

Article

A Conceptual Approach for the Knowledge-Based Computational Design of Prefabricated Façade Panels Using Constructability Features

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Abstract: The use of parametric models in the architecture, engineering, and construction (AEC) industry has made it possible to create complex and creative building designs. However, this design complexity creates major constructability issues, especially in projects that incorporate prefabricated façade panels. Computational design methods can solve some of these issues; however, such methods do not necessarily include the systematic approach to integrating domain knowledge, which results in inefficiencies in the design and construction processes. This paper introduces how constructability knowledge can be incorporated into computational design process using feature-based modeling (FBM). An ethnographic case study of a high-rise building with complex façade design is presented in this paper. The research identifies the critical geometric constraints that affect constructability and introduces a new three-level taxonomy (Micro, Meso, Macro) for classifying these constraints. The suggested taxonomy is then applied to inform developing a conceptual knowledge-based computational design approach that enables incorporating the insights of domain experts into the design process. Moreover, the research provides a range of external examples to validate the proposed taxonomy. The findings demonstrate the potential of FBM to streamline the design and fabrication of prefabricated façade panels, improving constructability without compromising architectural intent. This study provides a structured methodology that can be applied to enhance design efficiency and reduce construction risks in similar projects.



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Keywords: computational design; knowledge-based design; knowledge-based computation; constructability; constructability constraints; constructability features; building information modeling; parametric building modeling; prefabricated façade panels

1. Introduction

In recent years, the architecture, engineering, and construction (AEC) sector has increasingly adopted parametric models—models that dynamically control the geometry and its behavior—and building information models (BIMs)—enhanced parametric models enriched with semantic data—to leverage computational design techniques [1]. These computerized methods have allowed architects to develop extraordinary and unique designs. While this freedom can lead to innovative architectural forms, it also introduces constructability challenges due to the complexity of these designs [2].

While computational design techniques have enabled the creation of complex, unique designs, they have also facilitated the prefabrication of various building components and systems. However, the computerization of prefabrication processes by design teams

presents its own challenges, as most designers often lack detailed construction knowledge [3,4]. Consequently, identifying and addressing constructability issues has become a primary concern in projects featuring highly complex architecture with prefabricated components. In this context, the constructability of prefabricated façade systems is particularly challenging, as it involves both design complexity and the intricacies of prefabrication processes. Moreover, this responsibility is often given to the design team, including architects and computational designers, increasing their accountability to finalize construction details and address constructability issues as early as possible in a project [4].

Addressing constructability issues relies heavily on relevant construction knowledge and experience, according to [5]. Therefore, it is essential for designers to develop effective methods for integrating the necessary constructability knowledge into their workflows, particularly within computational design processes.

As Raviv et al. [6] suggest, most constructability challenges during the design phase arise due to (1) the lack of constructability knowledge; (2) insufficient information; and (3) poor coordination with other disciplines. These issues become particularly crucial in traditional project delivery models, where computational designers often work in silos, bearing primary responsibility for resolving constructability challenges. Even in more collaborative projects, the absence of a systematic approach for receiving and incorporating constructability knowledge into the computational design process often leaves outcomes dependent on the personal interpretation and understanding of individual designers. To address this issue, some efforts have been made to introduce methods ensuring that necessary experts' knowledge is considered during the design process. For instance, refs. [7,8] propose methods for establishing checklists for constructability criteria to enhance the quality of the computerized design process using BIM, while [9,10] focus on general constructability considerations incorporated into the design for manufacturing and assembly (DfMA) process. However, as noted by [11], the existing research still lacks methods that integrate constructability knowledge as a driving factor in the computerized design process. Therefore, it is essential to explore methods for systematically integrating experts' knowledge into the computational design process. For this purpose, the feature-based modeling (FBM) approach has shown the potential to be a viable tool for integrating the necessary knowledge into the computational design processes [12]. However, despite the great potential of FBM approaches to convey expert knowledge into the design process and its proven success in other engineering fields, only a few AEC studies have detailed how to develop such features and implement them in models computationally [12–17]. Furthermore, a systematically structured method for formalizing and developing design constructability constraints and features for prefabricated building components is still lacking.

The primary objective of this paper is to address this gap by presenting a systematically structured approach for capturing and transferring essential domain experts' knowledge on constructability into the computational design process of prefabricated façade panels. Furthermore, by leveraging the FBM concept, this approach aims to demonstrate how tacit domain knowledge can be transformed into explicit, machine-readable instructions. To achieve this, a new taxonomy for capturing typical constructability knowledge required for designing prefabricated façade panels has been developed, emerging from close observations in a relevant case study and supported by similar examples from related construction projects.

Constructability constraints of prefabricated building components are multifaceted, as is the required knowledge to address these constraints. These constraints range from those related to the geometry of prefabricated building components to various semantic attributes, such as material and performance [17]. Additionally, the context of constructability knowledge can vary based on the type and functionality of the prefabricated building

components, requiring specific additional expert input from fields such as architectural, structural, and mechanical, electrical, and plumbing (MEP) [18]. For example, the manufacturing and assembly processes for mechanical components [19] can differ significantly from those of prefabricated structural components [20], as do the constraints related to their geometries and semantic attributes.

These considerations suggest that a two-dimensional categorization of constructability knowledge for prefabricated elements could serve as a feasible framework for holistic and comprehensive investigations. However, due to the limitations of this research—primarily its reliance on data from a single case study—this study does not aim to propose or validate such a framework that is universally applicable to constructability constraints in prefabrication projects. Instead, the focus is on illustrating how computational designers can practically integrate the necessary expert knowledge and systematically review design elements across different levels of constructability constraints. Therefore, the main scope of this research is capturing and integrating constructability knowledge into the computational design of prefabricated façade panels as architectural elements, as well as their manufacturing and assembly, given the limited available data to the research team.

