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Review

Building Information Modeling (BIM) and Robotic Manufacturing Technological Interoperability in Construction – A Cyclic Systematic Literature Review

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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) which 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, building information modeling, robotic manufacturing, computational design, off-site construction

Abbreviations

AAD	Algorithms-aided Design
AEC	Architectural Engineering and Construction
AI	Artificial Intelligence
API	Application Programming Interface
BIM	Building Information Modeling/Model/Management
CAD	Computer-aided Design
CAM	Computer-aided Manufacturing
CD	Computational Design
CIM	Construction Information Modeling
CNC	Computer Numerical Control

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DfMA	Design for Manufacturing and Assembly
DfX	Design for X
ED	Evolutionary Design
GD	Generative Design
HBIM	Historical Building Information Modeling
IFC	International Foundation Class
IoT	Internet of Things
MEP	Mechanical, Electrical and Plumbing
MVD	Model View Definition
OSC	Off-site Construction
PD	Parametric Design
RM	Robotic Manufacturing
SLR	Systematic Literature Review

1. Introduction

The construction industry is experiencing significant challenges due to low productivity and a shortage of skilled labor [1, 2]. Digital transformation offers a promising alternative to overcome these challenges, mainly through digitizing design and manufacturing workflows [3]. This digital shift is the basis of a new revolution in construction known as Construction 4.0 [4, 5]. 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 [6]. 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 [7]. 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 [8, 9]. Indeed, *automation* in construction is defined as implementing industrial automation principles in built environment practices [10-12]. RM is adopting these principles at the manufacturing level, often through industrial robotics. 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 their technological interoperability. Originally, *interoperability* was defined as: "the ability of two or more systems or components to exchange information and use the information exchanged" [13]. 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 et al. [14] as "technological, organizational, procedural, and contextual" interoperability. However, due to the broad scope of each dimension, this study only focuses on BIM-RM technological 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 the 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.

2. The 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, Van Eck and Waltman, and Moher et al. [15-17] 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 [18-20]. 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 [21-23]. The results of this analysis were finally synthesized; they led to identifying research avenues and hypotheses. Figure 1 shows the steps of the cyclic SLR methodology, which the present study used to answer the identified research questions.

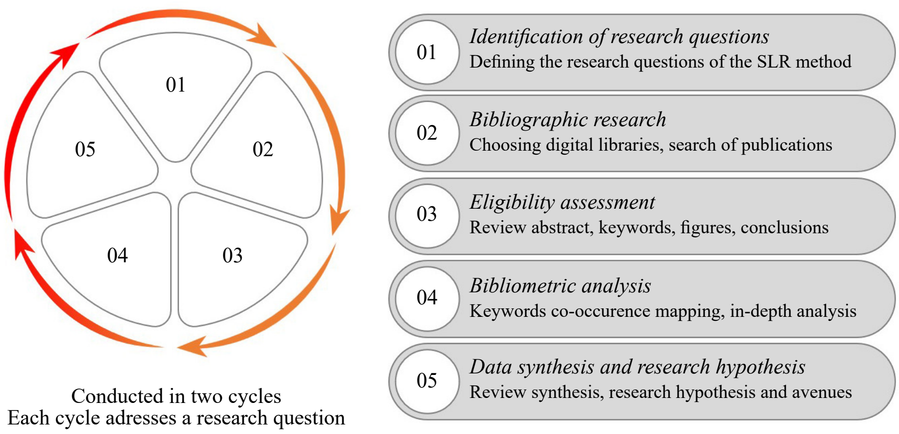

Figure 1. The cyclic SLR methodology

In engineering, the time before scientific publications become outdated is often debated. Depending on the field, this period is either five or three years [24]. 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 A. 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 [25-27]. 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.

3. 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.

3.1 *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 [28, 29]. 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 [30-33]. Indeed, since robots were introduced to production lines, RM has improved productivity and relieved workers of significant workloads [34]. Robotic equipment plays a central role in this perspective; their success in this context has given rise to the concept of *industrial robots*.

According to ISO 8373:2021 [35], ‘‘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 three-dimensional (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 [11, 36]. 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 Table B.1 (Appendix B).

3.2 *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, these publications are often limited to the prospect of coupling BIM and RM in the construction industry; they fail to address real-world case studies. 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. Nevertheless, despite the lack of research on the BIM-RM dyad, the bibliometric mapping performed in this study allowed us to assume that there is a potential common ground for these systems in the construction industry. This opportunity is noticeable through the BIM-RM technological interoperability keyword network, illustrated in Figure 2.

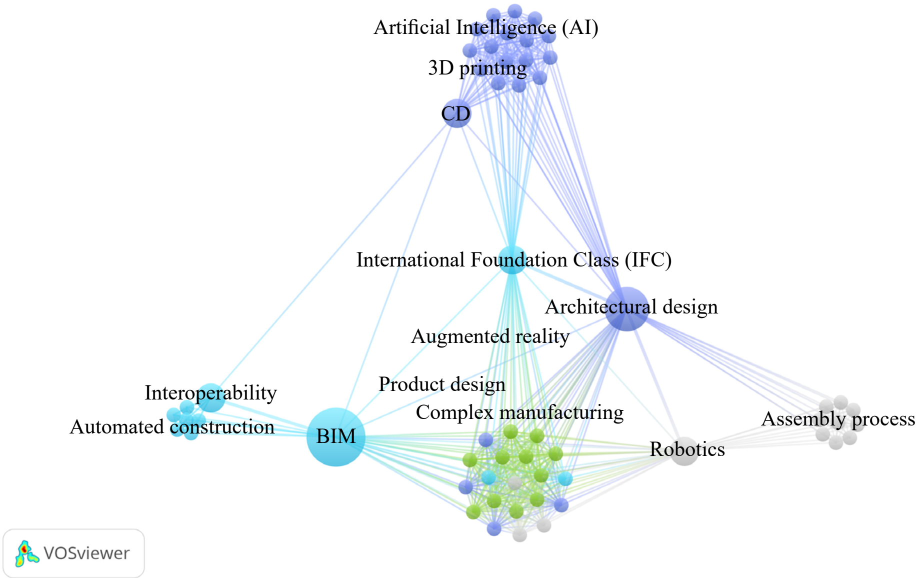

Figure 2. Keywords co-occurrence network of BIM-RM technological interoperability within the literature (2018-2022)

The bibliometric mapping presented shows that BIM-RM data exchange can follow three paths: either through a transfer of file formats (e.g., IFC), CD, or both. Therefore, the different approaches combining BIM and RM were classified according to Janssen [37], 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 the exchange of file formats. This alternative is named a *moderately coupled approach*. The three approaches are discussed in the following sections.

