely technological, it will constantly be subject to further developments. Indeed, the limitations of this framework have been highlighted throughout the different chapters of this thesis. The first limitation relates to the scope of this research project, which was acknowledged as quite broad in the context of a fragmented construction industry. Indeed, BIM, CD, RM and OSC are systems that involve various technological approaches. Merging them under a single framework implies a steep learning curve, which would limit their joint implementation in a real context. This limitation was reflected in the evaluation results (see Figure 3.13), where *ease of use* received the lowest score. The evaluators provided some comments about this:

> In my opinion, the overall quality of the framework is very satisfactory and I believe that it provides a valid basis for solving the stated problem. However [its use in real contexts] would present several challenges of transformation and change for the construction industry. (MEP Technician)

> [The DtM framework] collapses several different dimensions into a two-dimensional image. This [representation] makes it hard to tell which aspects are cross-cutting concerns vs. independent aspects. (Senior Structural Engineer)

The suggestions proposed for narrowing the extent of the first limitation were diverse and tended to be oriented towards in-depth technicalities. They covered the different sections of the DtM framework, requiring further investigation:

> The robotic side requires more technical study to ensure a good practical realization of the approach. [Future research directions can include] 1- Search for other useful robotic tools other than the robotic arm 2- Get to know the types of robotic arms 3- Technical studies in terms of capacity, precision and power of the robotic tool used. (Technical Director)

> Very interesting work, and good analysis of the problem. However, it is important to identify/ focus on areas that will be explored in relationship with others. For instance, what area of computational design relates to BIM? What type of robotic fabrication is relevant to BIM/ off-site construction? What method of off-site construction will be relevant to various research topics? (Laboratory Director)

> In general, the work is well defined and developed, but because there are four complex [systems], further development would have been appreciated. But I also think it would lead to a big dedication of time. (BIM Director)

The second limitation of the DtM framework is related to its validity. This limitation has influenced the *Ex Post* evaluation episode since it is generally more evident for practitioners to evaluate case studies conducted in natural settings. Nevertheless, the combination of computer simulations and laboratory experiments, together with the methodical approach used, enabled a clear picture of the potential of the DtM approach. However, although it was acknowledged that accessing a robotized construction context is complicated, the fact that no industrial case studies has been conducted raised many comments from the evaluators:

> With the DtM framework, the bridge is better defined between the work environment and the processes. I found that the demonstration of this approach in the modular construction system was very coherent. However, [it is advised to] give more realistic alternatives [and] use case studies where the need for robotic manufacturing is immediate. (Site Engineer)

> I would say that the use of the four [systems] can be considered of significant value for developing projects in a short amount of time when compared to current work methods where these procedures are required. However, [it is advised to] show more examples, or develop the examples presented a bit more. Although in general, I repeat, the work was well developed. (BIM Director)

> My only criticism of this framework is not really of the framework itself, but about what happens after. […] Construction is a very complex process that involves tons of different regulations (local, state level, etc.). The framework would have to be flexible enough to allow for this level of customisation. […] I am aware this is not the precise problem that this framework is trying to solve but I think it will be something that professionals will demand once this framework starts to be implemented in real projects […]. Preparing for this ''level of customisation'' of each project/user would be key to implementing it successfully on varying local levels. (AEC Software Engineer)

Some evaluators related to the last comment; by addressing technological interoperability, the DtM framework projected evaluators into real-world contextualization in the AEC industry. Many were interested in aspects not within this study's scope, such as O&M and workforce involvement in automated construction. However, these projections are a good sign since they reflect the evaluators inherent acceptance of the DtM framework's ability to reach its objective, which is only limited to technological interoperability. This deviation leads to the limitations that have been identified in-house.

The different demonstrations pointed towards a third limitation of the DtM framework related to computational power. Indeed, the first objective was to integrate the BIM-RM dyad. Initially, the dyad was characterized by different tools, inputs, and workflows. However, by means of the DtM framework, all these concepts were integrated into a central technological environment. This integration implies that the amount of data that was once spread across fragmented systems is now gathered within a central system. As a result, the computational power required to manage such an integration is being challenged, making the performance of the DtM framework highly dependent on the digital tools at hand. For instance, in the case of inadequate computational support, the technological integration of fragmented systems can have an inverted effect on construction projects' performance. This limitation can also be experienced in cloud-based collaboration or RM. Indeed, all these digital systems are vulnerable to data overload. Therefore, this limitation converts the data integration problem into a data management problem, leading to a need for further studies involving effective data management workflows in robotized construction projects.

The last limitation identified during this project concerns the tools used. The story underlying their selection is presented in the Recommendations section of this thesis, with one of its messages being that the tools used are very recent. This lack of maturity implies that bugs are expected when integrating different technological environments. In the case of the present research project, Revit was used as the BIM environment and Grasshopper 3D as the CD environment. These systems do not belong to the same parent corporation (Autodesk for Revit and McNeel & Associates for Grasshopper 3D). This difference implies that the two products were not originally designed in the same spirit. Furthermore, their data structures are different, which complexifies their interface. For these reasons, data processing conflicts could occur by integrating them through R.I.R. These limitations were perceived when modeling natively in Revit through Grasshopper 3D (e.g. rational surfaces, freeform Breps/meshes, walls by profile, fine scale models (<1mm)). Such limitations can also be experienced through cloud-based collaboration tools (e.g. Speckle.Systems). Indeed, working between a large range of software can lead to data loss if the different connectors are not stable.

On the manufacturing front, this last limitation is mainly related to industrial robots' physical boundaries. One of the most recurrent drawback concerns singularity points; they slow down the programming process in the case of versatile production. Nevertheless, it is possible to identify them during the simulation phase and bypass them by adding more control on the toolpath. Another limitation is the robotic arm's range, since it is restricted by a working area that requires strategic positioning in production lines. This barrier can be circumvented by implementing a mobile system; however, this adds a layer of complexity to the programming process. The weight of the robots also plays a role in this context, as it is a constraint in OSC, and most often in on-site construction as well.

The last limitation concerning physical boundaries can be time consuming, but it does not influence the DtM framework. As mentioned at the start of this section, the digital tools used are constantly evolving. In this sense, the DtM framework is generic, it does not depend on given tools, but anticipates their evolution. Therefore, the work's limitations and future directions communicated in this section provide insight into future work that could be done following this research project. Some future developments will consist of running detailed technical studies involving the DtM approach, allowing a realistic case study evaluation and the involvement of an industrial partner in robotized construction.

CONCLUSION

BIM and RM have been evolving in parallel in research and industry, and one of the reasons for this is the lack of technological interoperability between these two systems. By bringing these concepts together, this thesis demonstrates the potential of using BIM-driven computational design for enabling an industrialized production in construction. This technological integration results in merging the design and manufacturing phases and transforming data processing of building projects. From this viewpoint, RM allows for a direct connection between design and realization. It is a medium through which collaborative design can take shape in a controlled environment, making it a leading example of the added value of digitization and algorithmic design in construction. This research's primary outcome is the DtM framework proposing a closed-loop system based on technological integration. It is a system that brings CD to the core of the construction process, opening many avenues to non-conventional spatial forms. This impact is part of the digital shift in construction and the automation of manufacturing, thus challenging conventional modeling and planning processes and leading to the second digital turn.

The DtM framework is adaptable; it frames the construction process in a digital workflow encompassing design and manufacturing. Industrial robotics creates a bridge between digital data and its real-world materialization. It is a workflow that uses BIM as the information management and collaboration environment, CD as the design and programming environment, RM as the manufacturing process, and OSC as the industrialized construction system. The use of digitalization in such contexts facilitates the integration of new technologies. In this sense, many other research directions can be explored to improve the DtM framework, such as artificial intelligence techniques like machine learning and deep learning, among others. Moreover, the technological dimension of interoperability opens the path to exploring other dimensions, such as the organizational, procedural, or contextual dimensions. Thus, this research will evolve to a realistic context, involving real systems, real users, and real problems. Such research will conclude the overall cycle of the DSR methodology, which will bring additional improvements to the DtM framework and its use in the construction industry.

RECOMMENDATIONS

The DtM framework was developed using the tightly coupled approach; it is based on data transfer through the APIs of the software used, not through file formats. The underlying rationale for this approach is to have integrated data throughout the construction workflow, because the fewer layers of heterogeneous software needed for data processing, the less risk of information loss. Therefore, through the DtM approach, it is recommended to prioritize full integration of software, not only interoperability between them. Such integration permits the DtM workflow within a single user interface, allowing rapid responsiveness between design changes and manufacturing programming. In this section, the choice of the tools used throughout the thesis is explained to give insight into how to employ the DtM framework.

In this research project, the choice of tools was made from the range of software that allows a tightly coupled approach between BIM and RM. Indeed, the BIM-CD environment integration (not just tightly coupled) driving the DtM framework has greatly reduced the range of possible software available. As a result, the choice of the CD environment was either between Dynamo or Grasshopper 3D. This choice was made after a thorough comparative study of the two visual programming software and their potential to handle both BIM hierarchy and RM programming.

On the one hand, Dynamo is embedded in Revit. However, its graphics are not powerful and only has three plugins that allow robotic programming (Machina, Toro, Kuka|prc). Furthermore, of these three plugins, there is only Kuka|prc that allows robotic programming in the Dynamo interface; the others require external simulation software. This dependence is limiting since the interest of using the DtM workflow comes from having an integration of the data and a minimum of software in play. Therefore, if Dynamo is chosen, the only viable option would be to use Kuka|prc. However, the development of this plugin stopped in 2017, and its programming language is limited to KRL (only operational with Kuka robots).

On the other hand, Kuka|Prc is also available in Grasshopper 3D. It is continuously developed and competes with a wide range of plugins allowing robotic programming (Robots, HAL, RoboDK, TacoABB, Machina, FUROBOT). Moreover, Grasshopper 3D is much more developed than Dynamo; it incorporates a more extensive library of plugins and has better-performing graphics (displayed in Rhinoceros 3D). Indeed, this visual programming software is not integrated into a BIM software but into a design software (Rhinoceros 3D). Nevertheless, thanks to the release of Rhino.Inside.Revit (R.I.R) at the end of 2019, Grasshopper 3D has become integrated with Revit. It is also important to note that the Rhino.Inside product also extends to Tekla, Unreal, Illustrator, Bricscad, and Sofistik. This extensive deployment gives Grasshopper 3D a significant advantage over Dynamo. These reasons motivated the choice to use Grasshopper 3D as a CD environment; they led the way in selecting the rest of the software.

As for BIM, although Grasshopper 3D is tightly coupled with many BIM software (e.g. Archicad and Tekla through LiveConnection), Revit was selected as a BIM environment in the DtM framework demonstrations. This choice was made since Revit is an acknowledged BIM leader in the AEC industry and provides integration with Grasshopper 3D through R.I.R. When looking at RM, the choice of the plugin to perform the algorithms-aided programming was the Robots plugins. Indeed, compared to other RM plugins, Robots is open-source, and gives access to a wide range of robotic arms (ABB, UR, KUKA, STAUBLI). Moreover, it is one of the oldest (first release in 2016) and one of the most stable plugin.