Furthermore, the research focuses mainly on complex designs with repetitive prefabricated building elements frequently used to create unique façade designs, where computational design is already commonly employed. In this way, other unrelated computational challenges, such as software interoperability, workforce computational skills, and design coordination issues, can be filtered out. In this context, the research team chose to closely study a construction project with repeating prefabricated façade components. Such façade components can generally be fabricated in varying shapes and quantities, installed onto the primary structure using different techniques, and positioned in diverse relations to one another, making them highly susceptible to the lack of adequate constructability knowledge.

The methodology in this paper is based on an ethnographic case study of the Orchard Commons (OC) project on the UBC campus in Vancouver, Canada with its distinctive architectural design of façade panels. In addition to a comprehensive literature review of related works (Section 2), data collection was primarily based on direct observations of the OC project by the research team and semi-structured interviews with various project practitioners, especially the project's computational designer. The methodology in this research is detailed in Section 3. In Section 4, a series of geometric constructability features identified from the OC project is presented that should cover a variety of typical design intents and geometric constructability constraints. The outcome of Section 4 is a new taxonomy for classifying typical geometric constructability constraints on three generic levels, followed by a collection of similar features and constraints from relevant projects to support the proposed taxonomy's structure (Section 5.1). Using the new taxonomy, a refined approach for integrating domain-specific constructability knowledge into the computational design process using FBM is presented in Section 6. Finally, Section 7 provides concluding remarks and an outlook on future work.

2. Research Background

The constructability of unique and complex architectural concepts is a challenging task in the AEC industry that can be overcome by integrating the constructability knowledge into the design process. Therefore, this research focuses on ways in which domain constructability knowledge can be captured and integrated into the design process. The design complexity and the subsequent constructability challenges often result from the initial wishes of the clients and the preliminary architectural concepts. These are often visionary concepts that must be translated into constructible designs. This implies that they should be functional, technically resolved, and in compliance with the standards [21]. In

this context, understanding constructability and its related design issues is crucial. Additionally, it is important to investigate how relevant experts' constructability knowledge can be practically introduced to the computational design process. The following sections elaborate on these topics.

2.1. Constructability Review

According to [5], the term “constructability” refers to the optimum use of knowledge and experience of construction practitioners in planning, design, procurement, and field operations to achieve the overall project objectives. As awareness of the potential benefits of constructability reviews increased, many construction companies began conducting such reviews at different design stages to improve the reliability of the design and facilitate the construction process [22]. This trend has led to the need for more engaging contractors in the design process to provide input on constructability, allowing designers to make more informed decisions with fewer design iterations [23].

A lack of constructability insights can lead to significant challenges during construction. Raviv et al. [6] conducted a detailed study and identified basic constructability issues that should be addressed during design, including:

- Unfamiliarity with construction procedures, construction details, site conditions, acceptable tolerances, and rules and regulations
- Failure in understanding site and building conditions, O&M needs, and 3D information
- Failure in coordinating among consultants, i.e., architectural, structural, mechanical, electrical, and plumbing (MEP), and scheduling
- Failure related to receiving crucial information too late and the omission of essential details

These constructability issues can be aggravated by certain project-related factors that may vary from one project to another. For instance, Tatum et al. [24] identified project planning issues, site planning issues, and major construction methods, as factors that can impact constructability issues in a project. Additionally, ref. [25] consider project schedule (construction time), project budget, required resources, and the quality of the final product as vital factors for constructability performance. Nevertheless, most of the constructability issues identified by [6] can be attributed to shortcomings in considering experts' knowledge during the design phase, which is consistent with [26]'s findings. In other words, in the constructability review process, integrating experts' knowledge to resolve design and construction issues is critical. Identifying what expert knowledge is useful in addressing constructability challenges requires an understanding of the nature of constructability knowledge and how it can be effectively captured and applied in practice.

2.2. Constructability Knowledge

In this discussion, it is necessary to clearly distinguish between the terms “data”, “information”, and “knowledge”.

Data is defined as “symbols” or “signs” representing the characteristics of objects, events, and their environment [27]. In essence, data represents an unstructured set of symbols stemming from observations [28].

Information is useful in answering questions that begin with words like who, what, when, and how many [27,29].

Additionally, information can be considered as structured data useful for analyzing and resolving problems [28].

Knowledge is obtained by experts based on their experience, values, and contextual information [28,30]. Knowledge is also known as “know-how” [27], “information about

information” [28], or “a fluid mix of framed experience, values, contextual information, and expert insight” [30].

These definitions of data, information, and knowledge are foundational for understanding how constructability knowledge can be effectively utilized in the design process. In the context of construction, data and information provide the basis for generating actionable knowledge, shaped by experts’ experience and contextual understanding. In other words, constructability knowledge encompasses experts’ experience on constructability, which is critical for addressing the challenges of designing and building complex prefabricated building components and executing their associated processes.

Processes related to prefabricated building components are often categorized into manufacturing and assembly, with the associated design activities classified as design for manufacturing and assembly (DfMA) [31]. Manufacturing includes all off-site activities involved in constructing or building a component, while assembly refers to all on-site activities required to erect or install the component. However, a third set of activities is occasionally incorporated to these processes, covering the transportation and supply chain of prefabricated building components [32,33], which can become critical when approaching just-in-time deliveries [34]. Therefore, discussing the constructability of a prefabricated building component involves investigating whether the component is manufacturable, transportable, and installable under the given design conditions.

