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Review

Review of the Role of Building Information Modelling-Based Constructability in Improving Sustainability in Industrial Plant Construction Projects

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Abstract: The construction industry is well known for its problems in completing projects on time and within budget. While constructability has been promoted as a best practice to address these challenges, a clear gap remains regarding its practical definition and implementation, exacerbated by industry reluctance to share proprietary knowledge. This narrative review investigated the current state of constructability in industrial plant construction projects, synthesizing literature from leading databases and professional sources. The methodology involved a critical qualitative analysis of studies addressing constructability frameworks, critical success factors, and the impact of BIM technologies. The findings revealed that traditional constructability reviews, though valuable, are limited by human expertise and subjectivity. The integration of BIM offers transformative potential by enabling collaborative, comprehensive constructability analysis and facilitating the transfer of tacit to explicit knowledge. This study clarifies the constructability concept and highlights persistent knowledge gaps and it illustrates how BIM-aided constructability can optimize the design and planning of industrial plant projects, ultimately enhancing project sustainability and delivery outcomes.

Keywords: BIM-aided constructability; BIM; constructability; industrial plant construction projects; sustainable construction

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1. Introduction

The construction industry is notorious for facing challenges in delivering projects on time and within budget. Although the underlying causes are frequently complex, issues such as poor planning, inadequate preparation and miscommunication frequently emerge as significant contributors [1]. These problems typically originate in the earliest stages of a project, a phase when the construction itself seems distant, leading stakeholders to underestimate the critical impact of these issues. Unfortunately, this perception could not be further from reality, as these initial stages provide a window of opportunity to modify project inputs with positive effects on the project outcome.

Cost-influence models, a well-known concept in Industrial Plant Construction Projects (IPCPs) management, illustrate how the cost of making changes to a construction project increases exponentially as the project progresses through its lifecycle. According to those models, the earlier changes are made in the project lifecycle, the lesser the impact on the project costs. As a project advances, the impact of the changes increases steadily,

highlighting the importance of thorough planning and design processes in the early stages of the project to minimize costly alterations during later stages of the project.

Failure to pre-plan the work is a common mistake that can lead to various negative consequences, both in terms of efficiency and safety. The most frequent consequences are negative impacts on the safety of activities, loss of efficiency, and adverse impacts on resource management, schedule and cost slippage [2], and sustainability [3].

Although Industrial Plant Construction Projects share most of the common problems of the construction sector (low productivity; health, safety, and environment (HSE) issues; waste generation; fragmented supply chain [4]), they present some unique characteristics [5], like singularity [6], the environment in which the projects are developed [7,8], and their complexity and multidisciplinary nature [9]. Besides complexity, multiple factors affect the productivity of IPCPs. The extent to which these factors affect productivity can vary from project to project.

As consequence of both poor field planning and poor coordination between engineering and construction, projects face a large amount of rework [10]. In the IPCP context, rework refers to the need to redo or correct work that has already been completed due to errors, defects, or changes in project requirements, and as such is considered as an undesirable aspect. In addition to its adverse impact on the safety of the activities [11], rework in construction can have significant financial and schedule implications, as it often involves additional labour, materials, and time. To minimize rework, construction projects should emphasize effective planning, clear communication, rigorous quality control, and adherence to industry standards and best practices. Additionally, ongoing monitoring and problem-solving can help identify and address issues before they escalate into costly rework situations.

Numerous best practices within the construction industry have been proposed to address or mitigate these challenges, like Advance Work Packaging (AWP) [10] and constructability [12]. All of these are linked by an overarching objective: to ensure that a project can be constructed safely, within budget, and on schedule while meeting all functional and performance requirements.

Although there are several available definitions for the term constructability [11], in the scope of this study, constructability in IPCPs is defined as the degree to which the design, procurement and planning of a construction project have been optimized to enhance the ease and efficiency of its on-site implementation and assembly, focussing on the integration of construction knowledge throughout all phases of the project, from design to final delivery.

Despite the abundance of literature on constructability, significant research gaps remain unaddressed. Firstly, while constructability framework and its associated concepts are widely cited, there is a lack of consensus and clarity regarding what constructability truly encompasses in practical terms. The competitive nature of the construction industry may further contribute to this issue, as firms are often hesitant to disclose their proprietary approaches to constructability, viewing them as sources of competitive advantage. This reluctance to share practical knowledge has led to a scarcity of comprehensive studies exploring the real-world implementation of constructability principles and practices. Consequently, a persistent disconnect exists between theoretical frameworks and their practical application. Recent research by Osuizugbo et al. [13] focused on buildability came to similar conclusions, noting that the conditions that allow for effective implementation of buildability remain underexplored. Although there are differences between constructability and buildability [13,14] (while the latter focuses on the ease with which a design can be built, considering aspects such as material selection, simplicity of design and efficiency in execution, constructability encompasses a broader approach, including project planning,

procurement and execution, focusing on the integration of construction knowledge in all phases), the results of the study by Osuizugbo et al. can be extrapolated to the field of constructability.

Secondly, there remains limited understanding regarding the role and potential of emerging digital tools in enhancing constructability. Despite rapid advancements in digital technologies, few studies have systematically examined how these technological innovations can be leveraged to improve constructability processes and outcomes.

Therefore, this paper delved into how BIM-aided constructability can play a pivotal role in guaranteeing that IPCPs are designed and planned to optimize the ease and efficiency of their physical construction. Such optimization not only holds the promise of mitigating common industry issues but also has a positive ripple effect on the sustainability of these projects.

Objectives

Before exploring how new technologies can enhance constructability, is essential to establish a clear understanding of what constructability entails. Without this foundational knowledge, the ability to effectively implement technology would be severely limited. By clearly defining constructability, one can more accurately identify areas where emerging technologies can optimize procedures, increase efficiency, and ultimately lead to improved project results. The developing of such understanding could help to establish links between conventional construction methods and innovative technological approaches, ensuring that any application of technology is both meaningful and in line with the fundamental principles of constructability.