3.2.1 *The loosely coupled approach*

The *loosely coupled approach* illustrated in Figure 3 is the most commonly used approach for bridging BIM and RM [38, 39]. 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 Standard Triangle Language (STL), Standard for the Exchange of Product (STEP), or Object (obj). This disparity in data communication tools leads to data structure conflicts between proprietary software. Therefore, researchers tend to develop new extensions or use external converters to circumvent this problem [40]. But even with such solutions, exporting data disrupts BIM workflows. RM software

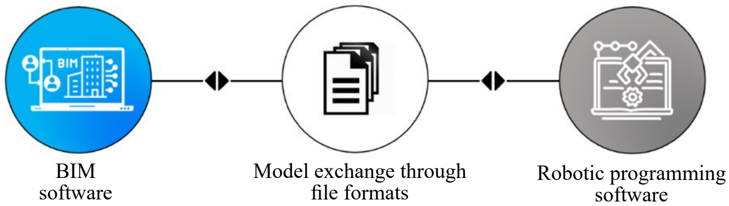

Figure 3. *Loosely coupled approach* for exchanging data between BIM and RM tools

remains disjointed from the design and management processes, reducing the value of using BIM. As a result, the model is often iteratively modified without real-time insight into its manufacturability. These limitations of the *loosely coupled approach* demonstrate that the undertaken research in BIM-RM technological interoperability is ambitious but not yet effective.

3.2.2 *The moderately coupled approach*

The *moderately coupled approach* is a step towards data integration. Researchers use the 3D modeling software APIs to either integrate a BIM workflow or robotic programming. For example, Chong et al. [41] and Momeni et al. [42] initially use an integrated BIM workflow for modeling. Then, this model is redesigned in a simulation environment and specifically programmed for RM through customized codes. Such an approach is tedious and requires significant manual efforts to have basic 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. However, the disjunction between BIM and RM environments is still prevalent. This approach is illustrated in Figure 4.

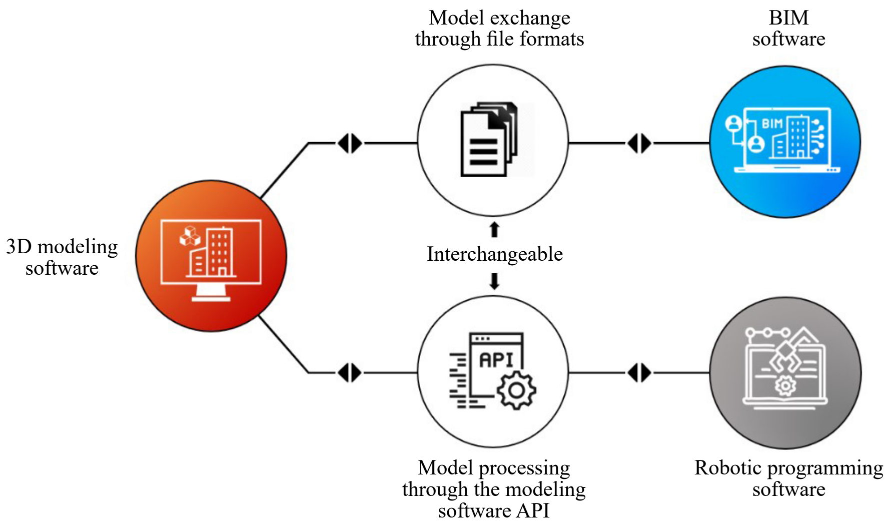

Figure 4. *Moderately coupled approach* for exchanging data between BIM and RM tools

3.2.3 *The tightly coupled approach*

Illustrated in Figure 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 provides reciprocal access to the different functions of the coupled software. As a result, this approach offers the most consistent BIM-RM technological interoperability compared to previous approaches.

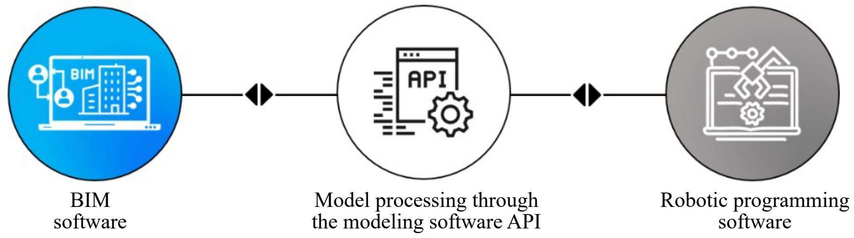

Figure 5. *Tightly coupled approach* for exchanging data between BIM and RM tools

In the case of a BIM-RM technological integration, the informed model is no longer transferred but processed for manufacturing in the same BIM environment. Unlike export and import, this method preserves the native characteristics of the models, overcomes data structure incompatibilities, and enables a feedback loop between the BIM-RM dyad. Therefore, this technological integration provides significant resource savings as the information is native and the workflows are centralized. However, the *tightly coupled approach* is the least used in the current literature on BIM-RM interoperability. Nevertheless, two publications have applied this approach [43, 44], both of which used CD tools.

This bibliometric review highlighted the lack of literature on BIM-RM interoperability 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: 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 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.

3.3 *CD taxonomy*

Understanding CD taxonomy is typically related to comprehending how it differs from computer-aided design (CAD) [45]. Indeed, CD is based on programming and CAD on ad hoc functions. A conceivable analogy between design and web development would be that CD uses back-end development for design, and CAD uses the front-end. Therefore, CD systems are generally associated with the nature of the information flow through a design program. Examples of CD systems are parametric design (PD), generative design (GD), evolutionary design (ED), and algorithms-aided design (AAD) [46]. Notably, these systems are accessible via CAD, but from the end-user perspective.

To further clarify the CD taxonomy, Figure 6 presents a color-coded illustration that depicts its different systems. 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, and the other algorithms [47, 48]. Second, AAD (in yellow) and ED (in orange) are presented together as subsystems of GD but not of PD [49, 50]. Indeed, ED uses algorithms to create various iterations collected from different genomes to satisfy one or more specific fitness criteria [51, 52]. However, ED does not necessarily keep a correlation between the output obtained and the input conditions and rules. This option, on the other hand, is available through AAD [46]. Therefore, ED is not necessarily associated with AAD.