As mentioned earlier, when conducting comprehensive research, constructability knowledge for prefabricated building components can be analyzed using a two-dimensional framework. One dimension focuses on constructability knowledge regarding individual components. For example, such knowledge is essential to determine whether the anticipated geometry (shape and size) of a prefabricated component is feasible for manufacturing, transportation, and installation in an effective manner. Examples in this regard include the extraordinary geometries implemented in the Eight Spruce Street project in New York [35], the Galaxy SOHO in Beijing [36], and the Palazzo Italia in Milan [37]. Additionally, on this dimension, constructability knowledge is crucial for assessing whether the semantic (non-geometric) attributes of individual prefabricated components are reasonably assumed. For instance, the authors in [17,20] discuss knowledge related to materials, the authors in [15] focus on associated costs, and the authors in [17,38] address the sustainability attributes of prefabricated components.

The second dimension of constructability knowledge pertains to the role that prefabricated building components play and the building system they belong to, which subsequently determines the field of expertise required for the constructability review. For example, the authors in [19,39] provide insights into the constructability of manufacturing and assembly processes for mechanical components, while the authors in [20,31,40] focus on structural expertise, and the authors in [35–37] emphasize the architectural domain. It is also noteworthy that in this dimension, the required expert knowledge often spans multiple fields. For instance, refs. [31,41] offer insights that combine architectural and structural expertise.

Since this research primarily relies on limited data from a single case study, it does not aim to comprehensively address all aspects of the two-dimensional framework described above. Instead, its main focus is on investigating the integration of experts’ knowledge related to the constructability of manufacturing and assembly processes for complex prefabricated façade panels, primarily from the architectural perspective.

Constructability knowledge, and knowledge in general, can be classified as: (1) explicit knowledge, articulated in written form; and (2) tacit knowledge, which resides in the minds of domain experts [42–44]. According to [45], it is widely accepted that most constructability knowledge is tacit. Thus, there is a need to convert this tacit knowledge into explicit

knowledge and systematically integrate it into the design process. According to [46], integrating constructability knowledge into the design process requires intensive exchange with general contractors and possibly with key trade contractors who will be responsible for building the structure during the design phase.

More specifically, it is vital to identify computational approaches that facilitate capturing, associating, communicating, coordinating, and disseminating construction-related “knowledge” [47,48]. While many studies have explored domain knowledge for constructability reviews, most have primarily focused on Knowledge Elicitation (KE) using methods like expert interviews, surveys, direct observations, and document analysis [22,49–51]. KE is indeed a critical step, but current research often falls short of discussing how to systematically integrate elicited knowledge into technical activities, including the computational design process.

Thus, while understanding constructability knowledge is fundamental, its integration into the design process requires robust computational tools and frameworks. The next section explores the existing body of knowledge on embedding constructability knowledge into computational design tools, utilizing constructability features to support the overall design process.

2.3. Integration of Constructability Knowledge into the Design Process Using Building Information Models and Constructability Features

Fadoul et al. [26] noted that most construction projects lack formal, explicit constructability knowledge bases connecting observed constructability issues with design processes. While the use of “informative construction methods and advanced technology” was once seen as a barrier to constructability [52], contemporary computational solutions, especially BIM and generative design approaches, now facilitate automated scenario creation for design constructability reviews [53]. With building information models (BIMs), the AEC industry can collect, produce, manage, and utilize essential data and information interoperably throughout a building’s lifecycle, as outlined in [46].

Researchers have demonstrated that BIM can bolster collaboration between design disciplines, especially between designers and constructors, to address constructability issues [54]. However, while BIM can be effective, the systematic integration of constructability knowledge into the design process demands new computational solutions beyond just BIM. Various studies have sought to fill this gap. For example, ref. [55] proposed a rule-based method for evaluating the constructability of cast-in-place concrete construction. While these rules can act as control measures for reviewing designs, they do not necessarily guide designers during the initial stages of a project. Similarly, ref. [7] introduced an automated constructability assessment of design BIMs based on various design factors, including dimensions, specifications, resources, and BIM component functions. However, like [55], this approach does not systematically introduce constructability knowledge during design activities. A similar gap was observed in [26], where research predominantly focused on assessment rather than providing design support. This highlights a clear need for the systematic integration of constructability knowledge into the BIM-based design process.

FBM approaches have been seen as a suitable method for qualitative knowledge specification and integration since the 1970s [56–59]. FBMs were conceived to allow for the integration of application constraints and specific expertise views [58]. Features can also be interpreted as the characteristics of the resulting product from a design process [60]. Similarly, the authors in [61] consider features as subsets of design products that have specific functions assigned to them. Therefore, in the context of constructability, a constructability feature can be described as a geometric condition, informed by the practitioner’s knowledge. In other words, constructability features represent specific design characteristics and functions while being linked to domain knowledge. Therefore, in the AEC field, FBM

can be instrumental in capturing and structuring specific knowledge about the product (building), process (construction), and organization (project stakeholders) [57].

Thus, the concept of features holds significant potential for adoption in AEC projects, enabling the systematic integration of practitioners' knowledge, including constructability-related knowledge, into the computational design process. In this regard, it is essential to develop a sufficient understanding and to formalize the design conditions and constraints that need to be addressed by specific constructability features. Addressing this research gap is the primary objective of this research.

3. Methodology

The previous section showed that there is a scarcity of using feature-based modeling for integrating experts' knowledge for constructability during the design process, and there is a need to develop a systematic approach to address this gap. For this aim, the research team conducted a retrospective study on a construction project that used a computational design approach and adopted various constructability constraints that required experts' knowledge. By analyzing such a case study, it was possible to identify examples of different constructability features (Section 4), create a new taxonomy for constructability constraints (Section 5.1), and subsequently develop a refined approach for the systematic enhancement of the computational design process with knowledge-based constructability features (Section 6).