Hence, this work has several objectives. First, to identify constructability practices in the domain of IPCPs, it examined the methodologies, processes, and decision-making frameworks employed to optimize project outcomes, minimize rework, and enhance overall constructability.

Second, this research explored innovative technological approaches and their potential connections to established constructability practices, with a particular emphasis on BIM workflows. Within this objective, special attention was given to identify the critical parameters for BIM-aided constructability, including the key attributes of digital models and the various levels of model maturity required for effective integration.

Third, this study further examined specific BIM-aided processes and tools relevant to constructability, focusing on areas such as BIM coordination, BIM-based planning and sequencing, and the use of augmented and virtual reality, and how these technologies can be applied to enhance and support traditional constructability processes within industrial plant construction projects.

The fourth objective of this work was to understand how IPCP industry practitioners can align their current skill sets and experience in the constructability field with the use of BIM-aided tools and practices, identifying the competencies required for successful digital transformation, and analysing the organizational and individual challenges that may arise during this transition.

Finally, this research aimed to contribute new insights to the body of knowledge on constructability and help bridge the gap between academia and industry practitioners. Table 1 summarizes the research objectives.

This publication is aimed at a diverse audience within the IPCP industry, including academics, researchers, project developers, design and construction professionals, as well as students that would like to start their career in this segment of the construction industry. By addressing the needs of these varied stakeholders, it provides valuable insights that are relevant to all stages of IPCP development. This work seeks to bridge the gap

between practical industry knowledge and theoretical research, fostering a more integrated approach to the design and execution of industrial projects. Ultimately, this publication serves as a comprehensive resource that enhances understanding and collaboration among professionals and scholars alike in the field of industrial construction.

Table 1. Research Objectives Summary Table.

Objective	Description
#1	Identify constructability practices in the domain of industrial plant construction projects (IPCPs)
#2	Identify critical parameters for BIM-aided constructability
#3	Identify innovative technological approaches and their potential links to established constructability practices
#4	Identify how IPCP industry practitioners can align their current skill sets and experience in the constructability field with the use of BIM-aided tools and practices
#5	Identify emerging challenges in the adoption of innovative technologies

2. Methodology

Within the framework of this research, this work is presented as a narrative review, offering a comprehensive overview of the concept of constructability and its application in the construction of industrial plants. The search methodology encompassed several academic and professional databases, including Scopus, Google Scholar, International Group for Lean Construction (IGLC), CII (Construction Industry Institute), COAA (Construction Owners Association of Alberta), among others. The search strategy was designed to identify relevant publications related to constructability, critical success factors in the construction of industrial plants, and emerging technologies applicable to this field.

For this purpose, the literature review was carried out following a five-stage filtering process. The first step of the research was to identify the state of the art and the existing gaps in the application of digital technologies to constructability. For this stage, a systematic review of the literature was carried out in the Scopus database. The search process was designed to ensure the relevance and specificity of the included studies. First, articles were included that used the keyword "*constructability*" in their title, giving a result of 442 articles. No time window was applied; all available literature up to the date of the search was considered.

In a second step, to avoid bias and ensure that the review focused exclusively on constructability of industrial plants and not on peripheral areas, additional exclusion criteria were applied. Thus, all publications that included keyword terms associated with specific materials, structural techniques or applications were eliminated. Among the excluded terms were "*concretes*", "*bridges*", "*structural design*", "*roads and streets*", "*precast*", "*transportation*", adding up to a total of 39 exclusionary keywords. A full list of the excluded keywords is presented in Table 2. The sample result was reduced to 226 publications relevant to the analysis.

In the third phase, a discrimination process was carried out based on the analysis of the content of the article's title, applying the same exclusion criteria previously established. This procedure was implemented with the fundamental objective of avoiding methodological biases and ensuring that the review focused exclusively on constructability, excluding peripheral or tangential areas. The application of this filter allowed the sample to be refined to a total of 205 potentially relevant articles.

Table 2. Excluded keywords.

Theme	Keywords
Materials and Techniques	*"Welding", "Asphalt", "Concretes", "Concrete Construction", "Cast In Place Concrete", "Precast Construction", "Reinforced Concrete", "3D Concrete Printing", "Offshore Technology", "Fiber Reinforced Plastics", "Offshore Oil Well Production"*
Structural Design	*"Trusses", "Structural Systems", "Structural Frames", "Structural Design", "Architectural Design", "Component State", "Bridge", "Bridges", "Architecture", "Mechanical Properties", "Piles"*
Transportation and Infrastructure	*"Transportation", "Highway Engineering", "Infrastructure Project", "Roads and Streets", "Highway Systems", "State Transportation Agencies", "Transportation Projects", "Pipelines", "Compaction", "Drainage", "Combined Sewer Overflows"*
Other	*"Office Buildings", "Tall Buildings", "Cultivation", "Existing", "Fuzzy Sets", "Commerce"*

Subsequently, in the fourth stage of the selection process, an exhaustive analysis of the abstracts of the shortlisted articles was carried out. This detailed examination allowed for a more in-depth assessment of the thematic relevance and methodological relevance of each publication in relation to the established research objectives. As a result of this scrutiny, the sample was limited to 74 articles that constituted the definitive corpus for subsequent systematic analysis.

In the final stage, a thorough and critical analysis of the selected literature was carried out. This process involved the detailed reading of the identified texts, the extraction of key concepts related to constructability, the identification of the most relevant success factors in the construction of industrial plants, and the analysis of innovative technologies with potential for application in this sector. A total of 52 publications were selected in this step.

The inclusion criteria comprised publications directly addressing constructability, critical success factors in industrial plant construction, and emerging technologies in the sector. The exclusion criteria involved works lacking relevant evidence or focusing on non-industrial sectors.