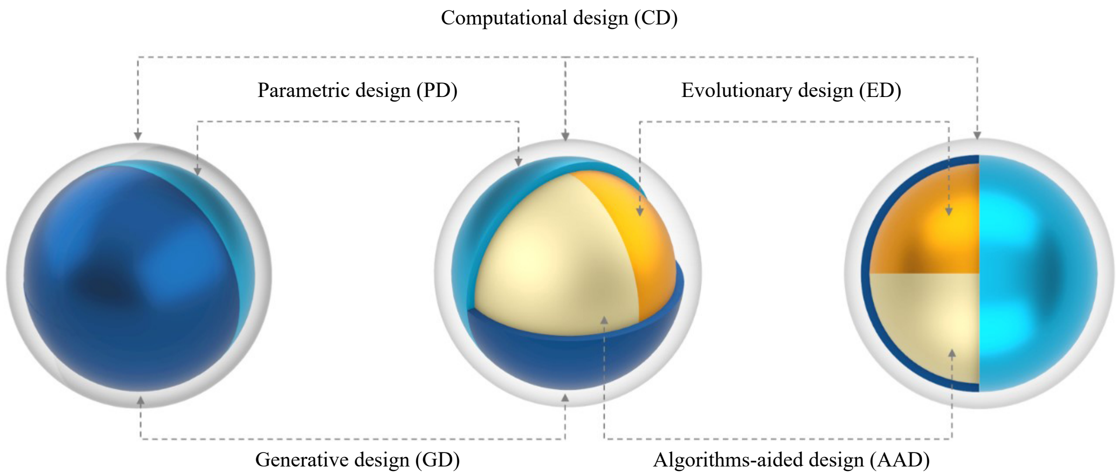

Figure 6. CD taxonomy

All these systems are interconnected, meaning they can support each other. However, the subsystems only depend on what embodies them. Therefore, Figure 6 shows that CD is the basis of all the mentioned design subsystems. PD is a potential driver for GD, AAD, and ED, 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.

3.4 *CD for technologically bridging BIM-RM dyad*

From a technological perspective, BIM and RM are based on computation. Therefore, bridging these two systems through CD is possible by transposing their interoperability to the design context. 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 2. It was synthesized by emphasizing indexed keywords related to the *tightly coupled approach*. As a result, the new keyword network visualization is presented in Figure 7.

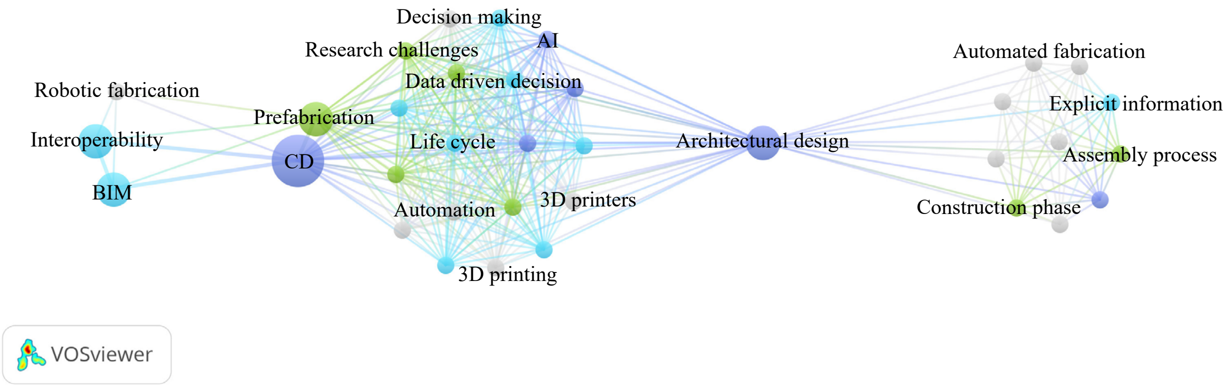

Figure 7. Refined keywords co-occurrence network of BIM-RM technological interoperability within the literature (2018-2022)

This bibliometric mapping provided a clear illustration of the BIM-CD-RM triad. It gave an overview of the main concepts related to this triad and enabled an in-depth analysis of the BIM-CD and CD-RM technological interoperability. 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 Figure C.1 (Appendix C); it revealed 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 [53-55]. 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 [56-58]. 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 [59-61]. 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 enables other digital processes such as reality visualizations, AI, and more [62, 63]. In short, BIM-CD 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 Figure C.2 (Appendix C); 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 [64]. 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 [65-67]. 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 [68-70]. 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 [71-73]. A sample of CD-RM technological interoperability results is shown in Figure 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 Kohler research and ICD/ITKE/IntCDC [74, 75].

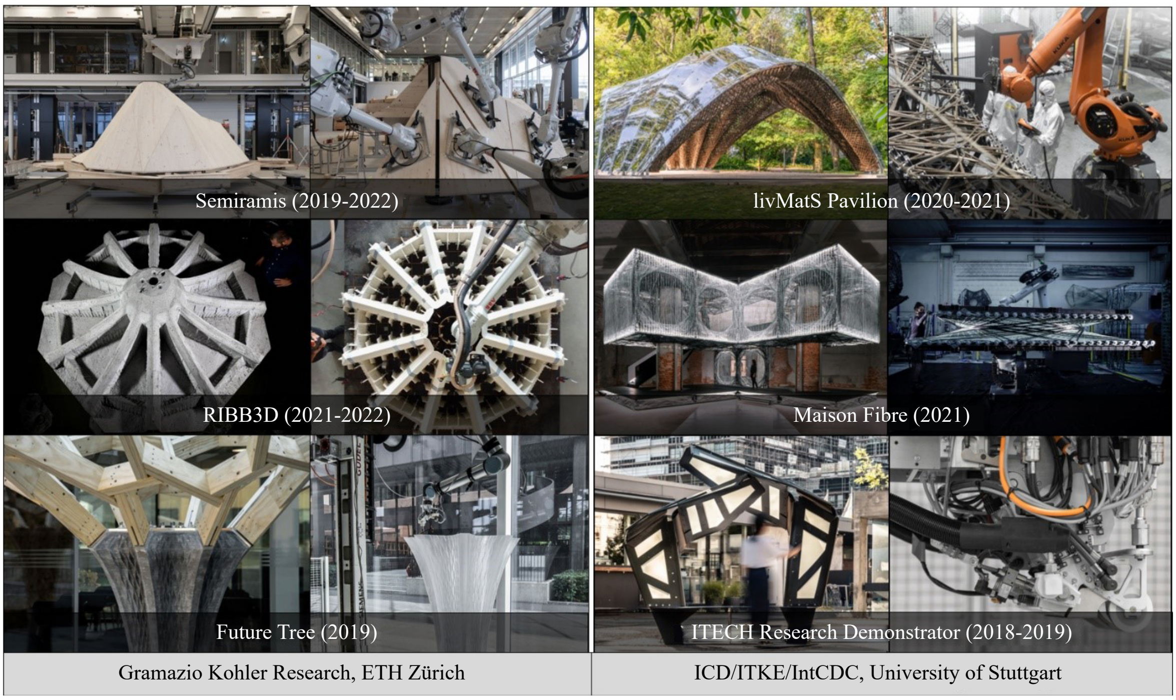

Figure 8. Projects involving CD-RM technological interoperability realized by Gramazio Kohler Research, ETH Zürich and ICD/ITKE/IntCDC, University of Stuttgart [74, 75]

These research outcomes illustrate the materialization of multi-manufacturing processes realized by a single workflow and 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 the drive of 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.