The research steps undertaken in this study and the corresponding sections where these steps are elaborated are presented in Figure 1.

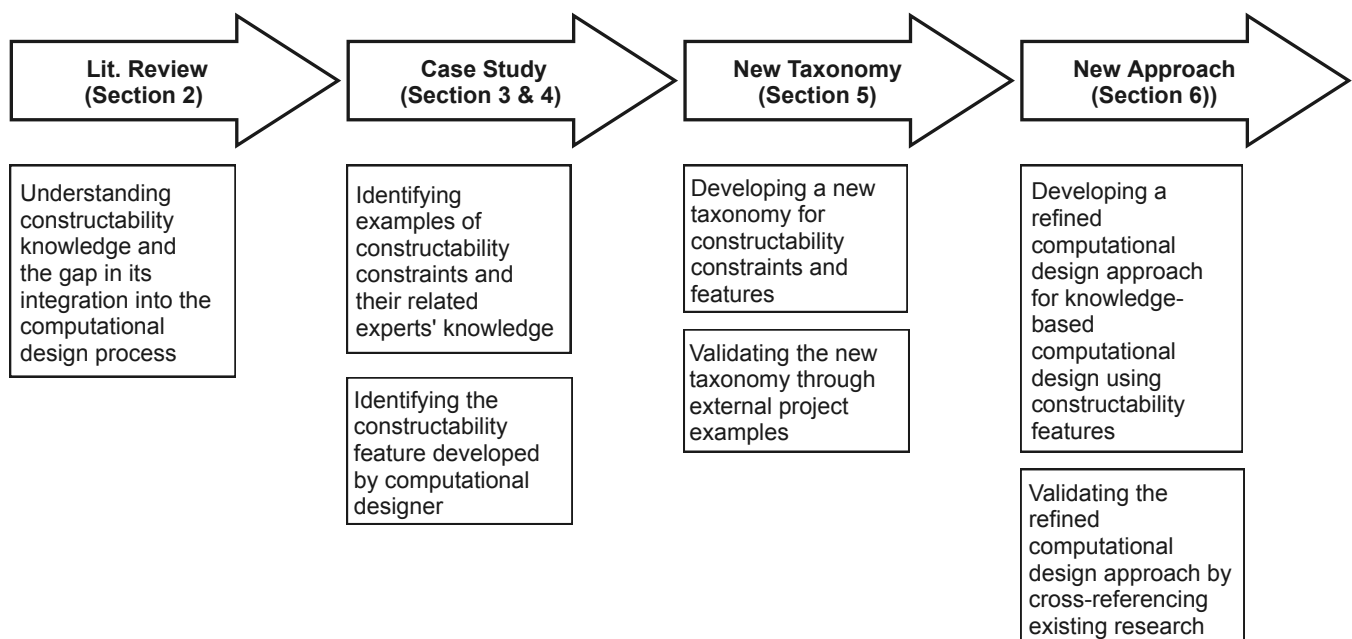


Figure 1. Research steps taken in this study.

3.1. Case Study

The practical motivation for this research is based on the intensive observations of the research team in the Orchard Commons (OC) project on UBC campus in Vancouver. The special design of the façade panels for the two 18-story towers in this project was complicated and required particular computational design to be constructible. This project provided the research team with various examples for design conditions that challenge constructability. These examples offered a great opportunity to identify typical constructability constraints and potential design issues. Furthermore, they could be used to better under-

stand the role of practitioners' knowledge in addressing constructability concerns using computational methods.

The OC project was completed in 2016 and was designed to be the home for new international students as well as the UBC Vantage College. The original design aspiration was for this site to have a net positive impact on human and environmental well-being. This 41,683 m² construction project includes two main high-rises for student housing. In this paper, the main focus is on the constructability features used in the computational design of 1205 façade panels in the selected case-study project. These façade panels were prefabricated in 18-panel types and were placed in the façade pattern in a specific order. According to the project architect, the original idea behind the shape of the façade panels was partly inspired by natural forms such as seaweed and partly from the art of calligraphy to create associations with nature and culture. In addition, a gentle vertical deviation was introduced to the placement of each bay, i.e., each vertical set of panels. This gentle deviation is a way to express diversity in a geometric fashion, echoing the cultural diversity expected by the future occupants of the residences. As a result, the original design suggested that the geometry of panel bays had to be curvy and smooth, as shown in Figure 2 (left). However, this requirement created financial and practical constructability challenges that subsequently led to the consideration of specific computational design techniques to integrate practitioners' knowledge and optimize design constructability. These considerations resulted in a design that only included façade panels with straight edges, while the overall design would suggest a curvy impression, as shown in Figure 2 (right).



Figure 2. Architectural design concept before the computational design for constructability (left) ©Perkins+Will; Constructed façade after the computational design for constructability (right) ©BIM TOPICS Lab.

3.2. Data Collection

A variety of methods were used to collect relevant data from the OC project. These data collections can be divided into three different categories:

1. **Design-related data collection:** More than 30 h of (virtual and in-person) meetings were conducted with the computational designer and other stakeholders. Through these meetings, the research team gained insights into the computational approach to creating different design scenarios and performing computational optimizations for constructability in the OC project. Furthermore, the designer provided access to various design documents, including their BIM in Autodesk Revit format, their parametric model in Rhinoceros format, their computational algorithm in Grasshopper, the delivered shop drawings to the fabricators of the concrete panels, and the relevant electronic communication between the computational designer and other project participants during the computational phase. This close collaboration was a significant driver for this research and led to the inclusion of the computational designer as a co-author of this paper.