Once the choice of the BIM-CD-RM (Revit-Grasshopper3D-Robots) triad had been made, the choice of the collaboration platform was initiated. In this context, several cloud platforms for collaboration are available (e.g. BIM360, Forge, Speckle.Works, 3DExperience). We chose Speckle.Works (developed since 2015) because it is the only open-source tool and gives access to a wide range of software (e.g. Revit, Rhinoceros 3D, Grasshopper 3D, Unity, Civil 3D, Excel, Power BI). Moreover, it is the only tool that allows collaboration through CD environments. This functionality is an essential advantage since most of the workflows are done in this environment.

This choice was also related to Elefront, the most stable plugin for defining attributes in Grasshopper 3D / Rhinoceros 3D. Elefront plays a critical role in this workflow; it keeps track of the BIM data in the CD environment. As for the choice of the rest of the tools (Kangaroo, Wasp, Fologram, Ladybug, Galapagos), it was based on their use context and native nature in Grasshopper 3D. The most important consideration is that the choice of tools used in the various contexts is mainly based on technological interoperability with the BIM-CD environment.

Finally, at the operational stage of the DtM framework, it is recommended to:

- Not overload the BIM-CD environments. Specifically, use the data where it is needed (e.g., it is useless to try to make a simulation in Revit even if it is possible to do it, because Revit is not designed for processing simulations);
- Distribute the use of environments according to their primary functions (e.g., Revit for information management, Rhinoceros 3D as a simulator, Grasshopper 3D for programming);
- Not code/parameterize every modeling step; basic CAD modeling is more productive in some cases;
- Have a clear understanding of the BIM-CD integration workflow. In the case of R.I.R, grasping the interoperability between Revit and Grasshopper 3D is critical to understanding how to use them in an integrated approach.

APPENDIX I

THE USE OF BIM FOR ROBOTIC 3D CONCRETE PRINTING

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Abstract

Digitization has proven its added value to the construction industry, particularly through Building Information Modeling (BIM). This digital shift addresses all phases and aspects of construction projects. Additive manufacturing (AM) through 3D Concrete Printing (3DCP), is one of the most remarkable technologies which development has accelerated in recent years. BIM and 3DCP are evolving in parallel, though, and the potential for their integrated use or convergence has not yet been sufficiently studied. Indeed, the association of these two systems faces challenges in terms of interoperability. This concept is not only limited to the ability to exchange information between two software, but also concerns the procedural, organizational and contextual aspects of these systems. Nevertheless, design process has evolved with the help of computational design tools and recent developments such as Rhino.Inside.Revit and Speckle.Works. This study aims to streamline the use of BIM in the 3DCP process. An overview of the technological interoperability between these two systems is presented. The necessary approaches to be used in concrete additive manufacturing applied to construction are defined. Finally, this research suggests the optimal approach for the application of BIM to 3DCP and identifies the obstacles encountered through a case study. Possible development paths for a better adoption of BIM in 3D concrete printing are identified.

Introduction

The construction industry is facing serious problems due to low productivity and lack of skilled workers. Digital transformation can be an effective solution to overcome these challenges (Poirier *et al*. 2018) especially with digital design. BIM and Virtual Design and Construction (VDC) are commonly used for coordination, project management, quality control and project handover. Digital tools offer a variety of functionalities that facilitate the design of innovative structures, but this capacity remains largely underutilized due to the complexity of nonconventional architectures (Hack *et al.*, 2020). Concrete construction through additive manufacturing has a strong capability to unlock this innovative potential (Mechtcherine *et al.*, 2019). This methodology has been proven, in various studies, to offer architecturally attractive projects with economically and environmentally efficient results compared to projects carried out using conventional construction methods (Weng *et al.*, 2020). Many of these research projects are limited to studying the material properties and use workflows specific to the field of additive manufacturing. As a result, the adoption of this technology in construction remains ambiguous for designers. In this context, through the visualization of construction data. The use of BIM represents the core of digital transformation in construction since it provides the technological environment necessary for project modeling (Poirier *et al.*, 2018). Many researchers have assessed that BIM systems contribute significantly to improving productivity throughout the building's life cycle, from design to operation and maintenance (O&M). It is a collaborative system that allows users to work in a BIM environment and exchange information through open file formats. Therefore, the integration of BIM-based construction activities with 3DCP can improve the performance of the construction workflow and contribute to the development of the industry.

This research project aims to integrate the two systems to facilitate the digital shift of the construction industry, but this association faces several interoperability challenges. Interoperability is defined as the ability to exchange information between all software or platforms used by the construction team throughout the project lifecycle (Wegner, 1996). According to Gallaher et al. (2004, 107), ''$15.8 billion in interoperability costs were quantified for the U.S. capital facilities supply chain in 2002''. This concept should not be limited to the technological dimension alone since it also includes an organizational, procedural and contextual dimension (Poirier *et al.*, 2014). The use of 3D concrete printing within a construction company provokes changes in its organization since this technology implies drastic alterations in work methods (Wu *et al.*, 2018). These interoperability challenges persist in both the industry and the academic field. There are few examples of any research that integrates the concepts of BIM and robotic 3DCP in any depth. Thus, this project seeks to clarify the main links between these two systems, including parametric design.

Literature review

To identify the processes used for applying BIM to robotic 3DCP, a bibliometric analysis is carried out. This analysis uses the systematic literature review (SLR) methodology to summarize the most relevant articles for the analysis (Kitchenham, 2004). In addition, the backward and forward snowballing method is used as a support for the SLR to be able to identify articles addressing the subject directly. This analysis is mapped using the VOSviewer software, which visualizes bibliometric maps (Van Eck et Waltman, 2010). The generated map is based on bibliographical data of the SLR output, it has a co-occurrence as a type of analysis and the authors' keywords as a unit of analysis. The minimum number of co-occurrences is set at two, resulting in 34 co-occurring keywords grouped under eight clusters. Figure-A I-1 shows the authors' co-occurring keywords in the literature review articles. Terms with a higher number of occurrences are displayed in larger font, and the line thickness represents the number of items in which all related terms appear simultaneously.

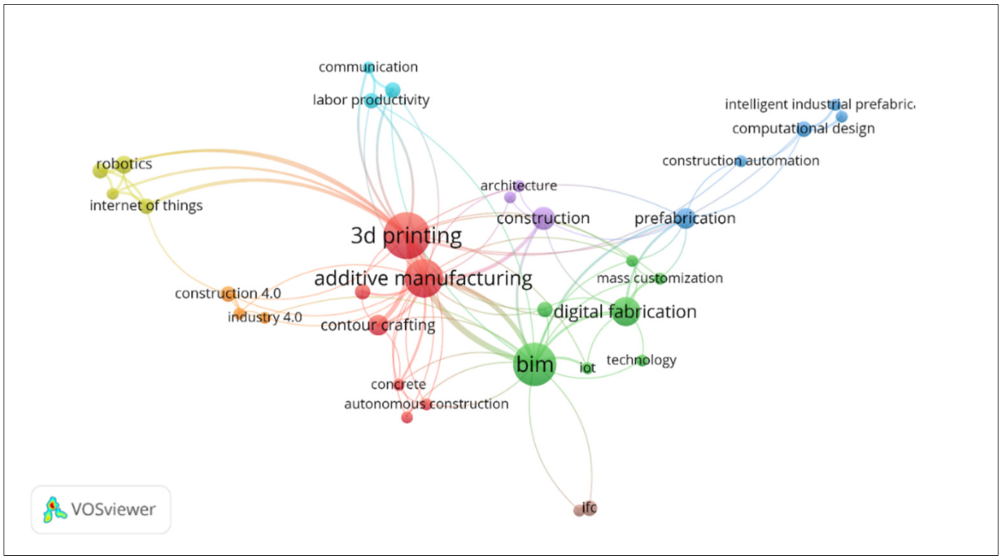

Figure-A I-1 Co-occurrence of authors' keywords in the literature review

Figure-A I-1 reveals the lack of research on the relationship between BIM and robotic 3DCP, as there is no connection between them. This reflects the limited number of citations of these two systems in the same document. Indeed, this literature review is characterized by a scarcity of articles that directly address the topic. It also demonstrates the lack of investigation into the interoperability between BIM and robotic arms. Thus, confirming the problematic of the parallel evolution between BIM and robotic 3DCP.

Methodology

BIM and additive manufacturing represent two very broad domains that are evolving in parallel. It is not possible to summarize the totality of the processes used in BIM that could be applied to additive manufacturing. This is the case since the technological tools of the two fields are quite diverse. Therefore, only workflows involving 3D printing with a robotic arm are addressed. This method allows the realization of complex architecture and can be carried out with modeling tools allowing to control simultaneously the trajectory of the extruder and the model parameters (Gosselin *et al.*, 2016). This document focuses on concrete printing as the material used in this method is the most widely used in construction (Bos *et al.*, 2016). It identifies the various scenarios where BIM and 3DCP are used collectively and aims to develop a seamless integration between them.

To explore the issue of interoperability identified in the literature review, the state of its technological dimension between BIM and 3DCP with a robotic arm is defined. The approaches involving this association are then categorized according to the classification of Janssen (2015) which addresses only the workflows characterizing parametric BIM modeling. Indeed, Janssen's methodology divides parametric BIM modeling between an embedded and coupled approach. The embedded approach is about using the software built-in functionalities. The coupled approach is subdivided to tightly coupled which associates two systems through the modeling software application programming interface (API), and loosely coupled, which involves a model exchange through the transfer of file formats. Adapting this methodology, our research categorizes the different approaches found in the literature review for using 3DCP in construction. It proposes two new approaches to apply BIM to this method. Finally, it suggests the most efficient approach by comparing the data transfers it involves and the functionalities it offers.

Technological interoperability between BIM and 3d concrete printing in construction

Technological interoperability is the exchange of data and information in a digital environment. In construction, this aspect has been recognized as one of the significant barriers to the adoption of BIM in the industry due to the paradigm shift it brings (Poirier *et al.*, 2014). Nevertheless, the use of BIM is currently expanding in the construction industry thanks to the potential of centralized information and facilitated collaboration. This level of adoption has not yet been reached in 3D concrete printing. The integration of BIM design activities into 3DCP offers the potential to significantly increase productivity by reducing implementation time and improving product quality. However, this integration still encounters critical challenges with respect to the transfer of information between BIM tools and automated construction systems. BIM is well known for its design of open file formats such as IFC. It is an open format that is in constant development and the reputation of this exchange technology is now well established since many of its aspects have reached maturity (Froese, 2003). IFC is a file format based on objects rich in information to represent building data. Janssen et al. (2016, 2) states that ‘‘the use of an open standardized file format ensures that the approach remains workflow agnostic.’’ This has contributed to its growing popularity in the industry and most CAD systems include it in their export formats (Fu *et al.*, 2006). However, IFC is not the most common format for 3D printing as there are other well-known file formats such as OBJ, AMF or 3MF. Yet the most common import format used by 3D printers remains the STL or STEP format depending on the type of information to be transmitted (Mechtcherine *et al.*, 2019). This highlights the parallel evolution of BIM design and 3D concrete printing tools. This project is part of the effort to propose an optimized approach that will support technological interoperability in the adoption of 3DCP in construction.