3.5 *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 illustrated in Figure 9: *CD is a medium for BIM-RM technological interoperability*.

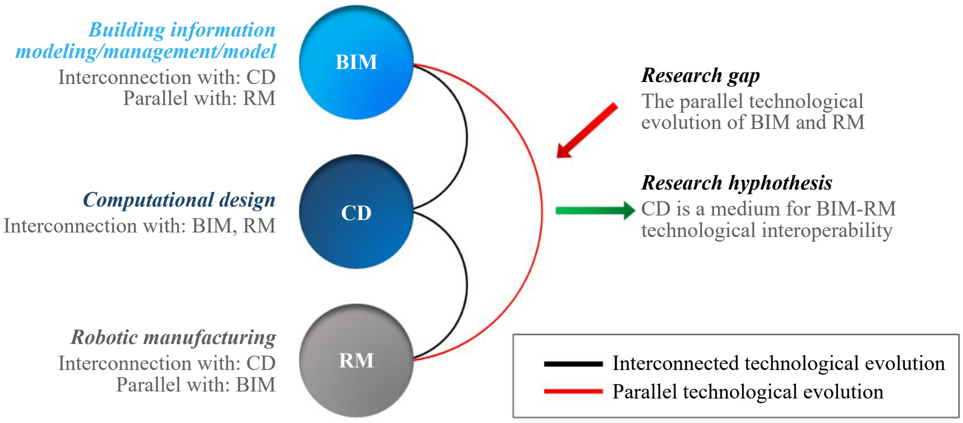

Figure 9. BIM-RM technological interoperability - research gap and research hypothesis

In the SLR context, this research hypothesis contributed to answering the first research question (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 AI services (e.g., machine learning and 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 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 and 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.

4. OSC as a construction system: Second SLR cycle

OSC is commonly defined according to two subsystems: *prefabrication and modular construction* [76]. *Prefabrication* can be used for structural elements, panelized constructions, and building or infrastructure components [77, 78], whereas *modular construction*, refers to volumetric modules, pre-finished units, or functional pods [79, 80]. 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.

4.1 *BIM-OSC technological interoperability (2018-2022)*

BIM and OSC are increasingly being implemented in industry and research, either separately or in combination [81, 82]. Indeed, research efforts are extensive in addressing these two systems since they closely reflect the digital shift's potential for enhancing construction productivity [83, 84]. Moreover, these systems are acknowledged as being critical drivers for construction industrialization [85-87]; 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 10 shows the co-occurrence keywords network generated from the collected publications.

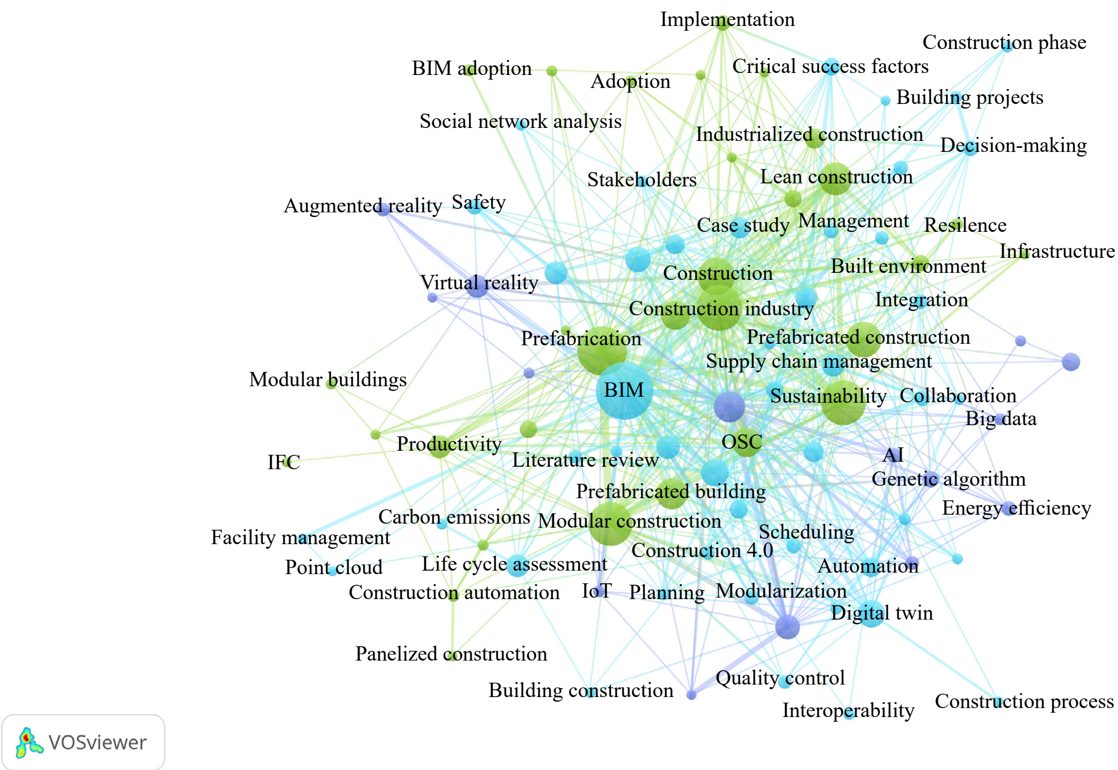

Figure 10. Keywords co-occurrence network of BIM-OSC technological interoperability within the literature (2018-2022)

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) [88, 89], especially in Design for Manufacturing and Assembly (DfMA) [90-92]. 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 [93] and the internet of things (IoT) [94, 95]. Finally, this dyad often aims to ensure sustainability by using lean processes to construct prefabricated or modular components [96-98].

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. [99], who proposed RM for OSC as a research direction. It is also reflected by the research of Yuan et al. [56], 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.

4.2 *BIM-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 11.