2. **Fabrication-related data collection (off-site):** The research team visited the fabrication site two times and interviewed the fabricators to understand the constructability issues, the impact of computational design and optimization from their perspective, and the information exchange between designers, fabricators, and installers. Furthermore, the research team obtained access to the modified shop drawings of the concrete panels developed by the fabricators and the related calculations. The most noticeable change in the design was the addition of panel embeds by the fabricator. Panel embeds are responsible for the connection of the panels to the main structure. The panel embeds are discussed in more detail in the next section. It should be noted that the fabricators did not have the capability to use BIM and had to work with 2D drawings generated from BIM by the architect.
3. **Installation-related data collection (on-site):** The research team conducted weekly site visits over a span of six months. During these visits, the research team interviewed workers with different roles and videotaped and photographed various installation cases and issues. These included ongoing activities on the ground, i.e., at the truck that transports the panels, as well as the actual panel installation process on the building façade.

It should be noted that as part of the data-collection efforts, 20 semi-structured interviews, each lasting about an hour, were conducted individually or in groups. The participants included practitioners from the manufacturing company, trades responsible for façade panel installation, project managers, and the design team, including the computational designer. In the interviews with the trades and manufacturers, the primary focus was on the constructability issues identified and the knowledge provided to the design team throughout the project. This is while the interviews with the design team, particularly the computational designer, were expanded to explore how the received expert knowledge was integrated into the computational design process.

Additionally, the research team had access to two time-lapse cameras with 5-min intervals installed at the project site, enabling the research team to monitor the installation progress of the concrete panels at any time.

3.3. Data Analysis

A general approach for the systematic integration of experts' knowledge into the computational design process does not exist. Therefore, developing a new approach requires a reversed reasoning process where solutions are derived from analyzing past cases. Following this approach, the research team began the data analysis to identify the relevant constructability constraints examples in the OC project, the respective knowledge (both explicit and tacit) that informed those constraints, and the associated constructability features implemented in the computational program used for optimizing the façade panels in the OC project. Specifically, the following steps were followed to conduct this analysis:

1. **Identifying the constructability constraints:** Identifying complex design conditions and the related constructability constraints through semi-structured interviews with various project participants, direct observation of the construction activities, and reviewing the project data.
2. **Investigating whether experts' knowledge was used to address the constructability constraints:** Investigating the decision-making process behind each identified constructability constraint to better understand the influence of domain experts in that decision. In this way, the focus can be laid only on design constructability constraints that were informed by domain knowledge.

3. **Developing a new taxonomy for constructability constraints and features:** Using the identified typical constructability constraint examples, a reversed reasoning process was adopted, where solutions are derived from analyzing past cases. This analysis was conducted in close collaboration with the project computational designer to review and identify the relevant implemented design features.
4. **Developing a refined conceptual approach for knowledge-based computational design using constructability features:** At this stage, the identified knowledge-based constructability features will be studied and categorized using a new taxonomy.

3.4. Validation of the Outcomes

The outcomes of this research include a new taxonomy for constructability constraints and a corresponding computational design approach. These outcomes are validated through cross-referencing with the existing body of knowledge. As outlined in [62–64], cross-referencing is a suitable validation method for this research because it evaluates the alignment and consistency of the findings with established knowledge in the field.

This method is particularly effective for research with limited primary data, as it leverages the broader literature to contextualize and assess the validity of the findings. Nonetheless, it should be emphasized that the validation efforts in this research do not claim universality for the findings, particularly regarding the identified constructability constraints and features, as these are inherently dependent on project-specific circumstances.

4. Examples of Critical Constructability Features in Façade Panels of the Orchard Commons Project

Developing a new approach for the systematic integration of experts' knowledge into the computational design process requires a reversed reasoning process, where solutions are derived from analyzing past cases. Therefore, this section presents the identified examples of critical constructability features in the OC project's façade panel. For each feature, it is discussed whether expert knowledge was used to address the respective constructability constraints and how these constructability features were implemented in the computational design. After analyzing the computational algorithm for the computational design in the OC project, the research team was able to identify many features that specifically address the constructability constraints created by the design conditions. Some of these features are computationally optimized in several computational iterations, and some others are fixed parameters that are considered in the computational algorithm. All of the implemented features by the computational designer were developed in consultation with domain experts. Additionally, the research team could identify a potential constructability feature that was not implemented in the computational design process due to the project circumstances. This feature is discussed later in this section to provide a thorough discussion.

4.1. Feature 1: Panel Thickness

Constructability Constraints and Experts' Knowledge: The thicker the concrete gets, the more eccentricity appears in its vertical loading on the concrete slab. Therefore, it is necessary to reduce the weight of the panels as much as possible. For this reason, the thickness of the panels has a crucial role, in addition to its other dimensions which are dictated by the architectural design. With the consultation of construction experts, the computational designer decided to set this constraint to 9 inches. This includes three different panel layers, i.e., inner wythe, insulation, and outer wythe, as shown in Figure 3. This decision was mainly based on the panel layers' composition as well as the depth limitation of the concrete panels' formwork.

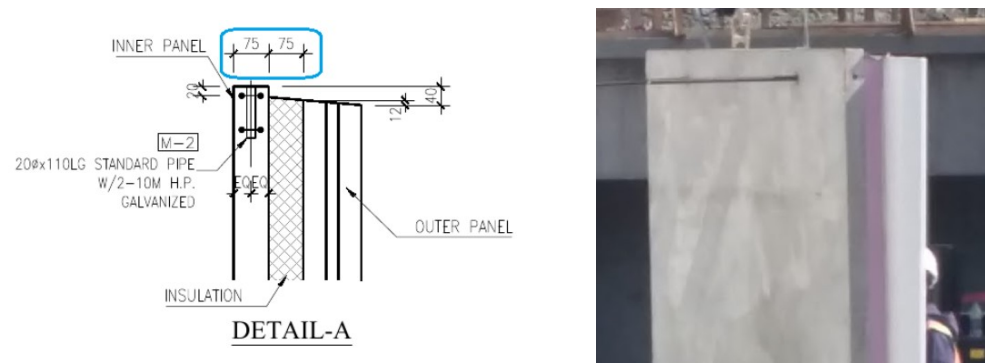


Figure 3. Shop drawing of panel layers (left); a prefabricated façade panel in preparation for lifting (right).