Additionally, to identify articles that established an explicit connection between digital technologies and constructability, an additional filtering process was implemented on the previously selected sample. From the 226 articles identified in the second step, the presence of terms related to digital technologies was specifically analysed, filtering the articles that included the terms "Technology", "BIM" or "Building Information Modelling" in their title, abstract or keywords. The result showed that only 19 articles included in their title, abstract or keywords terms that evidenced a direct link between digital technologies and constructability. This significant finding, i.e., the scarce presence of these terms in the analysed literature, could suggest a field of research with development potential, especially considering that the application of BIM technologies has been demonstrated.

To address this lack of results that relate digital technologies and constructability, it was decided to implement a mixed strategy by maintaining as the main core the systematic analysis of the literature on constructability identified in the initial phase, complementing it with a targeted selection of specific publications based on preliminary findings. This selection was made using criteria of thematic and application relevance, allowing significant publications to be incorporated without compromising the methodological integrity of the study.

The above-mentioned research conducted in the Scopus database was complemented by searches in additional professional databases, included but not limited to the Construction Industry Institute (CII) and Construction Owners Association of Alberta (COAA).

This methodological approach, adapted to the narrative nature of the review, is summarized in the flowchart of Figure 1. This methodological approach allowed for a deep and multifaceted understanding of the topic, providing a solid basis for the development of grounded conclusions and the identification of potential areas for future research in the field of constructability and optimization of industrial plant projects.

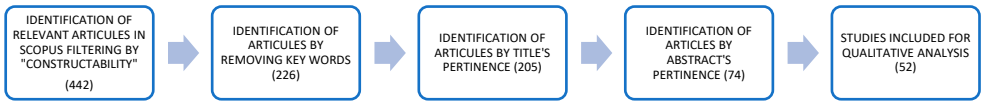


Figure 1. Methodological flow chart.

3. Results and Discussion

In this section, the results of the research are presented, focusing on current constructability practices in IPCPs. In addition, this study explored the potential to improve traditional experience-based reviews through more structured approaches, particularly those that leverage BIM technologies. This review of the available documentation has allowed the identification of current trends, persistent challenges, and emerging opportunities in the field of constructability. Throughout this section, how advanced methodologies, especially those based on BIM, can complement and enhance existing constructability practices is examined. Furthermore, this research examined the critical success factors in implementing enhanced constructability practices, as well as potential barriers that may hinder their widespread adoption.

3.1. Constructability Practices

As previously indicated in the introductory section, in the scope of this study, constructability in IPCPs is defined as the degree to which the design, procurement and planning of a construction project have been optimized to enhance the ease and efficiency of its on-site implementation and assembly. This concept focuses on how well the project has been conceived to facilitate smooth, practical, and cost-effective construction and installation processes. Birgonul et al. [15] identified causes of changes in construction projects, including poor constructability in design and the use of outdated or unsuitable construction methods, techniques, and technologies. While these changes might be unavoidable [16], many of these issues can be fully addressed or at least reduced by applying constructability principles.

An additional critical component in the application of constructability principles is the integration of personnel possessing specialized knowledge and extensive experience into design teams. The expertise and practical insights gained from hands-on involvement in IPCPs are fundamental to the effective implementation of constructability concepts. Key aspects of constructability in the context of IPCPs include safety considerations, design integration, feasibility assessment, materials and equipment selection, design to ease construction, and site access and logistics. Constructability includes, as well, the analysis, selection, and optimization of construction methods [17], with the aim of creating safe construction, fostering an enhanced sustainability of construction activities [18], while reducing the costs and construction execution schedule, achieving a balance between engineering and construction costs, and considering local conditions and the availability of resources.

At its very core, constructability processes are risk mitigation tools that ideally commence at the preliminary stages of the project [17] and continue throughout the engineering phase to assess that what is designed is constructible, identifying during the process potential risks that may arise during the construction phase. However, constructability implementation extends beyond the initial design phase, encompassing the entire project lifecycle through subsequent construction and operational commissioning phases.

To obtain the best results, constructability should be included at the very core of all the stakeholders' practices [19,20]. Wong et al. [21] noted that the implementation of constructability programs at different project stages as one of the three common measures to improve constructability. Those constructability programs can be implemented both at the corporate and project level; however the implementation of constructability through corporate-wide programs is strongly recommended. This emphasis on corporate programs underscores the importance of a systematic and organization-wide commitment to constructability. Both methodological approaches demonstrate validity and exhibit complementary characteristics; however, empirical evidence suggests that constructability programs implemented at the organizational level confer significant advantages over those confined to individual project applications [19,22,23]. This superiority derives primarily from the institutional frameworks embedded within corporate-level initiatives, which systematically facilitate the allocation of requisite resources, establish standardized protocols, and ensure comprehensive infrastructural support essential for the efficacious implementation of constructability methodologies. This organizational approach enables more consistent application of constructability principles through formalized knowledge management systems and integrated procedural frameworks that transcend the limitations inherent in project-specific implementations.

Constructability programs can be implemented in varying degrees of formality, ranging from the non-existence of constructability programs within the company or project to the existence of comprehensive constructability programs. The CII distinguishes five degrees in the application of constructability programs. The level of effort, and the resources needed for each degree of constructability implementation, naturally increase as the formality of constructability increases. When selecting the grade that best suits a given company or project, it should be considered that more formal approaches to constructability usually produce greater benefits than informal approaches.

The implementation of constructability programs, specifically when they are considered as a process of continuous improvement, align with the principles of "LEAN Construction". Informal constructability approaches, usually indistinguishable from other construction management activities, may include design reviews and construction coordinators. Formal programs, which typically have a documented corporate philosophy and budgeted resources, may involve following up on lessons learned from previous projects, team-building exercises, and construction personnel involved in project planning.