Approaches for the use of BIM for robotic 3d concrete printing

Loosely coupled approach

According to Hager et al. (2016), the workflow involving additive manufacturing begins with a model that is prepared in a 3D modeling application. It is then exported in a 3D data exchange format, often STL. This model is then sliced to constitute the successive deposited material layers. These layers define the control commands to position the extrusion head and start the printing of the model. This approach is defined by (Janssen, 2015) as loosely coupled because it involves an exchange of models between different software programs, typically a 3D modeling software and a digital fabrication software. However, the transfer of data throughout this process involves the risk of information loss. For example, the STL format only transmits geometric data and neglects information related to the component properties, such as the material properties or surface conditions. Moreover, the data processing in the slicing software is not always optimal (Mechtcherine *et al.*, 2019). As a result, a fragmented process occurs, losing critical information for the integration of the 3D printed project into a construction environment. This also concerns the BIM application's alternative to the workflow since the 3D model will be exported in a format accessible by BIM engines. Figure-A I-2 is realized in order to explain the loosely coupled approach associating BIM. This workflow is considered the least efficient due to the amount of format conversion it requires and the number of modeling and fabrication tools that it involves. This demonstrates the importance of integrated processes as once the model export is done, all the parameters related to the model are lost. With this, the user ends up with a bare model that is hard to modify depending on the printing parameters. In fact, the printing process is not always optimal from the very first attempt, thus requiring modifications to the model according to the challenges encountered during the fabrication process. With such a method, all the steps related to 3D printing will have to be repeated from the beginning without any possibility of rewinding. This will not be efficient within the time constraints incurred during construction. Data for O&M and 3DCP requirements are illustrated in this figure and all subsequent figures as dotted lines since it is not the focus of this study, which is primarily aimed at the realization of the project.

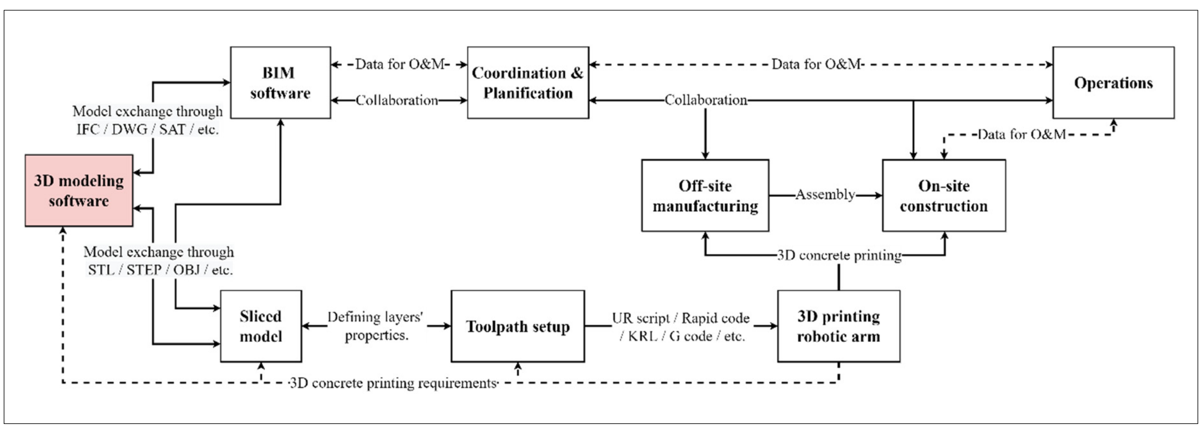

Figure-A I-2 Loosely coupled approach for applying robotic 3DCP in construction

In order to contribute to the evolution of robotic 3D concrete printing in construction, the integration of BIM in its development represent an appealing alternative. BIM has a lot of potential to offer from the perspective of its adaptability, the collaborative opportunity it offers and its ability to reduce costs (Poirier, 2015). Research has already been conducted to apply BIM to the loosely coupled type of approach (Davtalab *et al.,* 2018 ; Sakin et Kiroglu, 2017). Yet most have not mentioned the parametric workflow and have been content with a simple export of the BIM model for printing. These studies have been focusing on the advantages of using BIM functionalities and neglecting the optimization of 3D printing. The benefit of this approach is illustrated in Figure-A I-3. Taking advantage of BIM will lead to better integration in construction and allow better management of the 3D printed component throughout its lifecycle. It enables the use of BIM tools to predict clash detections and exploit the data collected for collaborative purposes.

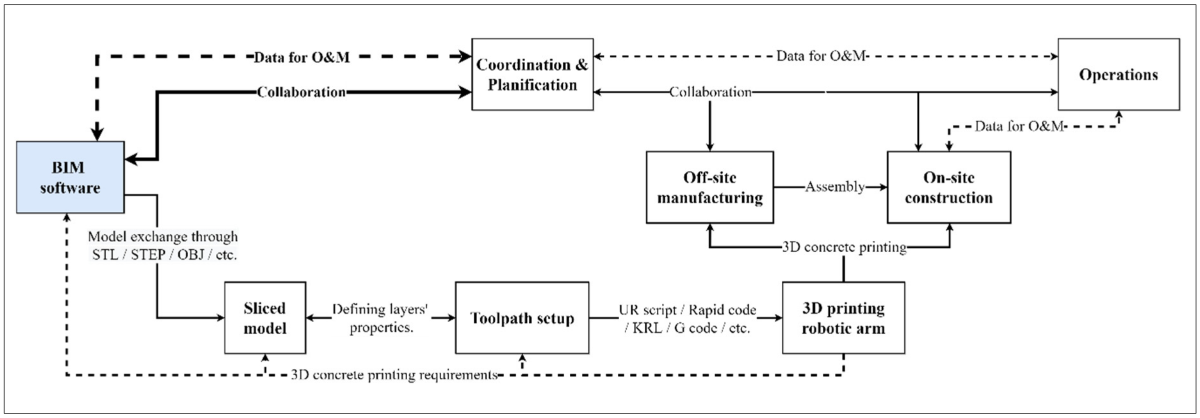

Figure-A I-3 Loosely coupled approach for applying robotic 3DCP in construction starting with a BIM software

In the context of this study, this process still presents a parallel evolution of BIM and robotic 3DCP. The use of a BIM software at the beginning of the process offers a considerable advantage. It allows a direct use of the information generated from the model and facilitates its integration into the construction environment. But this approach remains loosely coupled with 3D printing because it loses all the advantages of the embedded approach using BIM. By transmitting the model to the digital manufacturing tools, a discontinuity in the process is created, and a loss of information is possible.

Moderately coupled approach

In the context of this study, it was necessary to include another type of coupled approach other than those developed by Janssen (2015). The moderately coupled approach consists of adopting a tightly coupled approach on the one hand and a loosely coupled approach on the other. Examples of this approach can be identified through the use of parametric modeling tools such as Grasshopper 3D. This methodology allows the application of visual programming for the control of the 3D printing robotic arm using rapid iterations. That enables the user to modify both geometry and toolpaths as well as machine parameters, and then simulate the results in a single environment (Braumann et Brell-Cokcan, 2015). It is a methodology that has been widely used in research projects such as the work of Lim et al. (2016). These tools will generate a script that will be transferred to the robotic arm to print the model and will be combined with a modeling software to produce a 3D printing simulation. This process is not only dependent on visual programming tools, as it can also be adopted with a modeling software integrating a programming and robotic simulation plugin.

According to the literature review, BIM integration has not been thoroughly investigated in this approach. This integration can be explained in other research that addresses specifically parametric design. For example, the study by Janssen (2015) discussed the possibility of transferring information using other plugins of visual programming like GeometryGym. But these tools only offer a means of exporting to IFC which implies a model exchange. Figure-A I-4 illustrates that the process of applying BIM remains parallel to the 3D concrete printing process and is recognized as a moderately coupled approach. It involves model exchange on the one hand, and the use of parametric design tools using the modeling software API on the other.

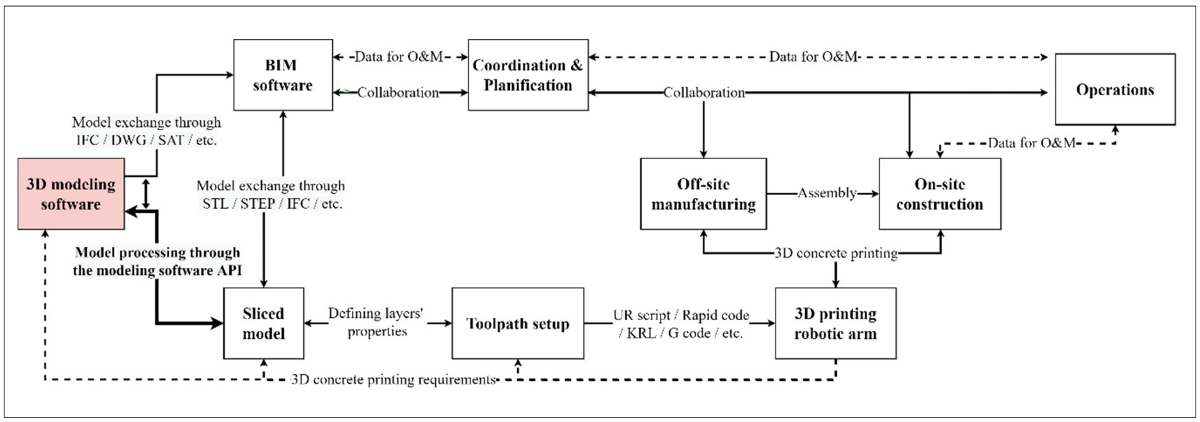

Figure-A I-4 Moderately coupled approach for applying robotic 3DCP in construction

Proposed tightly coupled approach

This study presents two alternatives to improve the efficiency of the use of BIM in robotic 3D concrete printing. With the first alternative, it is possible to avoid the need for a model exchange format by using representational state transfer (REST) APIs. For example, this can be available with Speckle.Works, which allows the transfer of 3D models between various design and analysis tools (Revit, Rhinoceros 3D, Unity, Blender, etc.). Figure-A I-5 illustrates this workflow which starts with a 3D modeling software like Rhinoceros 3D. The model developed is then transferred to Revit (as a BIM software) in almost real time with Speckle.Works. This workflow offers several opportunities for collaboration between the project participants and allows to collect a database of the 3D model evolution. In fact, it permits a parametric control of the 3D model and the printing mechanism in a simultaneous way. It allows the model to be transferred to a web viewer enabling cloud-based collaboration and uses an object-based version control system to design and structure the data (Poinet *et al.* 2020). However, Speckle.Works performance is dependent on the volume of data to be transferred. It is not yet possible to transfer voluminous models instantly with Speckle.Works, which raises the importance of data management.