Constructability Feature and Computational Implementation: The described thickness feature is an example of constructability features that address the “dimensional constructability constraints”. Dimensional constructability constraints are prevalent and influence not only the fabrication process of a component but also its transportation, storage, and installation. In computational design, to capture the dimensional constructability constraints for a component, it is necessary either to directly define its corner points ($p_{(1-n)}$), or indirectly determine its length ($l_{(d)}$), width ($w_{(d)}$), and height ($h_{(d)}$) with a point of origin ($p_{(x,y,z)}$). This origin point is essential for calculating corner points and spatial placement. Figure 4 shows the implementation of this feature in the Grasshopper environment for the OC project.

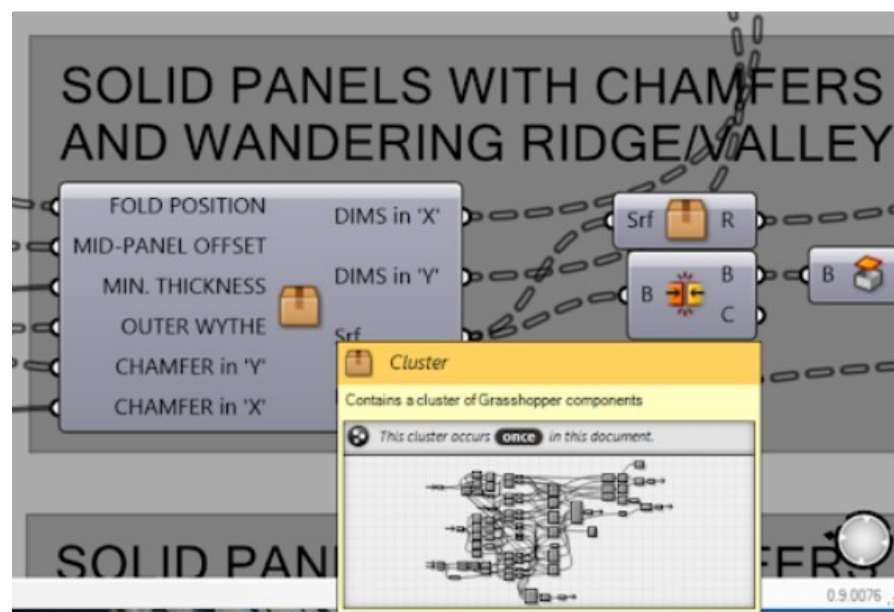


Figure 4. Implementation of dimensional constructability feature for panel thickness in Grasshopper environment.

Such constraints were also taken into account when developing features in the OC project, like the example above concerning panels’ thickness. Further features developed for dimensional constructability constraints in this case study include: “fixed panel height”, corresponding to the floor-to-floor height (2625 mm); and “varying panel widths”, stemming from a sustainability goal to achieve a 60/40 ratio between the opaque and glazed surfaces.

4.2. Feature 2: Inclined Straight Edges

Constructability Constraints and Experts' Knowledge: One important design goal in the OC project was to “do more with less”. This entailed offering a high degree of visual diversity while minimizing the complexity. As previously mentioned, the original design suggested façade panels with curved edges. However, fabricating curved concrete units necessitates specialized custom formwork and a high degree of precision. This makes the fabrication of such panels both costly and susceptible to errors.

Generally, using standard shapes is a common practice in the construction industry because they streamline the associated construction tasks, consequently reducing costs. Regardless of a component's dimensions, its unique shape might necessitate specialized fabrication processes, such as for formwork, assembly, and so on. Moreover, laborers require additional time to familiarize themselves with unconventional shapes. This aspect could impact both the fabrication and installation processes. For all these reasons, the practitioners on the OC project recommended avoiding curvatures for the façade panels altogether and pursuing a solution with inclined straight edges on the left and right side of the panels.

Constructability Feature and Computational Implementation: To realize this constructability feature, the computational designer delineated a specific range of variations for edge inclinations, termed as amplitudes, and optimized them to fulfill the design stipulations, as illustrated in Figure 5. Through these variations, multiple design options with diverse panel shapes could be reviewed, granting the client and designers the freedom to select a fitting design alternative.

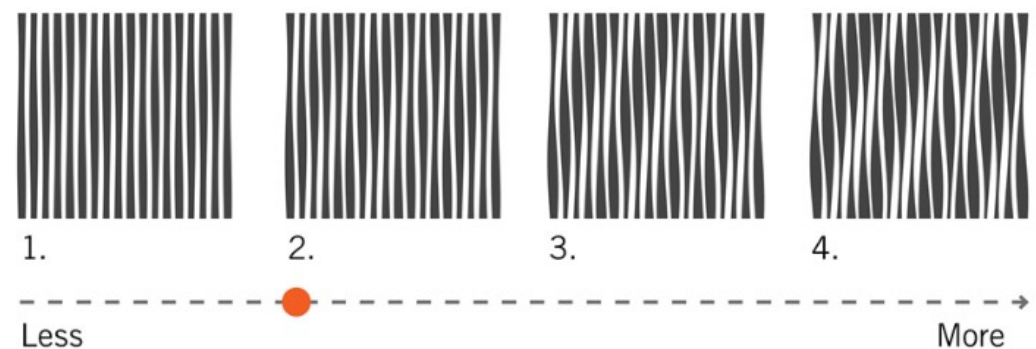


Figure 5. Amplitude study using straight panel edges showcasing different design choices. Each image represents different edge inclinations. The red dot is a slider that enables creating a new variation of the design by changing the edge inclinations.