3.2. Constructability Reviews

Constructability reviews are one of the most common tools used in constructability [21], and are typically conducted during the project life cycle following a more or less structured process [19]. Wong et al. [21] identified that the implementation of constructability reviews, together with constructability programs and quantified assessment of designs, are the most three common measures to improve constructability. In general, revisions made during the early stages of design have greater potential to bring significant benefits in terms of constructability, while their impact on the time and cost of project deliverables are minimal. However, when conducting constructability reviews at an early stage, there is a risk that the designs lack too much detail that prevent constructability issues from being

addressed appropriately. On the other hand, performing constructability reviews when the design phase is well advanced can cause problems, as the required changes can have a major impact on projects that have already invested a significant amount of time and money [23]. Although the process of constructability reviews can be significantly influenced by both the specific characteristics of the owner and the particularities of the project itself, therefore affecting the approach, frequency, and depth of the reviews, constructability reviews typically follow a multi-stage approach throughout the project lifecycle [24]. This approach generally recommends constructability assessments in the project initiation phase, followed by revisions at design milestones of 30%, 60% and 90% progress. In addition, it is a common practice in many projects to incorporate a final constructability review in the stages close to the completion of the work.

Along with the design teams, constructability reviews should involve the participation of construction professionals who can provide valuable input and feedback on how to optimize the design for a safe, efficient and cost-effective construction [25]. When the contractual strategy allows, constructability reviews can greatly benefit from the early involvement of the contractors that will later perform the activities on site [19]. Key professionals typically involved in constructability reviews include project managers with extensive site experience, construction managers familiar with construction methods and sequencing, estimators who understand the cost implications of design decisions, safety specialists capable of identifying potential design hazards, and quality control experts who can anticipate issues affecting construction quality [19,22,23,26]. These experienced professionals can provide crucial insights that designers might overlook. They can identify potential clashes between different building systems, suggest alternative construction methods to improve sustainability and save time or money, highlight design elements that may be difficult or dangerous to construct, and recommend material substitutions to improve constructability.

This traditional approach to implementing constructability reviews heavily relies on the experience and capabilities of the participants involved [27]. This methodology, while extremely valuable, presents both strengths and limitations within the context of modern construction project management [28]. The efficacy of this approach is fundamentally tied to the depth and breadth of knowledge possessed by the review participants. Experienced professionals contribute a significant amount of practical knowledge gained through years of direct involvement in construction projects. Their experience enables them to anticipate potential problems, propose innovative solutions, and identify improvement opportunities that might go unnoticed by others. This accumulated expertise is an invaluable resource in planning and executing complex projects.

However, this reliance on individual expertise also introduces an element of subjectivity and potential inconsistency [29]. The quality and comprehensiveness of constructability reviews may vary significantly based on the specific composition of the review team. Factors such as the diversity of experiences represented and the recency of participants' field involvement and their familiarity with emerging technologies and methodologies can all influence the outcomes of these reviews [28]. Moreover, this traditional approach may inadvertently perpetuate certain biases or outdated practices if not balanced with fresh perspectives and current industry standards. The rapid evolution of construction technologies, materials, and regulatory environments necessitates a continual updating of knowledge, which may not always be reflected in the experiential base of long-standing professionals.

Another consideration is the potential for knowledge silos within this system. Since projects are often carried out far from the company's headquarters, it becomes necessary to deploy large, multidisciplinary teams capable of adapting to unique site conditions—even when the design remains consistent [30]. This project-based organization further

complicates the capture and transfer of knowledge, as valuable insights and lessons learned may remain confined to individual projects or teams, limiting the broader dissemination of best practices across the organizations [7,27]. This can impede the systematic improvement of constructability practices on a larger scale.

Furthermore, the effectiveness of this approach can be constrained by human cognitive limitations. Even the most experienced professionals may struggle to consistently recall and apply all relevant considerations across complex, multifaceted projects. This human factor introduces the risk of oversight or the inconsistent application of constructability principles [28]. Thus, the following subsections examine how BIM-based tools can enhance the execution of constructability processes.

3.3. Critical Parameters for BIM-Aided Constructability Implementation

As seen in the previous part, constructability relays in a collaborative approach among all the project stakeholders to improve the design elements of a given project. The incorporation of construction professionals in the design team aims to bridge the gap between design and construction processes, supported by the incorporation of practical constructability solutions into the project teams. To foster this collaboration, it is essential to establish a supportive and collaborative environment. The ability of technologies such as BIM to generate collaborative environments is well described in academia [31]. As such, BIM technologies have enormous potential to improve the integration between design and construction [32]. The optimization of constructability reviews requires an evolution towards methods less dependent on the individual experience of the participants. In this context, the integration of BIM models emerges as a promising strategy.

However, to fully realize the potential of BIM in this area, it is imperative to address two fundamental aspects. First, it is necessary to establish precise parameters on the informative content that BIM models must incorporate to be effective in constructability assessments. This definition should cover not only the construction elements and their characteristics, but also information relating to construction sequences and other relevant data to assess the constructive feasibility of the project. Ding et al. [29] performed a revision of the existing available model for quantitative constructability evaluations and identified a trend towards their use mostly on building projects. The work of Zhang et al. [33] identified 16 factors affecting constructability, categorizing them into three primary domains: design, construction, and site impacts, and proposed a framework in which each factor is incorporated into the BIM model. Attributes are assigned to each factor, allowing designers to input the values of these attributes while developing their project. Thus, based on the BIM model, and as the design process progresses, spatial checks can be carried out using the parameters linked to each element and thus confirm, for example, the accesses, distances and spaces necessary to carry out certain operations. Through this methodological approach, the analysis of the critical activities of the future work in terms of potential risk or technical complexity is facilitated [34].