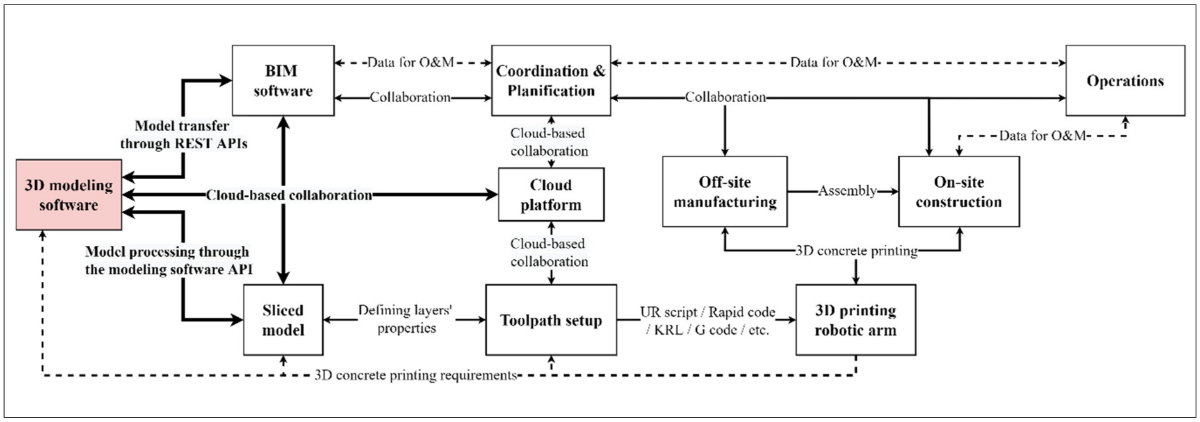

Figure-A I-5 Proposed tightly coupled approach for applying robotic 3DCP in construction starting with a 3D modeling software

To achieve a better adoption in construction and as demonstrated by the use of BIM in the loosely coupled approach. It is necessary to initiate the process with a BIM software for a smoother adoption in construction. In contrast to the moderately coupled approach, the second alternative illustrated in Figure-A I-6 proposes to start with a model developed with visual programming tools. This provides the advantage of having a tightly coupled BIM approach since these tools are directly linked to the BIM software API (Dynamo for its connection with Revit, Rhino.Inside.Revit for the Grasshopper 3D/Revit combination or Live connection for the Grasshopper 3D/Archicad combination, etc.). The quality and the number of plugins intended for digital fabrication vary between visual programming tools. For example, this approach is possible with Rhino.inside.Revit as it offers the necessary functionality to create 3D printing simulations. It allows to instantly generate printing scripts that can be transmitted to the robotic arm. This process offers design flexibility with centralized information, it reinforces the role of BIM as a facilitator of the adoption of robotic 3DCP. It provides both a model with the information required for its realization on the site or off-site, and also the simulation of its printing process.

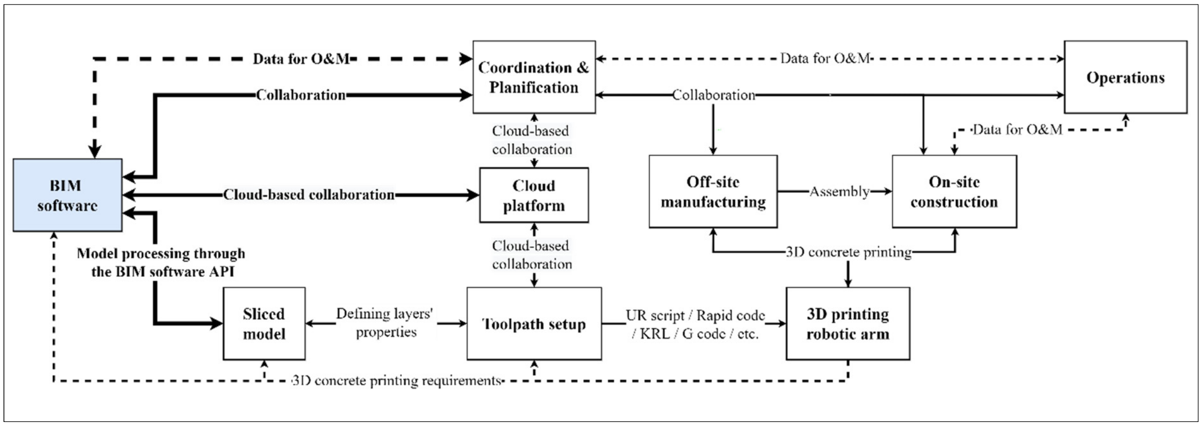

Figure-A I-6 Proposed tightly coupled approach for applying robotic 3DCP in construction starting with a BIM software

Compared to the first alternative, the advantage of this workflow consists in its structured information since it starts with a BIM software. In addition, cloud-based collaboration is better supported by this process given the range of platforms available through the BIM processes. This approach presents the fewest steps in the information flow with no model exchange format. It limits the loss of information during model transitions and transforms transfer challenges through format conversion into transfer challenges through the API provided by the system used.

Suggested approach

In this step, the suggested approach consists in the tightly coupled approach for applying robotic 3DCP in construction starting with a BIM software. Revit is taken as an example of BIM-modeling software and this approach is realized using the Rhino.Inside.Revit plugin. Therefore, the script for robotic printing is developed in Rhinoceros 3D. Grasshopper 3D is suggested since it is much more used in the digital fabrication environment compared to Dynamo. The case study focuses on the prefabrication of a building envelope realized with robotic 3DCP. This envelope will be covering a structure inspired by the Morpheus hotel in Macau. The modeling process is developed in Grasshopper 3D with the BIM schema provided by Rhino.Inside.Revit. The additive manufacturing script is also prepared in the same environment. As a result, the printing simulation and command lines are instantly generated. With Rhino.inside.Revit, it is Rhino running inside the Revit memory space. This means they can share all available data, saving considerable time and accuracy compared to loosely coupled approaches. No information transfer takes place through model exports and imports since the entire process is prepared in one environment. This combination will allow the use of all the advantages of both tools to have a multifunctional result. For example, the Speckle.Works plugin can be used for collaboration between the various stakeholders of a project. It will be employed to transmit geometry information and exchange printing data in real time between the software it supports. It will allow the visualization of the model through a web viewer which will guarantee an efficient collaboration. Cloud-based collaboration can also be executed with Forge, BIM360 or Unity reflect for information management and collaboration. Fologram could be used for the augmented reality representation of the 3DCP simulation and the model used. Ladybug and Honeybee could also be used for the sustainable development aspect through the different analyses that these plugins offer. BIM tools can be used for clash detection when integrating into construction environments and all dimensions of BIM including project documentation. The result of this process is shown in Figure-A I-7, which illustrates the simultaneous visualization of the developed model and 3DCP simulation. This visualization is represented in four columns from left to right, in Rhinoceros 3D, Revit, Speckle.Works web viewer and in augmented reality through Fologram.

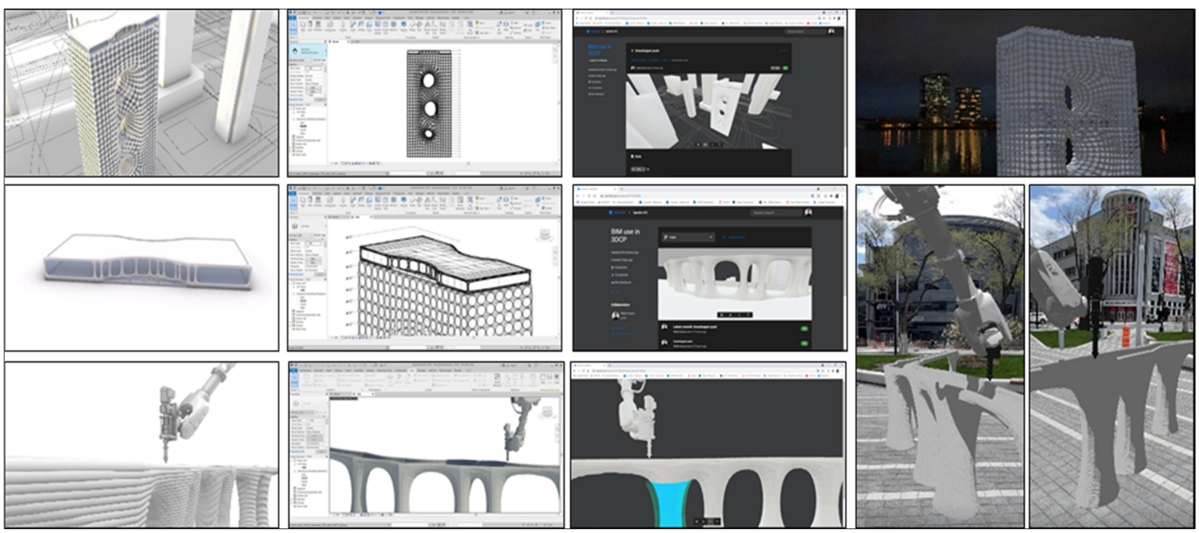

Figure-A I-7 Simultaneous visualization of the suggested process result in Rhinoceros 3D, Revit, Speckle.Works and Fologram

However, this approach has some limitations. 3D printing is based on meshes, and since Revit and Rhinoceros 3D use different geometry engines, the use of Grasshopper 3D models in Revit will not always result in perfect meshes. Moreover, meshes are often voluminous in data. Without reduction, they can cause limitations in their transfer to the cloud. This combination of tools gives a much more stable result in the management of Boundary representations (Breps). In the case of 3D printing simulations, there are no good ways to embed an object animation in Revit as this software is not designed for this functionality. Nevertheless, these simulations can be supported in any other tightly coupled software such as Rhinoceros 3D or Unity, which highlights the importance of information management. In spite of these limitations, the process remains more efficient than the loosely coupled approach. It keeps all the parameters of the design and printing process, and enables the modeling to be adjusted according to the printing tool. Rhino.Inside.Revit development defines a significant evolution of the technological interoperability between Revit and Rhinoceros 3D. It offers a multitude of possible application tracks, such as the one addressed in this approach which is robotic 3D concrete printing.

Conclusion

BIM and robotic 3D concrete printing have evolved in parallel in the industry and this is due to the lack of interoperability between these two systems, among other reasons. This research focuses on the aspect of technological interoperability by comparing the different possible approaches for the use of BIM in robotic 3DCP. Based on the various scenarios evaluated, we suggest that the most efficient process consists in the tightly coupled approach starting with a BIM software. By using this approach, the need for exchange formats is avoided. The risk of information loss is reduced and technological interoperability between the two systems is improved. This study constitutes a step towards clarifying the advantage of integrating BIM into the workflow. Indeed, the use of BIM in robotic 3DCP is a very interesting alternative for off-site manufacturing and the standardization of printed objects. It improves collaboration between the various stakeholders of a construction project, especially on the MEP side. This will certainly influence the other dimensions of interoperability defined by Poirier et al. (2014), i.e. the procedural, organizational and contextual dimensions of the two systems, which constitute future avenues for development.

The proposed methodology can apply not only to additive manufacturing, but also to the case of subtractive manufacturing or robotic manipulations. Fabrication of wood, for example, would constitute a quite promising development path since it requires both manufacturing and data. In this context, many other research directions can be explored, which reveals the potential of BIM's use in digital fabrication for construction.

Acknowledgements

The authors are grateful to Mitacs for its financial support through its Globalink Program.

The Bibliography section is presented at the very end of the thesis.

APPENDIX II

MODULAR ROBOTIC PREFABRICATION OF DISCRETE AGGREGATIONS DRIVEN BY BIM AND COMPUTATIONAL DESIGN

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Abstract

Discrete architecture is recognized as a computational design approach which uses computation to generate algorithmically combinable aggregations. It is therefore a promising innovation for increasing design process productivity through the adaptability of the aggregations it generates. In the built environment, discrete design is usually identified with the modular method. It is a construction process based on the aggregation of different modules assembled according to well-defined connections to ensure the building's integrity and functionality. It involves off-site manufacturing, and hence a controlled environment ensuring more predictability over weathering and change. But like in conventional construction practices, the fragmentation of modular construction processes hinders its productivity. As a result, this construction approach requires adequate technologies and communication tools to improve collaboration and productivity. This paper aims to address these requirements by adopting a BIM-driven computational approach to design processes and a robotic approach to prefabrication processes. It proposes a modular construction framework for design and production, and presents the results through a study adopting BIM-driven discrete design and robotic manufacturing.