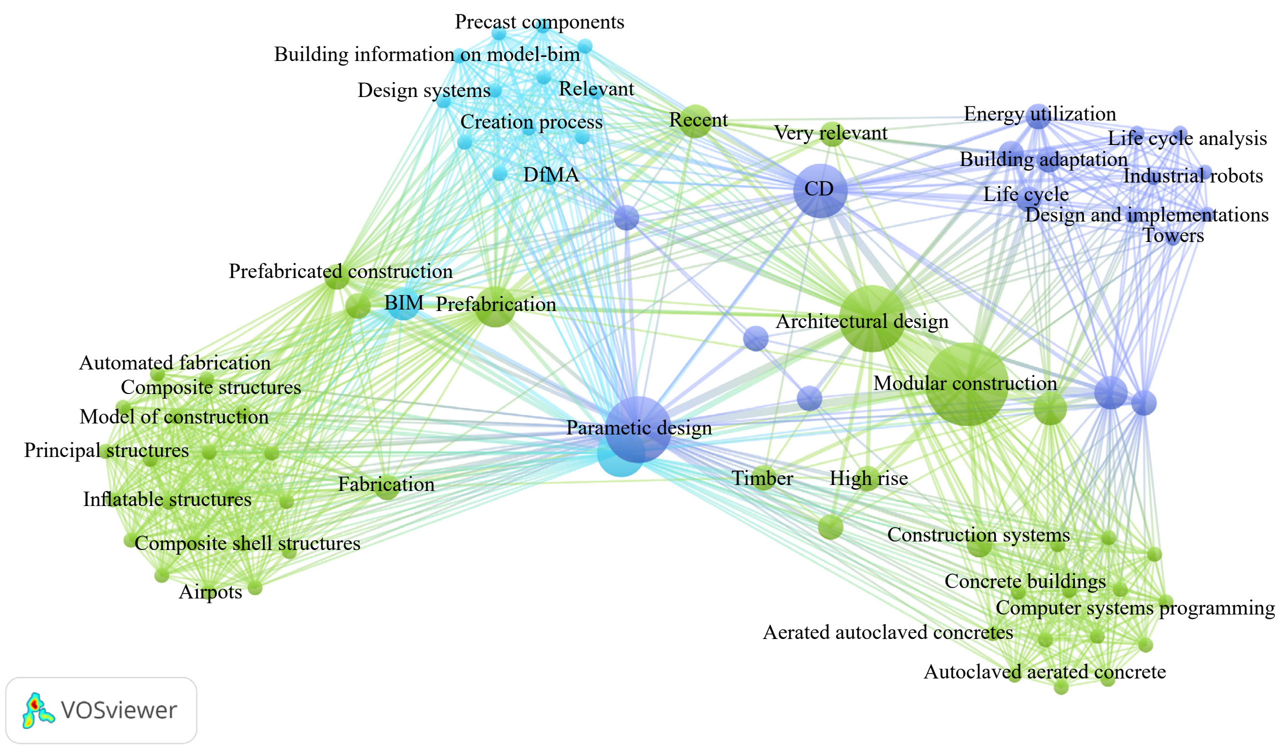

Figure 11. Keywords co-occurrence network of CD-OSC technological interoperability within the literature (2018-2022)

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 [100, 101]. In addition, OSC involves specific construction techniques that require high-level detailing, especially for manufacturing and assembly [102, 103]. 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 at the Bartlett School of Architecture, University College London (UCL).

Through the research of Carpo [104], Retsin [105], and Claypool [106], CD is performed in OSC design through discrete architecture. "Discreteness" in architecture refers to building components that are singular and distinct [107]. 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 [108, 109]. 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 [110]. Figure 12 illustrates some results of using discrete architecture in prefabrication [111].

Figure 12. Examples of projects involving CD-OSC technological interoperability through discrete architecture [112]

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 mechanical, electrical and plumbing (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 12, discrete architecture also linked CD to RM, giving rise to discrete automation terminology [112]. 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.

4.3 *RM-OSC technological interoperability (2018-2022)*

In the industrialized context, the architectural engineering and construction (AEC) industry is on an avid quest for a faster production process with ever-increasing shape complexity [113, 114]. 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 [115]. 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 13.

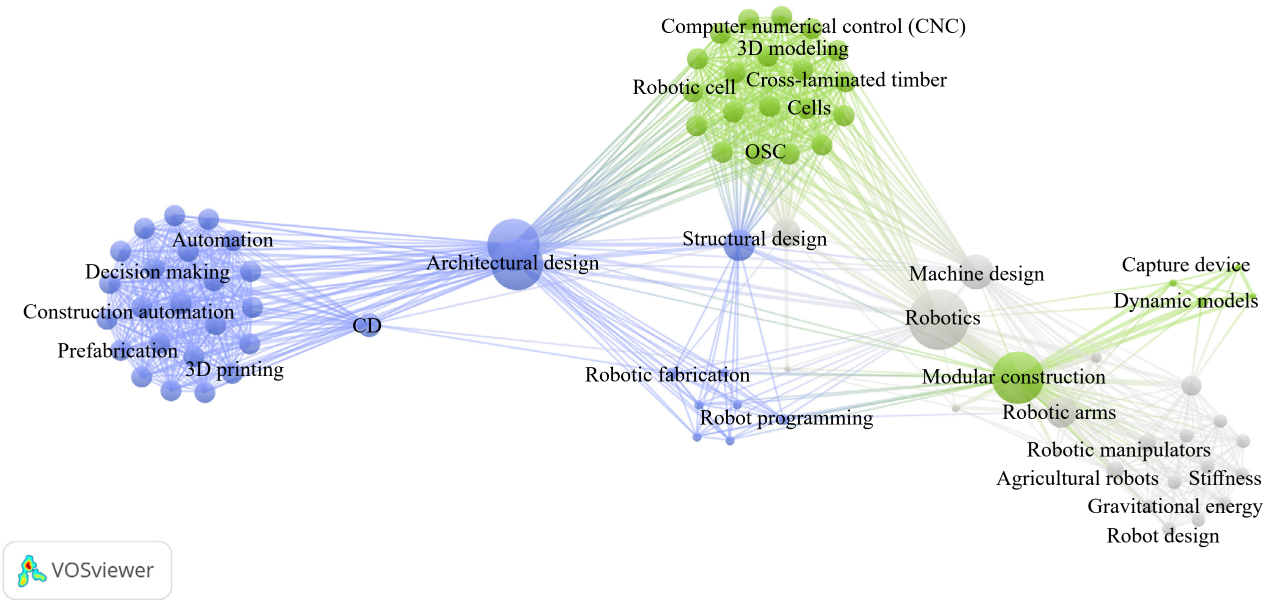

Figure 13. Keywords co-occurrence network of RM-OSC technological interoperability within the literature (2018-2022)

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 [116]. Moreover, RM is a system that implies drastic changes in prefabrication processes [117], which further limits its adoption in the industry. These limitations provide insight into the lack of investigation of BIM. BIM can be overlooked for occasional prototypes such as columns, walls, pavilions, or others. 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 review) 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 [118-120]. Snapshots of these projects and their manufacturing processes are illustrated in Figure 14 [75].