Secondly, it is crucial to determine the ideal time in the development of the BIM model to carry out these revisions. As the project progresses in its development, there will be a progressive increase in the volume and quality of information available for analysis and evaluation by the constructability team, which will influence both the scope and depth of constructability reviews. The traditional approach in which constructability reviews are executed at 30%, 60% and 90% of engineering progress may not be sufficient and may need to be revised. In BIM methodology, it is common to find references to levels of development (LODs). As LOD levels increase from 100 to 500, the models become progressively more detailed and accurate representations of the actual elements of the facility being built become available. Fadoul et al. [35] have proposed a constructability

assessment model based on LOD level. However, some authors [36–38] consider that the implementation of LOD in BIM modelling presents significant challenges. These challenges arise mainly when trying to link the accuracy of the design and engineering information, represented in the BIM components, with the different phases of the project and the various disciplines involved. In addition, it has been noted that the application of LOD levels in the industrial sector has limitations, as they are not directly translated or applied to this specific area. To try to mitigate these effects, García [36] proposed a new framework based on what is defined in his work as Model Maturity Index (MMI). In the original framework, seven different levels of maturity of BIM models are proposed. The application of the MMI levels follows a structured approach that incorporates two primary dimensions: discipline and location. García's framework delineates 12 distinct disciplines, offering a comprehensive categorization system: Piping, Equipment, Layout, Structural, Civil, Foundations, Instrumentation, Electrical, Buildings, HVAC, Fire Protection, and Process & Instruments Diagrams (P&IDs). This disciplinary classification serves as the initial layer of analysis, followed by the consideration of location as the second dimension. Project locations can be defined in a variety of ways, but regardless of the methodology used to define the areas, it is strongly recommended that they are aligned with the project's work breakdown structure (WBS). This dual-dimensional approach facilitates a systematic assessment of project elements, enabling a comprehensive evaluation of constructability factors throughout the project lifecycle. Within a single project, multiple disciplines coexist at varying maturity levels, irrespective of the implementation stage. Consequently, progress monitoring and evaluation gain significance when conducted at the level of the modelled discipline and the most granular layer of the WBS. This method has the potential to ensure a clear understanding of project advancement across diverse technical domains and project phases.

In Norway, key Norwegian industry associations and public agencies further developed the MMI Framework [37], adding to the original seven levels proposed by García [36], and that in the frame of this work will be referred to as primary levels, complementing them with a set of intermediate steps that will be referred to in this work as secondary levels. Both primary and secondary levels span the entire project life cycle, covering all the project phases from inception, or the conceptual phase, to the operation phase.

3.4. BIM-Aided Processes and Tools

Having established the essential parameters regarding model requirements and optimal timing for BIM integration in constructability analysis, it is now pertinent to examine the specific methodological processes through which these parameters can be operationalized. The preceding analysis underscores the importance of both content precision and chronological optimization in BIM implementation; these foundational elements constitute the necessary preconditions for effective constructability enhancement. Building upon this theoretical framework facilitates the practical application of constructability principles within digital construction environments.

3.4.1. BIM Coordination

BIM coordination is a systematic process in which interdisciplinary models are compared and analysed in order to identify, manage and eliminate interferences, thus improving the overall quality and efficiency of the project. However, for this type of checks to be effective, it is essential that the model reaches a level of maturity sufficient to detect and resolve potential conflicts accurately [39]. In practice, BIM models developed during the design phase often exhibit discrepancies with actual construction conditions, resulting from as-built deviations. Those as-built deviations can be caused by (i) deviations from the

original design or specifications due to construction errors, or (ii) permissible error ranges in different construction systems based on industrial capacities and common practices. This phenomenon might be partly explained by the fact that the integration of as-built versions of key disciplines, such as civil or structural, may not always be systematically incorporated into the federated model. In such cases, these discrepancies can generate errors that are propagated from one discipline to the next.

BIM coordination verification is typically performed by establishing a set of rules that define the compatibility among the different systems. To ensure fully functional installations—particularly in the context of industrial plants—these rules should not only address design and constructability considerations but also incorporate criteria for operability and maintainability. Within the framework of a research on constructability reasoning in mechanical, electrical and plumbing (MEP) coordination [40], Reza and Staub-French identified and documented the limitations that a coordinated system must satisfy. Their analysis was carried out ensuring that the design, construction and operation criteria were met in an integrated manner, with special emphasis on the collection of detailed knowledge on constructability. The results of this approach improve the quality and efficiency of the project, ensuring that the MEP systems are properly coordinated and work optimally.

Furthermore, when BIM model maturity allows it, BIM coordination processes can be used in addition to resolving conflicts or collisions between interdisciplinary models [41] (which in the MMI framework correspond to the secondary steps in between MMI300 and MMI350), to establish exclusion zones around certain systems or elements, in which other systems or elements cannot coexist. This possibility has great potential in terms of both constructability and maintainability, especially when the team includes experienced personnel with knowledge of the requirements in terms of space to execute certain tasks. In particularly congested areas, where different systems coexist (pipes, equipment, electrical and instrumentation trays, etc.), volumes can be modelled to define the space needed to transport materials, install scaffolding for temporary access, and account for spaces needed to weld pipes or to make electrical or instrumentation connections. This knowledge provided by construction experts, know-how [33] or tacit knowledge [41], through processes such as the one mentioned in the previous paragraphs, has the potential to evolve into a series of rules that can be applied systematically, thus transforming tacit knowledge into explicit knowledge, and thus making the process independent of the knowledge of certain individuals.

3.4.2. BIM for Planning and Sequencing

BIM tools can also be used to develop the planning and sequencing of activities through processes that are often referred as BIM safety, or simply 4D [42]. Explained in a very simple way, these processes connect 3D design elements with execution planning, thus generating sequences that in a visual way allow for checking both the correct planning and sequencing of the activities, as well as whether they generate constructability problems. These types of 4D tools are a very powerful element in terms of constructability, but they need careful planning and the existence of valid 3D models for construction that do not contain the complete systems designed as a whole but are a real representation of the prefabricated elements. Referring back to the MMI framework, the stage on which the designed elements correspond to the ones to be manufactured falls under the MMI400 level. The effects of 4D sequencing in the construction of a refinery, combined with Lean principles, was explored by Nascimento et al. [43], finding that this structured approach improved interdisciplinary coordination and prioritized critical tasks.