Introduction

In research, off-site manufacturing is presented as offering the potential to significantly improve the construction industry's performance and address many of its challenges (Wang *et al.*, 2020). Through volumetric modular design, this construction system saves both time and money and develops affordable and efficient projects. In fact, a modular building can take on the characteristics of any architectural style if the factory manufacturing conditions are met (Modular Building Institute, 2020). This balance between constraints and design strategy that can be found using a specific computational design method called discrete architecture. The term ''discrete'' represents a notion that refers to individuality and separation. Opposite from this is the notion of continuity, based on unity and uniformity (Retsin, 2019a). Thus, from a design point of view, this term defines the change of the design strategy from a continuous architecture to a modular architecture. According to Tessmann and Rossi (2019), discrete design involves modeling an aggregation of modules with reversible connections. These connections will then drive the aggregations defined according to the rules established by the designer. Therefore, these aggregations can be assembled, disassembled and reconfigured during their life-cycle. This concept could facilitate the design phase of modular projects, as this project phase is considered one of the major inhibitors to the adoption of off-site fabrication in construction (Goulding *et al.*, 2015). Furthermore, by providing a wide range of digitally trackable iterations, this approach could be enabled by BIM tools through their ability to provide parametric design and planning functions. BIM frames this as a holistic construction management system that covers the entire life-cycle of a construction project. This includes modeling, construction planning, cost estimating and post-construction facility management. The main characteristic of a BIM model is that it contains not only geometric information, but also material, resource, equipment, and fabrication data. Therefore, BIM-driven discrete design holds the potential to improve productivity throughout the building lifecycle, from design to operations and maintenance. It offers a promising alternative to modular robotic fabrication of complex shapes, and hence, the possibility to conceive 'unthinkable architecture' (Morel, 2019).

Automation of manufacturing processes using industrial robots has made its proofs in the automotive industry and is increasingly proving its potential application to construction. According to various studies, robotic manufacturing has been shown to be economically and environmentally efficient compared to conventionally built projects (Weng *et al.*, 2020). This manufacturing method is now technologically interoperable with construction design tools such as computational design and BIM tools. This marks a technological turning point, as it is now possible to link construction data in an embedded way to robotic arms for fabrication (Anane *et al.,* 2023). The present article addresses the conceptual combination of these different technological systems through a modular project realized adopting the developed framework. The off-site fabrication of the model is simulated in parallel in the same BIM environment with a reversible connection between the building data and the robotic manipulations. This development will facilitate technological interoperability between BIM and robotic manufacturing tools through algorithms-aided design, thus ensuring better management of information flow throughout the modular building life-cycle.

Proposed framework for modular robotic prefabrication of discrete aggregations driven by BIM and computational design

In the literature, the concurrent use of BIM and robotic manufacturing in modular construction lacks exploration (Yin *et al.*, 2019). This is primarily due to the parallel evolution of both the robotic and construction industries in terms of context, processes, tools, etc. (Mechtcherine *et al.*, 2019). This reality has motivated the research presented in this paper since such a lack of interoperability represents a significant barrier to automation in the construction industry. According to Poirier, Forgues and Staub-French (2014), interoperability is defined as the ability to exchange information between two systems along technological, procedural, organizational, and contextual dimensions. This is a key aspect for the development of a fragmented construction industry since its economic impact is considerable (Gallaher *et al.*, 2004).

The elements of the developed framework (Figure-A II-1) are categorized according to the environment of production and management of information during the design and execution phases. The design phase is divided in two since it includes the architectural design and its simultaneous programming for robotic manufacturing. Such a task requires a computational design environment that involves programming in order to simultaneously develop the design and act as a post processor for robotic manufacturing (Davtalab *et al.*, 2018). With its integration in a BIM environment, it is possible to incorporate information in the various components of the modular building, facilitating their identification and their manufacturing (Stumm, Devadass et Brell-Cokcan, 2018). BIM, in the collaborative context, also enables cloud-based collaboration to centralize project information and streamline its flow between the diverse stakeholders. It serves as an information continuity system linking design and production processes in order to minimize information loss (Yuan, Sun et Wang, 2018). Indeed, information accuracy is crucial in the context of robotic manufacturing. Through manipulations such as CNC milling, welding, or assembly, industrial robots must guarantee unequivocal accuracy to ensure the efficiency and safety of the manufacturing process. The end effector and the robot categories are also defined with computational design tools; they will allow to define the tool path and prepare the manufacturing script. This will allow the robotic arm in place to perform the instructed commands and provide feedback on the completed manufacturing step, remaining time, system warnings, etc. (Alreshidi, Mourshed et Rezgui, 2018). This framework is developed taking into consideration the technological interoperability of the tools used. It represents a specific development of the ‘‘tightly coupled’’ approach which is based on data exchange through the APIs of the software used *(*Anane *et al*., 2023). Revit is taken as an example of BIM modeling software and this approach is performed using the Rhino.Inside.Revit plugin. Therefore, the script involving robotic manufacturing is developed in Rhinoceros 3D whereas Grasshopper 3D is used for the generation of discrete aggregations through plugins like Wasp or Monoceros.

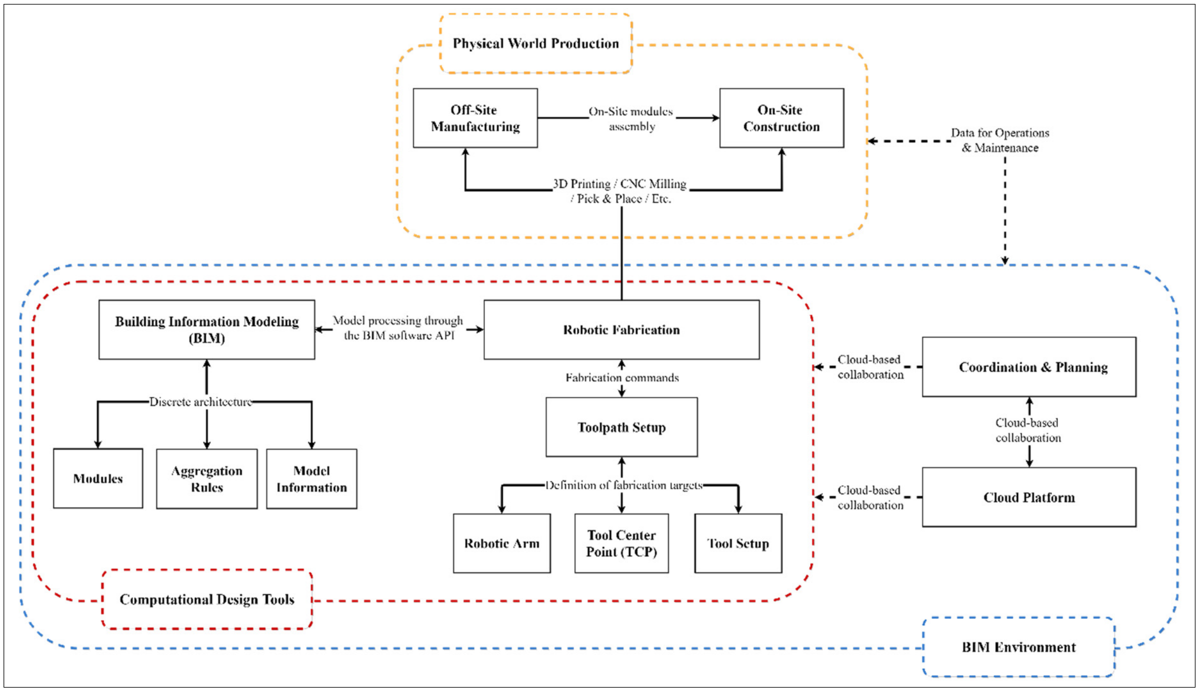


Figure-A II-1 Proposed framework for the use of discrete architecture and robotic manufacturing for modular construction driven by BIM and computational design

The study carried out with this framework is based on a project prepared for a modular design competition. It consists in the prefabrication of a modular residential building manufactured through subtractive wood fabrication and assembly manipulations. This building is designed to be built in Montreal and is based on a discrete aggregation of volumic modules. The modeling process is developed in Grasshopper 3D with a BIM schema provided by Rhino.Inside.Revit, and the robotic manufacturing script is prepared in the same environment. BIM usage explained in this study is for multidisciplinary collaboration and data consistency in a construction project. Further in this article, we describe the framework in its design and operation phases, followed by a discussion of the results and concluding statements.

Discrete architecture driven by BIM and computational design for modular construction

The productivity enhancement offered by computational design has marked a ‘‘computational shift’’ in building design. It has revolutionized traditional design processes that were heavily based on manual drawing and calculation tasks. Indeed, design computation aims to explore, develop and implement digital models of design drawings (CAD), engineering (CAE) and manufacturing (CAM) into the design process (Hägele *et al.*, 2016). It operates essentially with discrete data to enable working with complex shapes and complicated design tasks to redefine the entire architecture production chain (Morel, 2019). In the design context, discrete aggregation tools were developed to open new design perspectives computationally based on adaptability and functionality (Oxman, 2010). Through Wasp, the aggregation of modules is conceived as reversible discrete assemblies (Retsin, 2019b). Modules can be predefined hierarchically, which means that they can contain information with several design levels. They are assembled either according to their possible connections, or to the aggregation rules set by the user. As shown in Figure-A II-2, the modules used in this study are divided into two categories. First, there are core modules that can either be parallelepipedal or cubic and can include a kitchen, a living room and a work space. Second, there are two types of functional modules that are both cubic and constitute either a bedroom, a bathroom with a corridor, or another type of use. When configuring these modules, it is sufficient to define their aggregation in their volumetric form for the massing to be achieved. This design strategy is enhanced with BIM tools as each floor, column, beam and other building element is recognized and mapped according to their unique families. Such a use of BIM allows the acquisition of structured information for each module. This information will be valuable for the documentation of the project and for the management of the building information throughout its life-cycle.

Figure-A II-2 The hierarchy of selected external modules used for the project aggregation

According to Yuan et al. (2018), a computational design method specific to modular construction could potentially improve the adoption of modularity in construction and optimize the design phase of projects. This article could constitute an interesting technological advancement in off-site construction. For example, using the modules already predefined in our context and a field-driven design technique (Rossi et Tessmann, 2019), discrete architecture allows to generate different modular aggregation proposals (presented in Figure-A II-3). This aggregation process, coupled with more structural and functional rules, has the potential to be an innovative technique for the modular massing design phase.