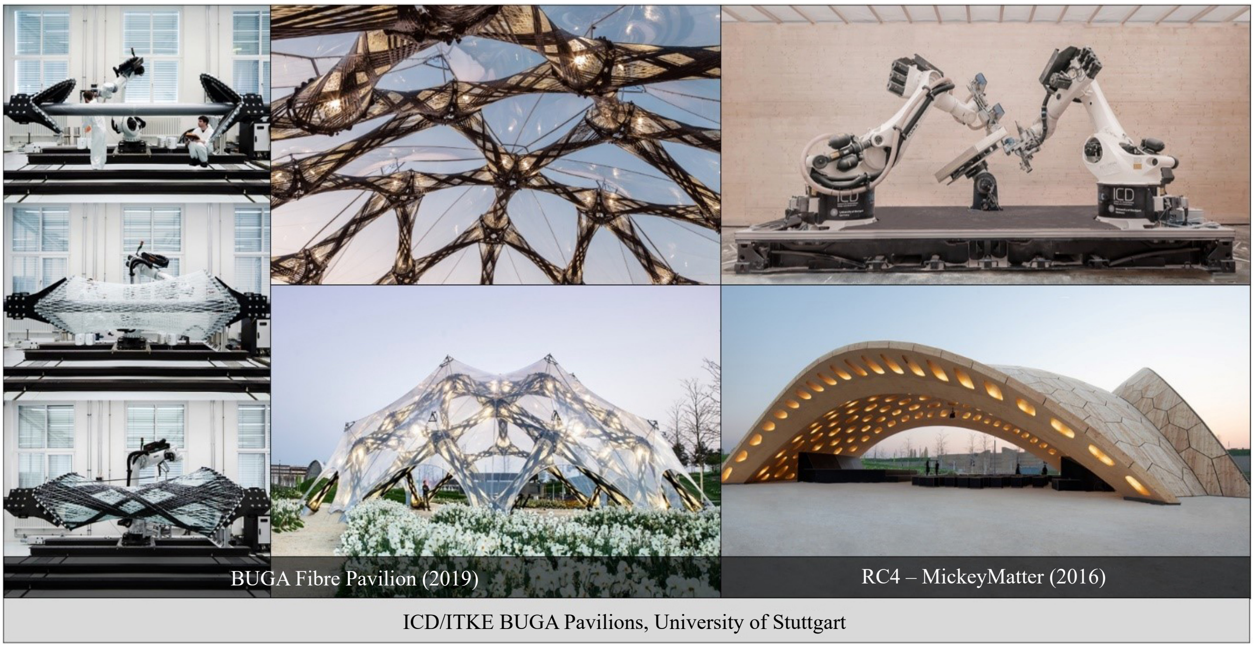

Figure 14. Examples of projects involving RM-OSC technological interoperability: ICD/ITKE BUGA Pavilions [76]

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 [121] and Maison Fibre [122]). 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.

4.4 *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 hypothesis is that *BIM is a medium for CD-OSC technological interoperability*. Figure 15 illustrates the research gap and hypothesis identified through the study of the CD-OSC technological dyad.

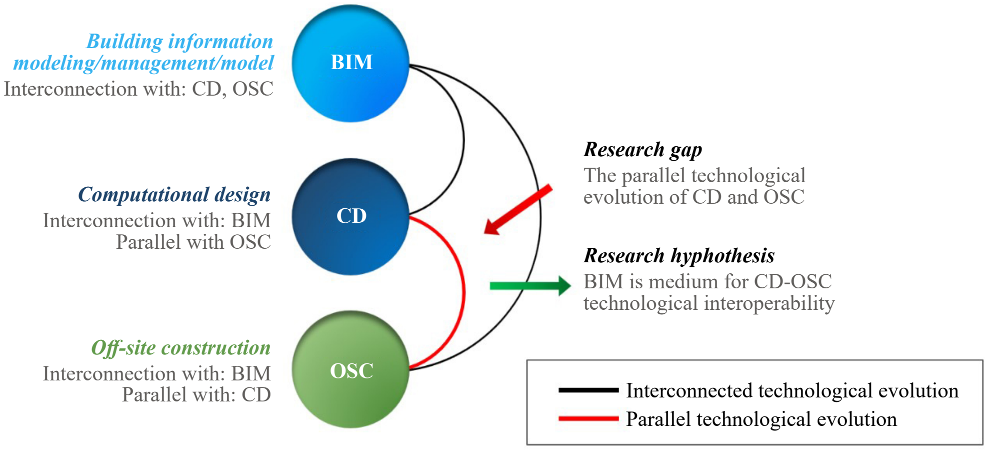

Figure 15. CD-OSC technological interoperability - research gap and hypothesis

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, *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 16.

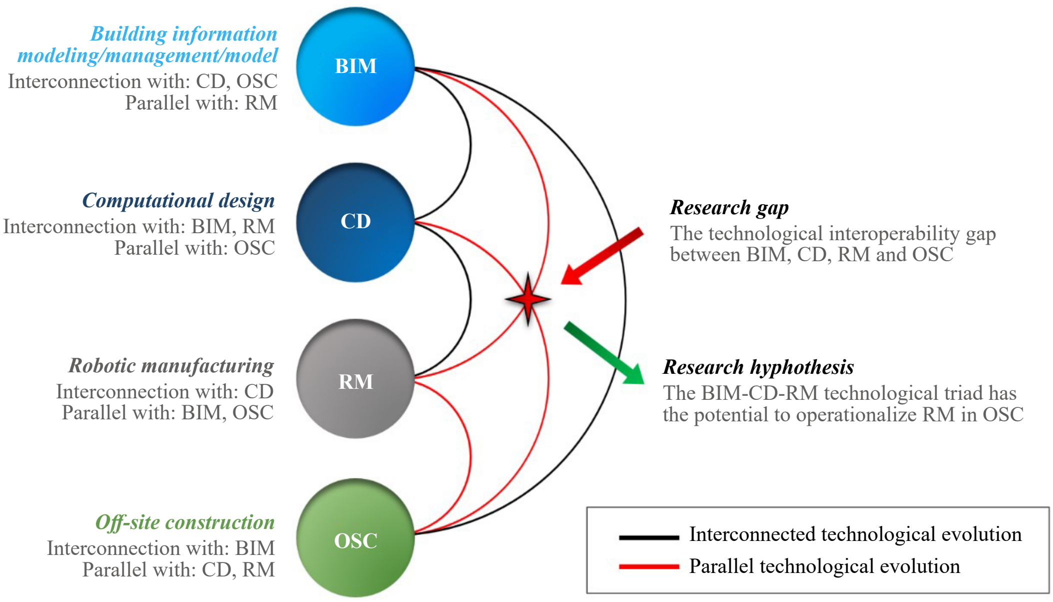

Figure 16. RM-OSC technological interoperability - research gap and hypothesis

With these additional research hypotheses, the second cycle of the SLR addressed the second research question of identifying *the construction system that is currently technologically suitable to put into practice 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 toward the different identified parallelisms.