Planning activities using 4D techniques, combined with the creation of volumes or exclusion zones, can also be a powerful element of constructability and maintainability

within an industrial plant. A section of an industrial plant, such as a process unit, can be taken as an example. The classic construction sequence normally follows a logical sequence, in which the civil works are executed first, then the mechanical part, followed by the electrical and instrumentation part. When checking the multidisciplinary model of that part of the industrial plant, and that the model includes the relative volumes or exclusion zones, it could be found that certain elements are not compatible. For example, the area necessary to weld two sections of pipe is not compatible with the electrical trays installed in proximity. Now, when including the perspective of time in the model, using 4D techniques, it could be found that at the time on which the pipes are planned to be welded, the trays cannot be installed. In other words, the installation of the electrical trays in that given area will have as a condition for its start that the welds of the two sections of pipe have been completed. Although this is technically possible, and if implemented it would solve many problems of constructability and quality, it is imperative to acknowledge that the level of effort required to perform these verifications is very big, especially in an industrial plant requiring thousands of welds between different sections of pipes. Another important factor to consider is that information regarding prefabricated elements is usually only available at late stages of engineering, corresponding to MMI400, which can add further complications to this process.

3.4.3. Augmented and Virtual Reality

The integration of BIM tools with virtual reality (VR) and augmented reality (AR) also has the potential to significantly improve the ability to identify and solve constructability problems [44]. VR, by immersing constructability team members in a virtual representation of the plant to be built, allows for a more intuitive understanding of spatial relationships and potential conflicts that might not be evident in traditional 2D drawings or even 3D models displayed on screens. This immersive experience makes it possible to detect conflicts, accessibility issues and ergonomic issues in the early stages of the design phase, before construction begins. In this sense, Qasem and Almohassen have developed a VR-based constructability assessment model [45], which not only confirmed the effectiveness of the technology for conflict detection and accessibility, but also demonstrated its usefulness as a communication and decision-making support tool.

On the other hand, AR, by superimposing digital models on the physical construction site, allows real-time comparisons between design and construction conditions [4]. This ability is invaluable in identifying discrepancies, ensuring proper installation, and facilitating quality control. Both VR and AR allow for collaborative problem-solving sessions where team members can visualize and interact with the model simultaneously, thus fostering better communication and decision-making among project members.

Reality capture technologies function as a pivotal resource in industrial plant construction projects and can become valuable instruments in different stages of a project. 3D reality capture has evolved significantly from its origins in traditional surveying, integrating advanced technologies such as LIDAR and photogrammetry to create accurate digital representations of the built environment. In the initial phases of project development, reality capture technology can serve as an important asset in supporting constructability efforts by generating a three-dimensional representation of the project's intended site. For brownfield projects, where new units are added to existing facilities, reality capture is particularly interesting. It provides accurate representations of the current plant status, facilitates early detection of interferences, optimizes connection planning with existing systems, and minimizes operational disruptions. This digital environment proves particularly advantageous as it enables the constructability team to gain comprehensive spatial awareness without necessitating physical site visits, thereby significantly enhancing productivity and effi-

ciency in the planning process. The utilization of such advanced visualization techniques facilitates a more thorough understanding of site-specific challenges and opportunities, potentially leading to improved decision-making and optimized project outcomes.

During the construction phase, the reality capture can be used to control both the progress and the as-constructed status. In terms of constructability, the possibility to record site progress in a form of an updated 3D model can prove to be a worthy tool, as it could allow the verification of the interfaces between systems [46]. In IPCPs, where several systems coexist in cramped spaces, precise positioning of elements is crucial to achieve constructability. To mentioned only a few, concrete wall penetrations, designed to accommodate future pipeline or cable installations, embedded plates intended for welding supports, and equipment connection interfaces, are critical components that require meticulous placement.

Advanced scanning technologies now enable the accurate measurement and digital representation of these elements' positions. These data can then be compared with the original design, facilitating the identification of discrepancies between the as-built condition and the intended design. This comparative analysis serves as a proactive measure, allowing project teams to detect and address potential conflicts early in the construction process. Upon identifying discrepancies, stakeholders can make informed decisions regarding necessary modifications. These adjustments may involve altering the position of the structural elements themselves, revising the routing plans for pipelines or cable ways, or implementing a combination of both strategies. This methodology allows project teams to increase constructability and mitigate risks associated with late-stage modifications, which often incur significant costs and delays. This approach not only enhances construction accuracy but also contributes to improved project efficiency and overall quality assurance in industrial plant development.

3.4.4. BIM-Aided Processes and Tools Summary Table

As a summary of the above subsections, Table 3 presents a correlation between a variety of tools, including those based on BIM, applicable in the different stages of the project. This relationship matrix provides a comprehensive view of how constructability principles can be employed through specific instruments, thus facilitating their effective implementation throughout the project lifecycle. The incorporation of BIM tools in this context underlines the growing importance of digital technologies in optimizing construction processes and improving interdisciplinary collaboration.

Table 3. Constructability concepts and tools across project phases.

Project Phase	Available Tools
Conceptual and Basic Design	Construction knowledge expertise. Lessons learned database Constructability reviews BIM-based tools (reality capture, etc.)
Detail and Construction Design	Construction knowledge expertise. Lessons learned database Constructability reviews BIM-based tools (4D, 5D, AR, VR, reality capture, etc.)
Construction and Start-Up	BIM-based tools (4D, 5D, reality capture, AR, VR, etc.) Lessons learned database
Operation	Lessons learned database

3.5. Aligning Practitioners Experience with BIM-Aided Tools

Constructability, as a best practice, is rooted in the philosophy that addressing construction-related issues early in the project lifecycle can yield substantial benefits during the execution phase of the IPCPs. This concept is complemented by a second crucial paradigm: the imperative to integrate construction expertise into the early stages of the design process. Early integration of constructability analysis is critical for strengthening decision-making in construction projects [47], as it not only improves the design efficiency and quality, but also optimizes the timing, reduces costs, and ensures that facilities meet profitability targets. Enhancing the efficiency of the construction sector through the adoption of sustainable construction practices has the potential to produce favourable outcomes across the triple bottom line—social, environmental, and financial dimensions [48]. Furthermore, sustainability can serve as a valuable tool in project management, enriching the decision-making process [33,49].