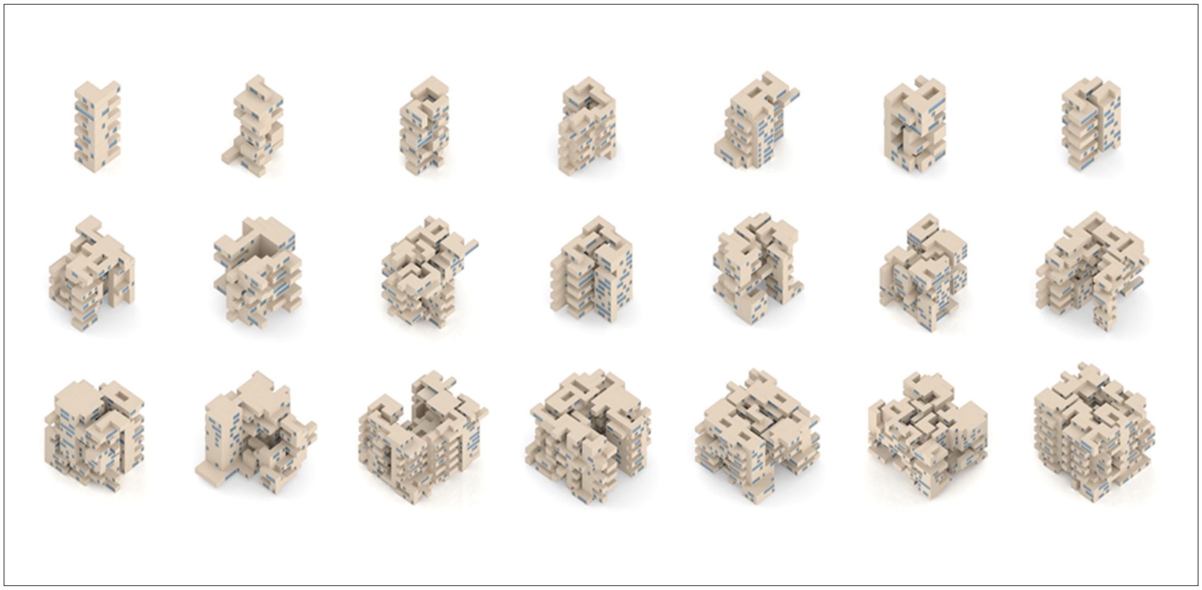


Figure-A II-3 Sample of preliminary iterations obtained during the massing design of the project

To ensure more control over these aggregations, we took into consideration the limitations of the above-mentioned competition and the contextual analysis of the construction site. The code regulations regarding modular construction were also taken into consideration to determine the number of floors and the size of the modules. To date, a completely modular construction in Quebec must not exceed five floors, and the modules to be transported must not exceed 15 m (Québec Official Publisher, 2021). If exceeded, there is a penalty of being confronted with the use of exceptional convoys. The chosen site and the regulations put in place constrain our modular building to exploit only three facades as it has a five-story building at its back. We therefore opted for a configuration that combines the complexity of aggregation with the simplicity of massing - proposing a solution with three non-uniform facades with cantilevered balconies. The plumbing aspect was a key consideration for this project. We respected the rule that one toilet must be superposed over another, and connected to a main cubic module of the apartment on the kitchen side. This is to minimize the dispersion of the piping through the floors of the building and between the compartments of each apartment. An analysis of exposure to solar radiation was also conducted on the building with the Ladybug tools. This allowed to determine the optimal width of the windows as well as the appropriate offset of their shaders to minimize exposure with the help of the evolutionary algorithm of Galapagos. The solar radiation analysis also informed the design of a canopy, which will allow the use of the building's roof as a cafeteria. This canopy transforms into a staircase to connect the various sections of the building's roof and will be robotically manufactured. With this specific aggregation approach, the strategy is to maintain controlled connections guided by the functional needs of a building. The results of this design study are illustrated in Figure-A II-4, which shows the final rendering of the different building facets, its various floor plans and its exposure to radiation.

Figure-A II-4 Final rendering of the different facets of the building, analysis of its radiation exposure and illustration of its floor plans

Discrete architecture driven by BIM and computational design is a paradigm shift for the design phase in modular construction. Such a design process demonstrates the potential behind delivering detailed and documented designs in the preliminary phases of projects with a reduced timeline. In fact, it results in an automated architectural design that is both efficient and mass produced (Retsin, 2019b). It reallocates the distribution of efforts, placing more emphasis on functional design and reduces redundant processes like clash detection. With their interoperability, BIM and computational design eliminate the need for multiple entries of duplicate data and facilitates automation. This combinatory potential constitutes an innovative approach that incites rethinking the production chain of contemporary architecture, opening the door to mass customization in construction.

In the context of the developed framework (Figure-A II-1), the result of the established modeling is simultaneously processed for off-site manufacturing. This step will be performed by robotic arm cells appropriately equipped to perform cutting and assembly operations. They will be technologically interoperable with the computational design tools used since they will be programmed in these same environments. In this way, computational design tools will act as post processors for industrial robots and will provide the link between design and robotic control. This will provide a parametric aspect to robotic programming and will lead to a modular robotic prefabrication of discrete aggregations driven by BIM and computational design.

Discrete architecture driven by BIM and computational design for modular construction

Construction automation, as defined by Cousineau and Miura (1998), is the application of industrial automation principles to construction. This industrial automation is applicable to the construction of buildings, structures, and any other project related to the built environment. The use of this terminology is frequently linked to robotics. With nearly 1.5 million robotic arms installed in 2014, this technology has therefore become the largest commercial application of robotics, making it the most related to the automation term (Hägele *et al.*, 2016 ; Bademosi et Issa, 2021). Unlike hard automation, robotics provide flexibility in manufacturing processes. It is a technology capable of adapting to design changes while ensuring accuracy, reliability and low operating costs (Reinhardt, Saunders et Burry, 2016). According to Stumm et al. (2018), off-site construction is one of the most promising methods for facilitating the adoption of robotic technologies for fabrication. With repetitive processes and a controlled environment, the incorporation of robotics for modular manufacturing represents a promising development. This automation perspective has the potential to save time and costs, provide a safer working environment, reduce waste, and improve project performances (Bock, 2015). But this integration faces many challenges, particularly in terms of technological interoperability between design and robotic tools (Goulding *et al.*, 2015).

With the proposed framework (Figure-A II-1), it is possible to employ robotic manufacturing tools natively in BIM environments. This type of system allows access to a tightly coupled approach where the information related to the building is centralized and the manufacturing process is integrated (Anane *et al.*, 2023). With a BIM-driven discrete design as a method, the information related to the established aggregation of modules is structured with visual programming tools. These tools will allow the control of the robotic arms available to perform the necessary operations, varying between 3D printing, CNC milling, and Pick-and-Place, among others. This allows the user to simultaneously adapt the robotic toolpath to geometry changes, and then simulate the results in a similar environment (Ali, Lee et Song, 2021). Once the design and programming process is set, the manufacturing commands are generated and then transferred to the robotic arms in real time. In this study, the robotic manufacturing process is integrated into a BIM environment to allow collaboration with other project stakeholders. This is done to demonstrate the effectiveness of the proposed framework for multidisciplinary collaboration within a discrete design process. The model and robotic commands coordination within the design team was done with a connected design platform named Speckle.Works. It is a cloud-based open-source platform focused on the technological interoperability of different software. It provides real-time collaboration, data management, versioning and automation of various workflows in the AEC industry (Poinet, Stefanescu et Papadonikolaki, 2020 ; Sheil *et al.*, 2020). As shown in Figure-A II-5, elements that will incorporate plumbing systems are manufactured by a robotic cell. These collaborative robots prepare the piping locations by CNC milling and then assemble them by automatic screwdrivers according to the Mechanical Electrical and Plumbing (MEP) model. Since both design and robotic programming are performed in the same environment, building blocks that will incorporate the plumbing components are directly nested separately in the digital robotic cell. This will allow the simulation of the manufacturing process and generate the fabrication commands for the robotic arm. A robotic program that will take into consideration the routing of the pipes according to the parameters (diameter, slope, category, etc.) included in the BIM model.

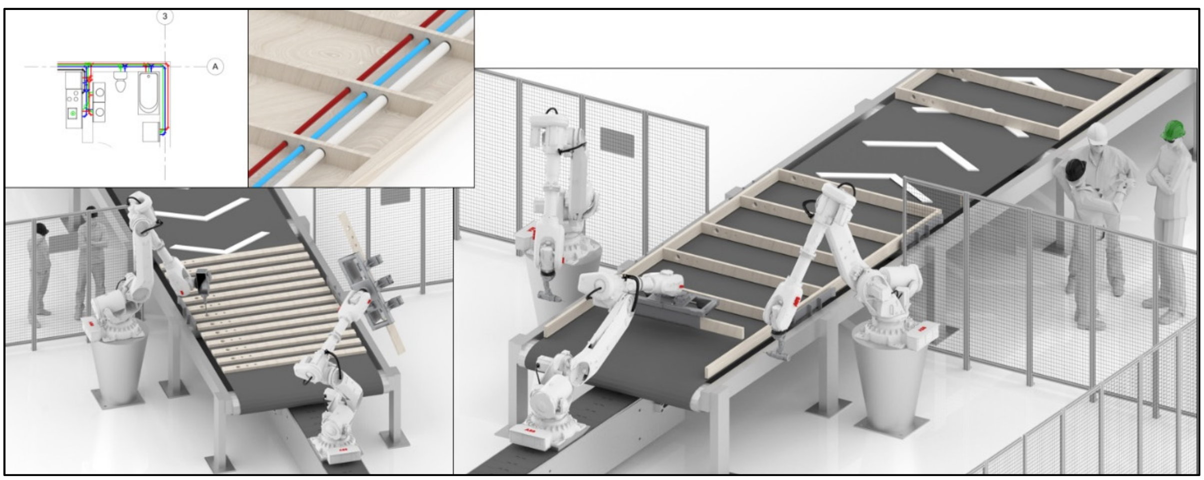


Figure-A II-5 Robotic manufacturing and assembly of the elements that will incorporate plumbing systems based on the BIM model

With the automation of modular manufacturing practices, a BIM-driven discrete design approach defines a feedback loop between manufacturing and design processes. It allows for the development of strategies for the manufacturing of adaptive and permutable components. These components can be assembled by robotic arms to form modules that will be transported to the construction site, where they will be assembled. This method of construction will allow the modules to be re-configured if the building serves a different function than the one initially planned (Claypool *et al.*, 2019). Therefore, the notion of digital material intervenes since it links the material and digital world by offering a reversible and programmable manufacturing process (Claypool, 2019a). This terminology could nevertheless be contested with the argument that materials are analogue, and cannot be recognized as being digital (Leach, 2019). However, it could still be defended depending on the context in which it is used (Retsin, 2019b ; Claypool *et al.*, 2019 ; Chiappone-Piriou, 2019). Figure-A II-6 shows the canopy that is placed on the roof of the building. It is composed of wooden parts interlocked in a male-female system to ensure their stability. This canopy is multi-functional as it simultaneously provides sun protection for the cafeteria and a passageway between the different roof compartments. Finally, the parts to be manufactured are parametrically identified and optimally nested on the wooden plate to minimize manufacturing waste and to generate their documentation with BIM tools.