5. 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 categorization illustrated in Figure 17, which is 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

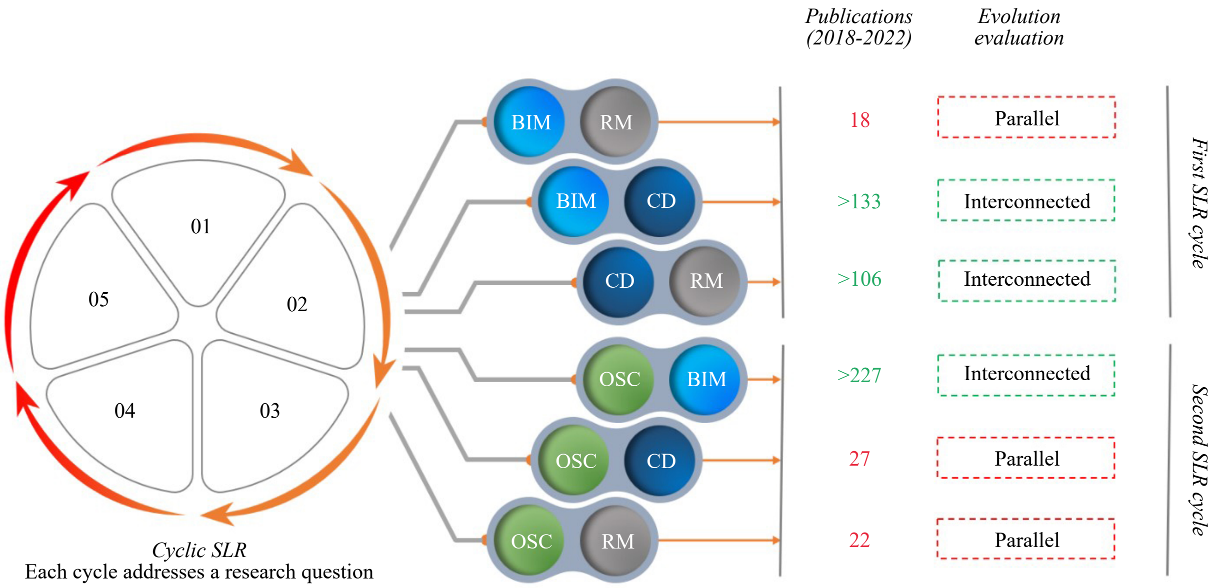

Figure 17. Summary of the cyclic SLR results

The results of the cyclic SLR generated three research hypotheses. These assumptions are intended to address the different research gaps identified and contribute to the specific research objective. The first research question was related to the parallel BIM-RM dyad. This question has been addressed through the first SLR cycle and led to the hypothesis that CD is a medium for BIM-RM technological interoperability. Indeed, in contrast to the recent research prioritizing new software developments for integrating BIM and RM, this review revealed that CD - already deployed in the industry - provides one-to-one integration with both systems. Therefore, this finding suggests that future research is needed to confirm the effectiveness of CD tools in bridging the BIM-RM dyad.

Regarding the second research question, the second SLR cycle has expanded on the first and demonstrated that OSC systems are potentially suitable for BIM-RM integration. Indeed, this study found that BIM and OSC are in an interconnected technological evolution. Based on the previously established interconnection of BIM-CD, this review has identified the second research hypothesis that *BIM is a medium for CD-OSC technological interoperability*.

Furthermore, by involving RM, this study revealed the last research hypothesis 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 then supported by BIM for its use in OSC. As a result, future research could investigate RM implementation in real-world OSC systems by integrating the BIM-CD-RM triad. Such an implementation would uncover the drawbacks of technological integrations (i.e., data overload, integration maturity, complex data management, and steep learning curves).

Through the analysis of these results, it was found that BIM, CD, RM, and OSC are inherently interrelated. Indeed, this analysis provided the answers to the research questions by addressing the identified parallel technological dyads. These findings were enabled by interpolating the Chasles' relations on the different dyads investigated. Thus, this study proposes to bridge the dyads in parallel evolution by those in technological interconnection. Table 1 presents the findings of this study and illustrates the different research questions, the parallel dyads they entail, the proposed solutions, and their associated research hypotheses.

Table 1. Findings of the cyclic SLR

Research questions	Parallel dyads identified	Proposed solution through the interconnected dyads	Research hypotheses raised
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)

The technological evolution of the studied systems varies from one dyad to another. Nevertheless, 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 8, 12, and 14. This digital nature provides the opportunity to integrate other technological innovations related to the Construction 4.0 paradigm. However, more than analyzing the technological interoperability of these four systems is required to drive the industrialization of construction. The interoperability investigation must also cover their organizational, procedural, and contextual dimensions.

These dimensions may overlap in cyber-physical systems and may encounter the same limitations identified in this study. Indeed, even if this review 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 Table A.1 (Appendix A), 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 to integrate the BIM-CD-RM technological triad and use it in OSC systems.

6. 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 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, thus studying the BIM-CD-RM technological triad and its potential to operationalize RM in OSC.

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Conflict of interest

The authors declare that they have no conflict of interest.

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Appendix A. Dyads' search tags used in the cyclic SLR

Table A.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	("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")

Table A.2. Filtering results of the cyclic SLR

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 B. Available literature on BIM-RM technological interoperability

Table B.1. List of references on BIM-RM technological interoperability

No.	Titles	Reference	Year
1	An innovative digital workflow to design, build and manage bamboo structures	[123]	2022
2	Automated fabrication of reinforcement cages using a robotized production cell	[42]	2022
3	BIM-based simulation of construction robotics in the assembly process of wood frames	[41]	2022
4	BIM-based task and motion planning prototype for robotic assembly of COVID-19 hospitalisation units—Flatpack house	[124]	2022
5	Real-time state synchronization between physical construction robots and process-level digital twins	[125]	2022
6	Towards fully BIM-enabled building automation and robotics: A perspective of lifecycle information flow	[126]	2021
7	BIM-enabled computerized design and digital fabrication of industrialized buildings: A case study	[40]	2021
8	Development of communication protocols between BIM elements and 3D concrete printing	[43]	2021
9	Fabrication information modeling: Closing the gap between building information modeling and digital fabrication	[38]	2021
10	Real-time digital twin of on-site robotic construction processes in mixed reality	[127]	2021
11	Robot-based facade spatial assembly optimization	[44]	2021
12	Use of BIM and 3D printing in Mars Habitat design challenge	[128]	2021
13	An integrated review of automation and robotic technologies for structural prefabrication and construction	[129]	2020
14	BIM-based task-level planning for robotic brick assembly through image-based 3D modeling	[130]	2020
15	Collaborative welding system using BIM for robotic reprogramming and spatial augmented Reality	[131]	2019
16	Design of a robotic software package for modular home builder	[132]	2019
17	In-situ construction method for lunar habitation: Chinese Super Mason	[133]	2019
18	Perspectives on a BIM-integrated software platform for robotic construction through Contour Crafting	[39]	2018