Many complex problems in the construction industry stem from a lack of integration between design and construction knowledge and experience [50], directly impacting projects' time, cost, and quality. While experienced construction personnel have long provided input to enhance constructability [23], it is widely accepted that designers play a pivotal role in achieving optimal constructability outcomes [25]. Thus, bridging the gap between design expertise and practical construction knowledge is a key element for improving overall project performance. Liu et al. [51] analysed, in the frame of large engineering–procurement–construction (EPC) hydropower projects, how designer–construction alliances, leveraging their complementary skills, contributes to secure EPC contracts and enhances constructability through integrated expertise.

The implementation of constructability programs has for a long time been considered to have beneficial impacts both on project costs and schedule improvements. Studies comparing similar projects with and without constructability applications revealed cost improvements ranging from 1% to 14% [19,33,52], with comparable schedule improvements [33]. Even with adjustments at the lower end of the range, modest values between 1% and 3% still represent a significant improvement, particularly given the large budgets associated with industrial plant projects. In terms of effectiveness, that is, the cost–benefit ratio of implementing constructability, the studies developed place this relationship at 1 to 10 [19,53].

Constructability analyses are considered a key element to improve project outcomes. The involvement of professionals with construction experience during the design phase, and how this positively impacts safety during construction, was examined by Araújo et al. [11], concluding that their participation leads to more effective health and safety measures on site.

Constructability during the design phase was also identified as a crucial factor [54] to a more efficient design, leading to minimized waste generation throughout the project lifecycle in Waste-to-Energy projects. A reduced number of construction claims, increased employee willingness to exceed contractual obligations, quality, and greater satisfaction among project personnel, are also reported [52]. However, due to the inherent nature of IPCPs, the benefits of constructability applications can only be estimated [53], as each project, even with twin plants, presents a complex endeavour in a challenging environment.

The timing of constructability reviews is a critical element in the project development process [11,55]. The implementation of the constructability reviews must be carefully considered to maximize its effectiveness. If conducted prematurely, when the design is still in its nascent stages, the analysis may lack the necessary depth and relevance. Conversely, if delayed excessively, the required modifications could necessitate a complete redesign, potentially resulting in significant cost escalations and schedule delays. Therefore,

identifying the optimal moment to perform the constructability review is crucial to ensure that it contributes positively to the project's progression without compromising the design integrity or project efficiency.

Despite the different approaches that might be taken for performing constructability reviews, there is an undeniable advantage of performing them throughout the design process. To conduct effective constructability reviews and optimize the associated cost, all participants must share a common understanding of input data maturity. Unfortunately, design teams sometimes report progress in overly optimistic ways, which can mislead other stakeholders. Modern industrial plant design predominantly uses 3D authoring tools, potentially leading to inconsistencies in model maturity calculations. The MMI framework addresses this challenge by providing a comprehensive approach to assess model status accurately [36].

The implementation of constructability concepts and their associated barriers have been extensively studied since the 1990s, with seminal works by O'Connor and Miller [56,57] laying the foundation for subsequent research. These early studies identified and categorized significant inhibitors preventing effective implementation of constructability programs, ranging from general barriers to those specific to owners, designers, constructors, and other stakeholders. Eldin [52] studied constructability success factors, implementation barriers, and lessons learned from both process and human-centric perspectives, suggesting that success factors are more likely to be related to human factors, while implementation barriers are more closely associated with tangible factors such as budget constraints, training deficiencies, and regulatory requirements.

Recent research indicates that the landscape of constructability implementation has remained largely unchanged over the past two decades [55,58]. A notable finding by the Construction Management Committee of the ASCE Division [23] is the lack of uniformity in applying constructability concepts across the industry. Similar conclusions were reached by Jadidoleslami et al. [59], who confirmed that there is still a significant gap between design, construction, and achieving the desired project objectives. This divergence in priorities highlights a significant gap in the integrated approach to project development and execution between these two key stakeholder groups. Such misalignment may have far-reaching implications for project outcomes, potentially leading to inefficiencies, conflicts, and suboptimal resource utilization throughout the project lifecycle. Addressing this disparity could yield substantial benefits in terms of project streamlining, cost-effectiveness, and overall success rates in construction endeavours. Similar conclusions were reached by [34], who highlighted that the disconnect between project design processes and construction processes leads to difficulties in integrating the project's constructability and actual working conditions into the project definition by the designer. Site organization and management are also integral components of effective constructability, complementing the critical role of design analysis.

3.6. Emerging Challenges in the Adoption of Innovative Methodologies

A comprehensive approach to constructability necessitates the reciprocal integration of both design considerations and on-site operational strategies. This presents an opportunity for BIM methodology, as its nature facilitates the inclusion of systems and procedures from the project's inception, playing a strategic role in accelerating the efficiency both in the design and construction phases [60]. Integrating BIM into constructability practices introduces a powerful tool for improving project visualization and coordination. BIM enables stakeholders to create a digital representation of the project, providing a comprehensive view of the construction process before it even begins. This allows for more informed

decision-making, identification of potential clashes or inefficiencies, and streamlining of the construction workflow.

In the context of IPCPs, the application of BIM-aided constructability has the capability to become particularly valuable. These projects often involve complex structures, intricate systems, and a multitude of interconnected components and systems. Ensuring that the design and planning stages are meticulously executed can result in substantial benefits during the physical construction phase.

One key advantage of BIM-aided constructability is its ability to facilitate better communication and collaboration among project stakeholders. The digital representation created through BIM serves as a common platform for designers, contractors, and other involved parties to collaborate seamlessly. This collaborative environment fosters clear communication, reduces the likelihood of misunderstandings, and promotes a unified approach to project execution.