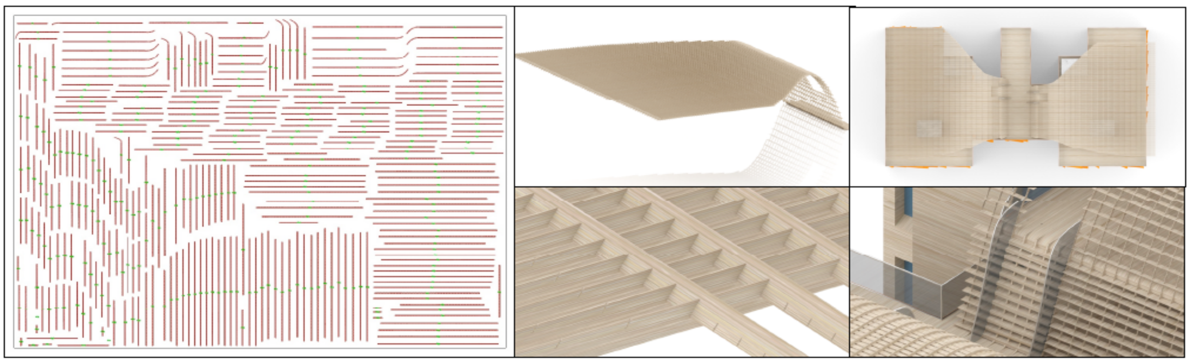


Figure-A II-6 Illustration of the canopy placed on the roof of the building (right) and nesting of its different components (left)

The use of BIM processes integrating computational design tools to design, collaborate and manufacture modules off-site, favors the development of a workflow centralizing information. This workflow allows the distribution of products with a reduced timeline and an enhanced quality. The interoperability between both robotic and BIM-driven discrete design tools provides instant adaptability of robotic toolpaths. In fact, by acting as a powerful design tool for adaptability to change through computing, robots can adapt to change. Initiated with the various categories of computational design, this workflow will facilitate the fabrication of free-form project designs that have remained a considerable problem in conventional off-site fabrication (Modular Building Institute, 2020). Indeed, one of the main advantages of robotic arms compared to conventional digital manufacturing methods is their ability to operate with different degrees of freedom. Such an ability allows them to manufacture freeform and complex shapes, and to ensure operational flexibility through simple tool changes. Figure-A II-7 illustrates the fabrication and assembly of the canopy components placed on the roof of the building (see Figure-A II-6) using a robotic arm cell.

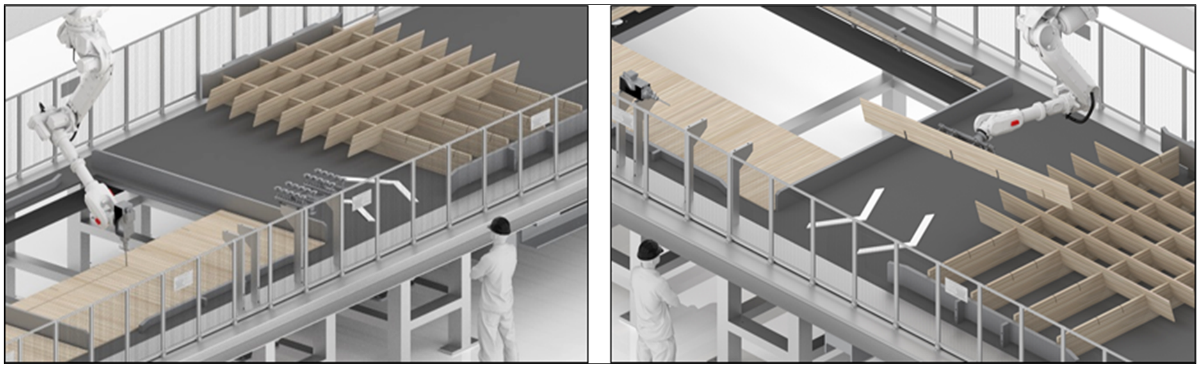


Figure-A II-7 Manufacturing and assembly of the canopy elements with a robotic arm cell equipped with a tool changer

Discussion

According to literature, the contribution of discrete architecture will have a significant impact on modular design (Retsin, 2019a ; Tessmann et Rossi, 2019 ; Rossi et Tessmann, 2019 ; Claypool, 2019a ; Trotter, 2019). A design phase that is not yet sufficiently mastered in industry with a cost that remains more expensive than conventional design (Modular Building Institute, 2020 ; Yin *et al.*, 2019). However, discrete architecture used through computational design tools is insufficient on its own to produce modular buildings. The adoption of BIM, which is fundamentally contrary to the notion of discontinuity, has the potential to perform a key role in the adoption of these innovative technologies in construction (Poirier *et al.*, 2018). This provides the opportunity to move from a classic discrete design to one that is conducive to manufacturing and assembly on the site. With the proposed framework (Figure-A II-1), it is possible to ensure an automatic integrated building-related information flow during two main phases of the modular construction. Namely, from the automation of the design process through the BIM-driven discrete design, to the automation of its production phase with robotic arms. It is a process that has ensured the intrinsic programming of the design and its manufacturing, while ensuring its flexibility and adaptability to possible changes. Such a framework would facilitate the digital shift of the construction industry through the controlled environment it provides and the adaptability of the operations on which it is based. But the combination of these conceptualizations is not without flaws since it is costly in terms of data consumption. Discrete design associated with robotic manufacturing in the same environment consume a lot of computational power. This excessive consumption remains an aspect that generally causes a considerable loss of time during the design and programming process. Moreover, this process is based on discretization and separation. These notions influence the stakeholders since the other dimensions of interoperability in the context of the developed framework (i.e. organizational, procedural and contextual) are not as developed as the technological aspect. Collaboration on the cloud using data-intensive models is also not as effective as expected and requires further development. This proves that automation is highly dependent on information management and justifies the use of a BIM environment in the developed framework to drive technological innovations. Therefore, the combined use of discrete architecture algorithms and robotic arms in construction is a technological association that holds a promising future for modular construction in the AEC industry.

Conclusion

As defined by Retsin (2019a), discreteness in architecture is associated with the notion of individuality. It is not linked to continuity, but with what is separate from other components. Such fundamentals are contrary to the notions of BIM, which relies on the continuity of processes to address the AEC industry's fragmentation (Eastman *et al.*, 2012). By bringing these concepts together, this article demonstrates the use of computational design to develop modular structures with a BIM-driven discrete design approach. This is done to provide an automated manufacturing process, that will be carried out by robotic arms. This article proposes a framework that enables the use of these different concepts, apparently distinct in their foundations but deeply linked in their application within construction projects. This approach is illustrated by a modular residential project designed with discrete architecture concepts and robotically prefabricated offsite.

The results of this article clearly demonstrate that the developed framework offers the potential to have an accelerated design phase based on centralized information through a BIM model. It disrupts conventional design concepts by shifting the paradigm from a whole to an assembly of parts, and combines those parts into a whole that is driven by BIM. Therefore, it presents the intrinsic connection between continuity and discontinuity in the design processes of architecture and manufacturing. By adopting the tightly coupled approach of Anane et al. (2023), it is possible to gain access to the potential of BIM-driven computational design functionalities. These functionalities include discrete design, cloud collaboration, project documentation and robotic manufacturing. This provides the possibility to improve the construction industry's productivity and automate its processes on both the conceptual and real-world levels. It provides an innovative framework for modular manufacturing and contributes to its democratization among designers. Additionally, it opens the door to many research topics such as mass customization, robotic production cells for construction, and discrete automation. Although this approach is certainly not void of shortcomings, it is an innovative development contributing to the automation in construction processes.

Acknowledgements

The authors are grateful to Mitacs for its financial support through its Globalink Program. They also thank Nouha Boufares for modeling the MEP components, and Amirhossein Mehdipoor for his feasibility study of the project.

The Bibliography section is presented at the very end of the thesis.

APPENDIX III

DAYDS' SEARCH TAGS USED IN THE CYCLIC SYSTEMATIC LITERATURE REVIEW (SLR)

Table-A III-1 Dyads investigated in the cyclic SLR and their related search tags

Dyads	Search Tags
BIM-RM	(bim OR ‘‘building information model*’’ OR ‘‘building information manage*’’) AND (‘‘robotic arm*’’ OR ‘‘robotic manufactur*’’ OR ‘‘robotic fabricat*’’ OR ‘‘robotic simulat*’’)
BIM-CD	(bim OR ‘‘building information model*’’ OR ‘‘building information manage*’’) AND (‘‘computational design’’ OR ‘‘parametric design’’ OR ‘‘generative design’’ OR ‘‘algorithms-aided design’’ OR ‘‘evolutionary design’’)
CD-RM	(‘‘computational design’’ OR ‘‘parametric design’’ OR ‘‘generative design’’ OR ‘‘algorithms-aided design’’ OR ‘‘evolutionary design’’) AND (‘‘robotic arm*’’ OR ‘‘robotic manufactur*’’ OR ‘‘robotic fabricat*’’ OR ‘‘robotic simulat*’’)
BIM-OSC	(bim OR ‘‘building information model*’’ OR ‘‘building information manage*’’) AND (‘‘offsite* construction’’ OR ‘‘offsite* manufactur*’’ OR ‘‘prefabricat* construction’’ OR ‘‘modular* construction’’)
CD-OSC	(‘‘computational design’’ OR ‘‘parametric design’’ OR ‘‘generative design’’ OR ‘‘algorithms-aided design’’ OR ‘‘evolutionary design’’) AND (‘‘offsite* construction’’ OR ‘‘offsite* manufactur*’’ OR ‘‘prefabricat* construction’’ OR ‘‘modular* construction’’)
RM-OSC	(‘‘robotic arm*’’ OR ‘‘robotic manufactur*’’ OR ‘‘robotic fabricat*’’ OR ‘‘robotic simulat*’’) AND (‘‘offsite* construction’’ OR ‘‘offsite* manufactur*’’ OR ‘‘prefabricat* construction’’ OR ‘‘modular* construction’’)

Table-A III-2 Filtering results of the cyclic Systematic Literature Review (SLR)

Systematic Literature Review (SLR) steps	First Cycle			Second Cycle		
	BIM-RM	BIM-CD	CD-RM	BIM-OSC	CD-OSC	RM-OSC
Documents found in Scopus + Dimensions	10 + 07	127 + 68	78 + 32	182 + 193	23 + 24	15 + 14
Number of duplicates	01	48	19	100	12	04
Eligible documents	14	103	76	197	18	15
Documents found with the ‘‘snowballing’’ support	04	>30	>30	>30	09	07
Total eligible documents for the bibliometric analysis	18	>133	>106	>227	27	22

APPENDIX IV

AVAILABLE LITERATURE ON BIM-RM TECHNOLOGICAL INTEROPERABILITY

Table -A IV-1 Collected references on BIM-RM technological interoperability

N	Titles	Reference
1	An innovative digital workflow to design, build and manage bamboo structures	(Guo, 2022)
2	Automated fabrication of reinforcement cages using a robotized production cell	(Momeni *et al.*, 2022)
3	BIM-based simulation of construction robotics in the assembly process of wood frames	(Wong Chong *et al.*, 2022)
4	BIM-based task and motion planning prototype for robotic assembly of COVID-19 hospitalisation units—Flatpack house	(Gao *et al.*, 2022)
5	Real-time state synchronization between physical construction robots and process-level digital twins	(Liang *et al.*, 2022)
6	Towards fully BIM-enabled building automation and robotics: A perspective of lifecycle information flow	(Zhang, Luo et Xu, 2022)
7	BIM-enabled computerized design and digital fabrication of industrialized buildings: A case study	(He *et al.*, 2021)
8	Development of communication protocols between bim elements and 3D concrete printing	(Forcael *et al.*, 2021)
9	Fabrication Information Modeling: Closing the gap between Building Information Modeling and Digital Fabrication	(Slepicka, Vilgertshofer et Borrmann, 2021)
10	real-time Digital Twin of On-site Robotic Construction Processes in Mixed Reality	(Ravi *et al.*, 2021)
11	Robot-based facade spatial assembly optimization	(Ali, Lee et Song, 2021)
12	Use of BIM and 3D Printing in Mars Habitat Design Challenge	(Carrato, 2021)
13	An integrated review of automation and robotic technologies for structural prefabrication and construction	(Chea *et al.*, 2020)
14	BIM-based task-level planning for robotic brick assembly through image-based 3D modeling	(Ding *et al.*, 2020)