Appendix C. Bibliometric visualizations of BIM-CD and CD-RM dyads in VosViewer

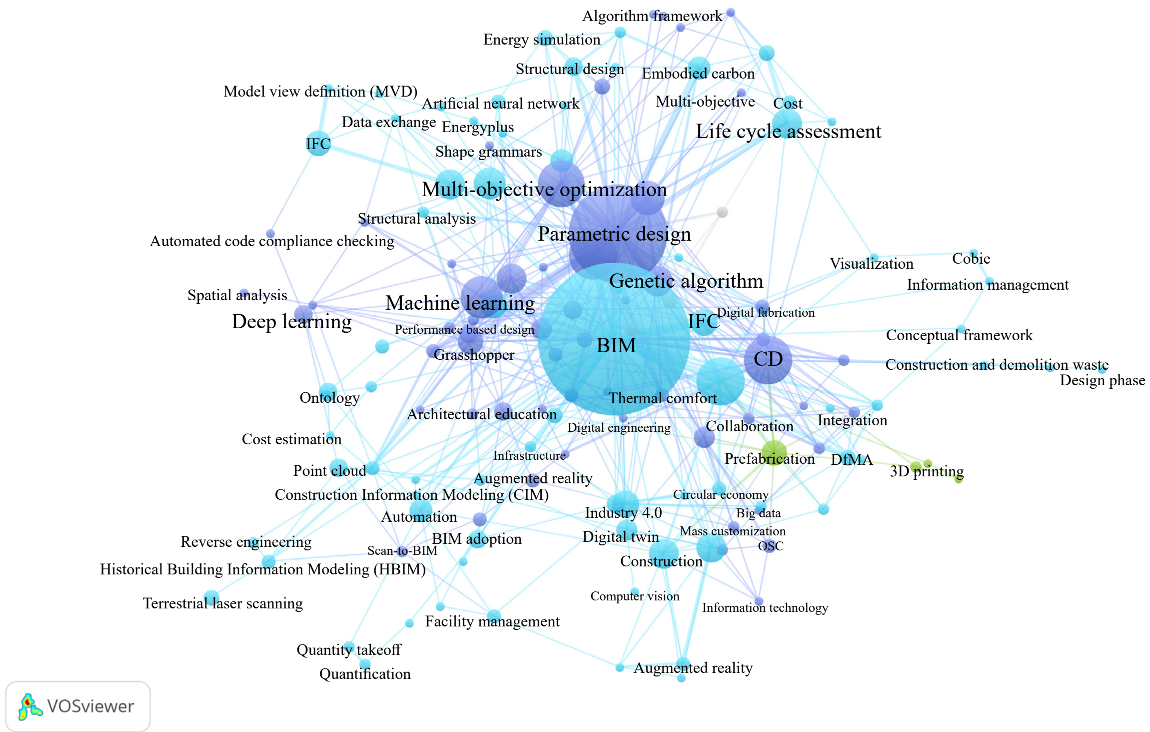

Figure C.1. Keywords co-occurrence network of BIM-CD technological interoperability within the literature (2018-2022)

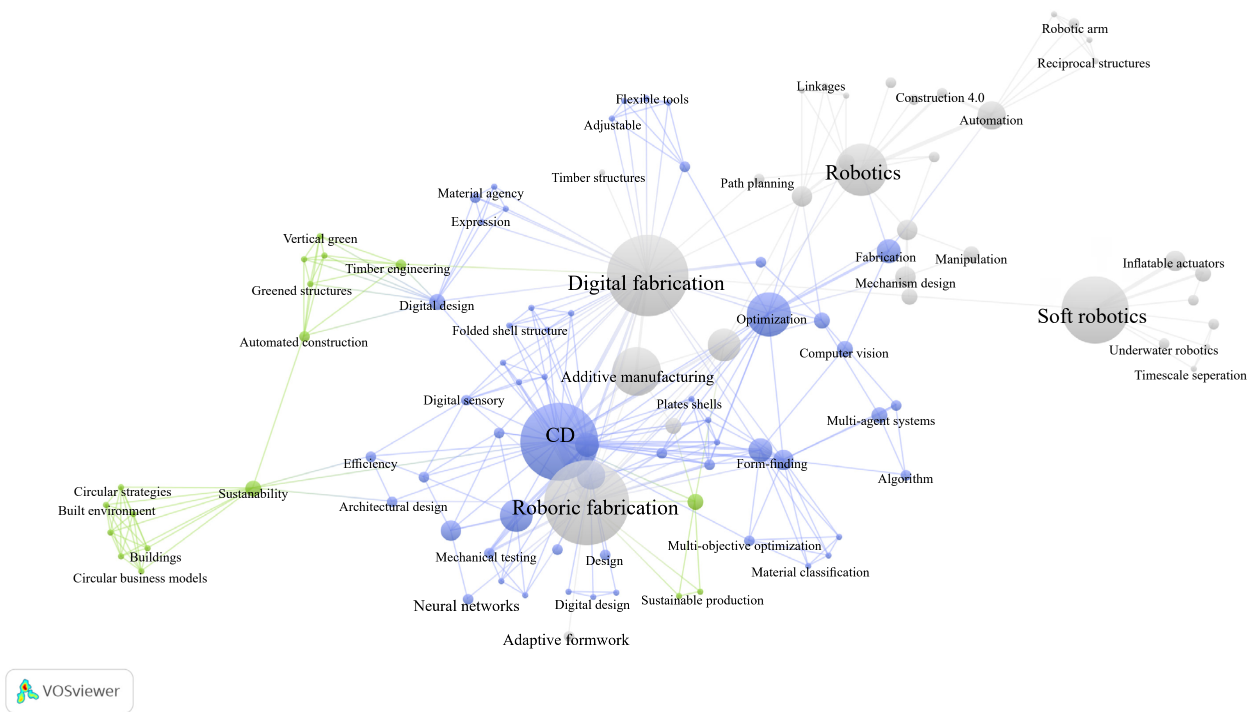

Figure C.2. Keywords co-occurrence network of CD-RM technological interoperability within the literature (2018-2022)