Furthermore, the use of BIM allows for the creation of detailed 3D models that provide an in-depth understanding of the project's spatial requirements. This spatial awareness is crucial in IPCPs, where precise placement of equipment, machinery, and infrastructure elements is paramount.

With BIM, potential clashes or conflicts in the design can be identified and addressed well before construction begins, preventing costly rework and delays. In addition to spatial considerations, BIM-aided constructability has the potential to enhance project cost estimation and budget management.

The detailed digital model could enable more accurate quantity take-offs and cost assessments, providing project members with a reliable basis for budget planning. This proactive cost management contributes to avoiding budget overruns and ensures financial predictability throughout the construction process.

However, the implementation of collaborative approaches in IPCPs necessitates the development of new competencies that diverge from those required in traditional control and coordination methodologies [61]. This shift in approach is particularly evident in the context of BIM implementation, where studies have highlighted the need for substantial training of project participants to effectively leverage BIM's capabilities in planning and schedule management [32,42].

These findings underscore a crucial insight: while technological advancements offer potential benefits, they are not a panacea for IPCP's challenges. The effective implementation of innovative technologies and collaborative approaches in IPCPs is highly dependent on the human factor [52], emphasizing the importance of developing relevant skills and fostering adaptive practices in an ever-evolving sector.

4. Conclusions

4.1. Findings

This study revealed that traditionally, constructability reviews were conducted manually, relying heavily on the experience and expertise of construction professionals. While this approach is, and will remain, valuable and necessary, it is often limited by human factors such as individual knowledge, time constraints, and the inability to visualize complex spatial relationships effectively.

Additionally, this research has identified that the advent of BIM has the potential to fully transform the constructability process, providing both (i) powerful tools that enable a more comprehensive and collaborative approach to constructability analysis, and (ii) transforming tacit knowledge into explicit knowledge, and thus making the process independent of the knowledge of certain individuals.

BIM technologies offer a digital platform where all aspects of a building can be virtually constructed before physical construction begins. One of the key advantages of utilizing BIM methodologies is the ability to build projects twice, first in a digital environment and then in the physical realm. This approach allows for the identification and correction of errors, as well as the elimination of inefficiencies throughout the process.

While technical proficiency is crucial, it is the practical application of knowledge by skilled professionals that ultimately drives success in construction projects. The engineering and construction industry, being fundamentally service-oriented, relies heavily on the expertise and capabilities of its workforce. The strategic selection and development of project teams is a critical management function that significantly influences project outcomes.

Even though team members generally possess adequate skills, the successful implementation of constructability aided by BIM tools demands specialized knowledge and a refined understanding of its principles and concepts. To fully realize the benefits of constructability, organizations must proactively plan for the sourcing and development of experienced construction personnel. This requires not only recruiting individuals with specialized skills but also fostering an environment inclined to the application of constructability practices. Moreover, continuous professional development is essential to ensure that team members can effectively apply these concepts in diverse project contexts.

The careful selection of the project teams, paying particular attention to the balance of skills among its members, coupled with ongoing training and a supportive organizational culture, is paramount for optimizing constructability implementation. By prioritizing human capital development in the context of constructability, the industry can enhance project efficiency, mitigate costs, and improve overall project outcomes.

4.2. Contributions

Throughout this research, it has been shown that the implementation of constructability analysis in construction projects is a highly recommended practice that optimizes the ease and efficiency of their physical construction and ultimately has positive impacts in the sustainability of such projects. However, it is important to note that its execution does not necessarily fall on a single corporate entity. The diversification of the agents involved and the distribution of responsibilities throughout the project lifecycle are intrinsically linked to the selected contractual strategy. This relationship between constructability, project stakeholders, and the contractual model underscores the complexity and dynamic nature of IPCPs. The choice of contractual approach not only defines roles and responsibilities, but also significantly influences how the various stakeholders at different stages of the project apply and benefit from the principles of constructability.

Moreover, in the construction industry, there is a debate about the relationships among developers, designers, and contractors. One school of thought holds that developers and designers should not consider the methods and means that contractors will use in their work. However, there are voices that argue that this separation between those who make decisions and design, and those who carry out construction, may be one of the causes of many problems in the sector. This distinction raises important questions about how construction projects are managed. The idea that greater collaboration between design and execution could help address some of the current shortcomings deserves further investigation. Therefore, it is suggested that this topic be the subject of future research to assess the potential benefits of a more integrated approach in the development of construction projects.

4.3. Recommendations for Further Research

Despite decades of academic research and recommendations in the field of constructability, there appears to be a persistent gap between theoretical knowledge and practical application. This disconnect is further exacerbated by the limited access that key industry professionals, such as designers, project managers, construction professionals and contractors, have to constructability research findings. Consequently, valuable academic insights may not be adequately integrated into construction projects, potentially hindering the industry's overall progress in these critical areas.

This situation underscores the need for improved mechanisms to bridge the gap between academic research and industry practice. It also highlights the importance of developing strategies to encourage the sharing of constructability knowledge within the industry, while still allowing firms to maintain their competitive edge. Future research efforts should focus on exploring and validating factors that enhance constructability in practical settings, with an emphasis on developing methods to effectively translate these findings into industry-wide improvements.

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Abbreviations

The following abbreviations are used in this manuscript:

AR	Augmented Reality
BIM	Building Information Management
CII	Construction Industry Institute
COAA	Construction Owners Association of Alberta
EPC	Engineering, Procurement and Construction
HVAC	Heating, Ventilation, and Air Conditioning.
HSE	Health, Safety, and Environment
IPCP	Industrial Plants Construction Projects
LIDAR	Light Detection and Ranging
LOD	Level of Development
MEP	Mechanical, Electrical and Plumbing
MMI	Model Maturity Index
P&IDs	Process & Instrumentation Diagrams
VR	Virtual Reality
WBS	Work Breakdown Structure

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