4.3. Feature 3: Vertical Shift Between Panel Bays

Constructability Constraints and Experts' Knowledge: In the OC project, the ideal constructability scenario would involve repeating the panel bays (vertical stripes) at certain horizontal intervals along the building façade. Nonetheless, given the design intent was to evoke a sense of diversity and uniqueness through the façade design, mere repetition would not capture the unique and intricate essence from an architectural standpoint. Simultaneously, from a constructability viewpoint, adhering to a specific sequence in panel positioning would emerge as a pragmatic constraint in contrast to a random placement. Consequently, the OC project's designers opted to integrate a constructability constraint for the vertical alignment of the panel bays. This allowed them to induce a vertical displacement from one bay to the next, fostering more variety in the façade pattern and embodying the notion of subtle variation.

Upon consulting with practitioners, the designers settled on vertical displacements ranging from 3 to 7 floors between adjacent panel bays. Moreover, for constructability reasons, they ensured each displacement was a whole number of floors, ruling out shifts like 3.5 floors. By embracing such constraints, each panel bay mirrored the panel sequence of other bays, with the sole distinction being the commencement with a different panel type. Figure 6 displays the positioning of panels across different bays and the vertical displacement between them, which can be identified via diverse color shades and corresponding numbers.

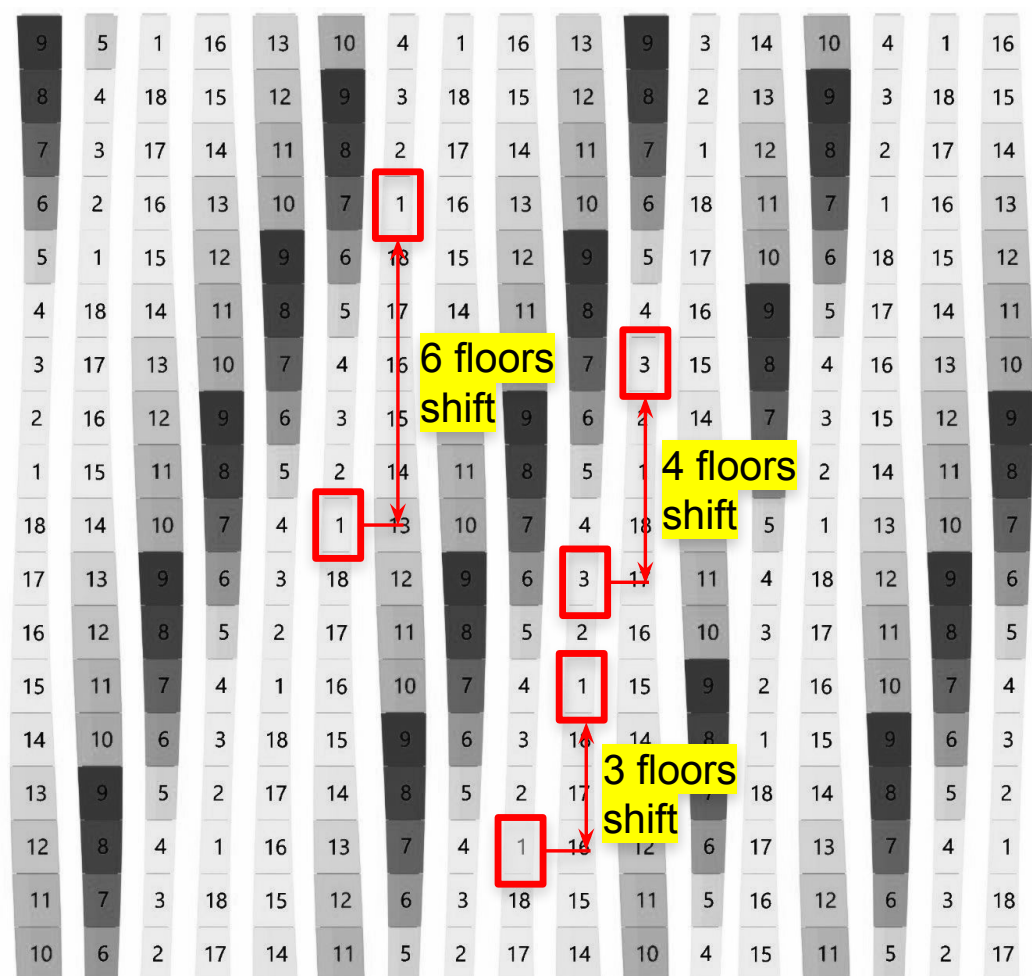


Figure 6. Vertical displacement between panel bays.

Constructability Feature and Computational Implementation: The highlighted constructability feature here serves as a paradigm for features addressing constraints tied to the “relational placement” between two or multiple components. In numerous architectural concepts, exceptional patterns emerge by arraying similar components in unique manners, achievable through either component shifting or rotation. The relational placement attribute profoundly affects the installation and synchronization of components, as minor errors would manifest in the overarching façade pattern. In computational design, relational component positioning can be articulated through a function that relocates each component based on its relative position and orientation to an adjacent component ($f(p_{(neighbor)}, \Delta d, \Delta \alpha)$).

Another noteworthy constructability feature in this context pertained to the “Max. and min. horizontal distance between panels” in this study, which was aligned with the relational placement constraints.