N	Titles	Reference
15	Collaborative Welding System using BIM for Robotic Reprogramming and Spatial Augmented Reality	(Tavares *et al.*, 2019)
16	Design of a Robotic Software Package for Modular Home Builder	(Yang *et al.*, 2019)
17	In-situ construction method for lunar habitation: Chinese Super Mason	(Zhou *et al.*, 2019)
18	Perspectives on a BIM-integrated software platform for robotic construction through Contour Crafting	(Davtalab, Kazemian et Khoshnevis, 2018)

APPENDIX V

BIBLIOMETRIC VISUALIZATIONS OF BIM-CD AND CD-RM DYADS IN VOSVIEWER

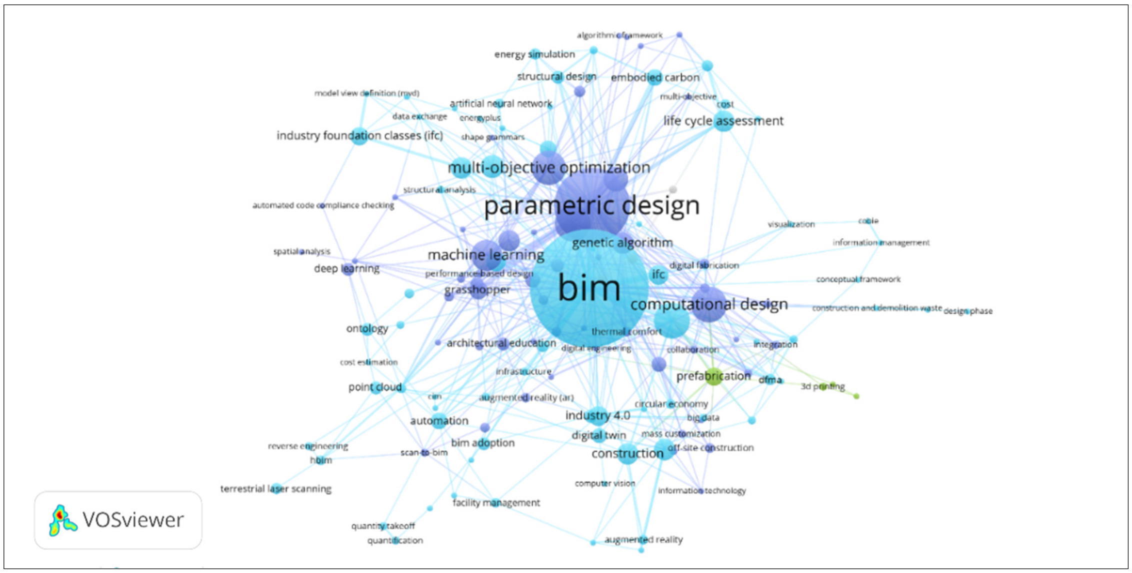


Figure-A V-1 Keywords co-occurrence network of BIM-CD technological interoperability within the literature (2018-2022)

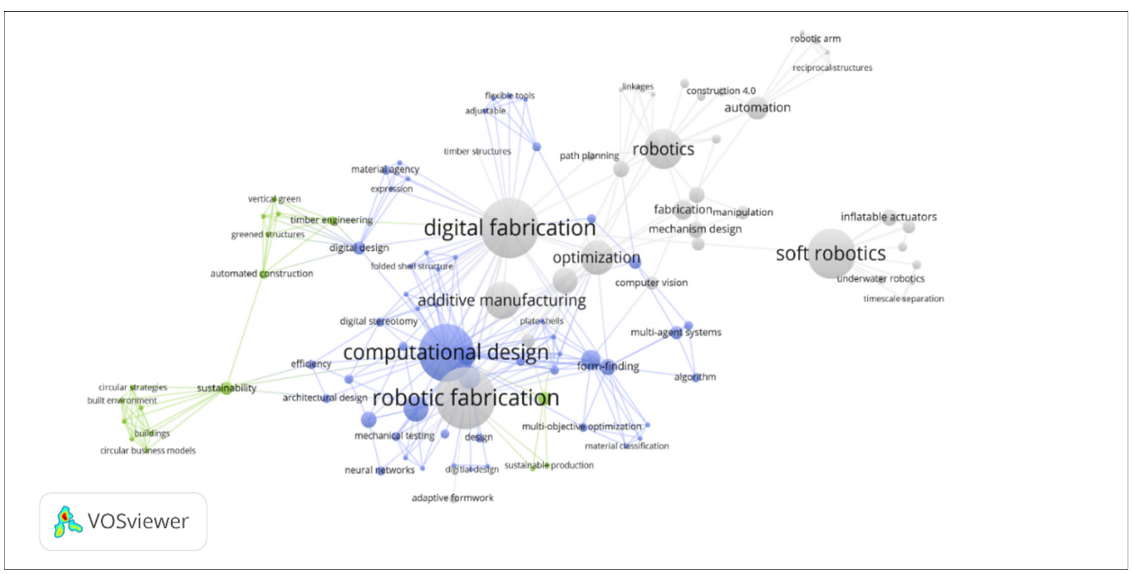


Figure-A V-2 Keywords co-occurrence network of CD-RM technological interoperability within the literature (2018-2022)

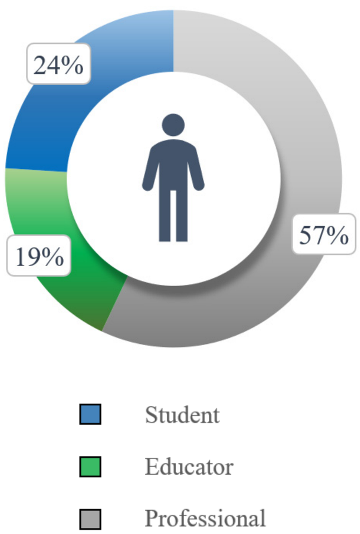
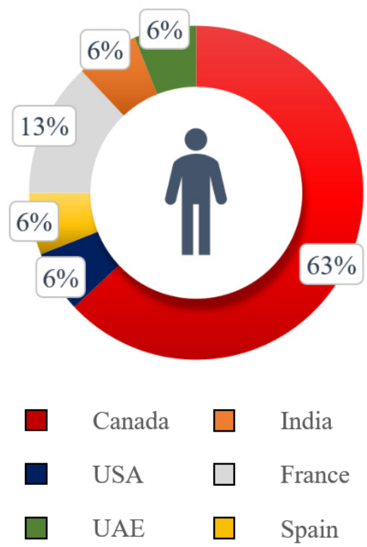
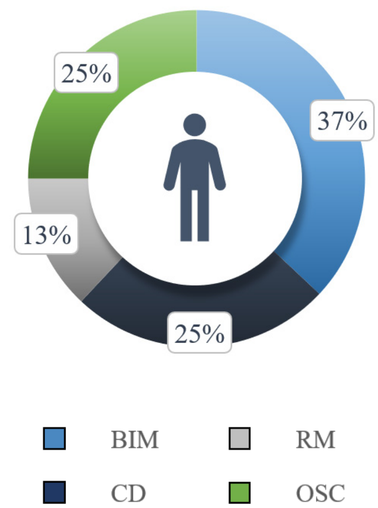
APPENDIX VI

BOARD OF EVALUATORS

Table-A VI-1 Organization and roles of the board of evaluators

Board of evaluators		
Organization		Role
ADVANCED MOTION & CONTROLS LTD. Since 1986	Advanced Motion	Automation Technician
apynov	Apynov	Technical Director
ARUP	Arup	Senior Structural Engineer
CANAM Better Building Solutions	Canam	Project Manager
Carleton University	Carleton University	M. Arch
CoDe_Lab Collaborative Design Laboratory	Code_Lab	Laboratory Director
DIFAB	Difab	CEO
centralelille ÉCOLE CENTRALE DE LILLE	École Centrale de Lille	Chair Holder
Grid Solutions	Grid Solutions	Site Engineer
lemay	Lemay	BIM Designer
NCK	NCK Inc.	BIM Technician
N	New Story	Computational Designer
Public Services and Procurement Canada	Public services and procurement Canada	MEP Technician
	Speckle.Systems	AEC Software Engineer
STENDEL + REICH architecture	Stendel + Reich Architecture Inc.	BIM Director
UQÀM	Université du Québec à Montréal	Educator

Table-A VI-2 Occupation, location, and expertise of the board of evaluators

Board of evaluators		
Occupation	Location	Expertise
		

APPENDIX VII

EVALUATION QUESTIONNAIRE

Table-A VII-1 The 17 survey questions provided to the evaluators

<table>
<tr><th>N.</th><th colspan="2">Introduction
This section covers the evaluator's background information:</th></tr>
<tr><td>01</td><td colspan="2">Full Name</td></tr>
<tr><td>02</td><td colspan="2">E-mail address</td></tr>
<tr><td>03</td><td>What is your current occupation?</td><td>• Student
• Educator
• Professional</td></tr>
<tr><td>04</td><td colspan="2">What is your area of expertise?
How many years of experience do you have in the AEC/Robotics industry?</td></tr>
<tr><td>05</td><td colspan="2">Please identify your level of knowledge in the following approaches</td></tr>
<tr><td>06</td><td>Please rank these different approaches according to your current interest</td><td>• BIM
• Computational Design (CD)
• Robotic Manufacturing (RM)
• Off-Site Construction (OSC)</td></tr>
<tr><td>07</td><td>What is your perspective on the use of robotic manufacturing in off-site construction?</td><td>• This is not a feasible solution
• This is a short-term solution (5-10 years)
• This is a short-term solution (5-10 years)
• This is a very long-term solution (20 years and more)</td></tr>
<tr><th>N.</th><th colspan="2">Evaluation of the framework
This section is reserved for the evaluation of the DtM framework</th></tr>
<tr><td>08</td><td colspan="2">What is your evaluation of the identified research problem, is it realistic? Relevant? Original?</td></tr>
<tr><td>09</td><td colspan="2">Do you evaluate that the framework proposed through this research addresses the technological interoperability of the four stated approaches (BIM, CD, RM, and OSC) globally?</td></tr>
</table>

N.	Evaluation of the framework This section is reserved for the evaluation of the DtM framework	
10	How would you evaluate the usefulness of this framework in relation to the stated problem?	
11	Please elaborate on your evaluation of the usefulness of the framework	
12	On a scale of 0 to 5, how would you rate the following quality criteria of the framework	• Clarity: Is the framework presented easy to understand? • Ease of use: Is the proposed framework simple to use? • Functionality: Does the proposed framework serve its purpose successfully? • Performance: Does the framework perform well? • Reliability: Does the proposed framework work as intended in different contexts? • Consistency: Are the framework's design and processes coherent? • Completeness: Does the framework include all the required systems to address the problem?
13	Please elaborate globally on your evaluation of the quality of the framework	
14	How do you evaluate the effectiveness of this framework?	Effectiveness of a framework: The degree of success in producing the desired result.
15	Please elaborate on your evaluation of the effectiveness of the framework	
16	What are your main criticisms of this framework?	
17	What suggestions do you have for improving this framework?	

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