4.4. Feature 4: Placement of Panel Embeds

Constructability Constraints and Experts’ Knowledge: Panel embeds are responsible for the connection of prefabricated panels to the rest of the main building structure, i.e., the receiving building elements such as slabs, columns, and walls. Therefore, the placement of embeds on the panels must be carefully designed in relation to the position of receiving elements. In a design where panels are not placed in a simple repetitive order, it is possible that panels with similar shape and dimensions require embeds at different positions. At the same time, due to constructability issues and to facilitate the fabrication process, practitioners often recommend normalizing the positioning of the panel embeds so that the variation in their location is minimal. This normalization of the embeds’ placement is another type of constructability constraints.

Although designing the placement of embeds on the panels requires close collaboration between different disciplines, especially between fabricators and designers, such collaboration was not possible in the OC project due to the project contract model and other project circumstances. Hence, there was no experts’ input on this specific constructability constraint, and subsequently, this constructability constraint was not addressed through computational design, and no constructability features were specifically developed for this constraint.

As a result, the positioning of the embeds in the OC project was the responsibility of the panel fabricator. The related calculation for all panels was performed manually based on the available experience on the fabricator’s side. Figure 7 (left) shows the panel embeds designed by the fabricator for one of the façade panel types. Figure 7 (right) shows a worker adjusting the panel embeds on-site after identifying that those embeds do not meet the receiving embeds on the main structure.

Constructability Feature and Computational Implementation: While no specific constructability feature has been developed in this case study to address the constructability constraint related to embed positioning, it is valuable to examine this type of feature in more detail, as it often necessitates close collaboration between designers and fabricators. This constructability feature pertains to constraints associated with optimizing the positioning of connecting elements on a building component, such as a façade panel. Its primary objective is to optimize the placement of connecting elements, whether they are extra connecting elements like embeds or mechanical fasteners such as rivets, screws, and nails, particularly concerning their intersections with other components, often of different types. Developing constructability features to optimize the positioning of connecting elements not only influences their fabrication but also significantly impacts their installation process. Inefficiencies in this regard can lead to additional workarounds and delays on-site, as observed in the OC projects.

The constructability feature for optimizing the placement of connecting elements can be described in computational design through a location point on the host component ($p_{(x,y,z)}$), which is relative to the origin point of the host component. In cases in which components overlap each other, the implementation of the overlap in the computational algorithm requires the length of the overlap ($l_{(d)}$) in addition to the location point on the host component at which the overlap starts ($p_{(x,y,z)}$).

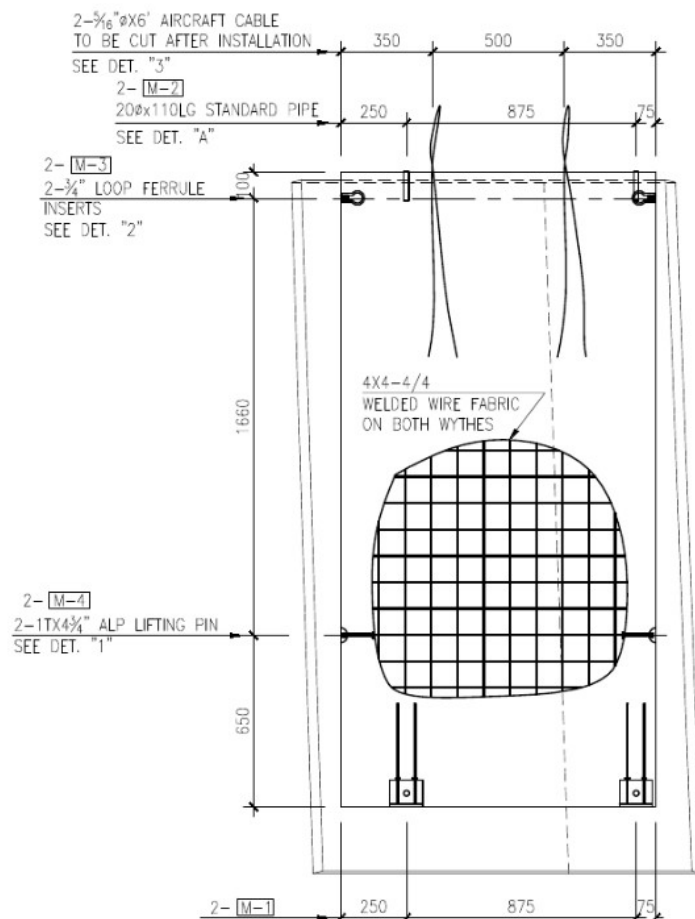


Figure 7. Details of a panel's embeds from the shop drawings designed without computational optimization (**left**); workers adjusting the panel embeds on-site due to the misalignment with the receiving embeds (**right**).

4.5. Feature 5: Minimum Panel Types

Constructability Constraints and Experts' Knowledge: The fabrication of panels with many different types is costly. Therefore, in the OC project, the designers aimed to have the minimum possible panel types on the façade and defined this as a constructability constraint. This constraint is an example of constructability constraints related to the “variety of component types”. Earlier, it was explained that the main focus in this research is on cases in which the studied components are used multiple times, such as repeating façade panels. The main reason for this scoping is to enhance the research scope and include the mass-fabrication aspect, which would not be represented in cases with unique components. Moreover, the focus was on cases in which the components have minor differences from each other while all of them belong to the same building object category. Through these considerations, it would be possible to enhance the research scope and capture a significant fabrication constraint, namely the “typing”. This constraint requires having the lowest possible number of types for a specific design task.

In consultation with practitioners, the OC project stakeholders agreed on establishing a pattern with only 18 different panel types that correspond with the number of building floors. In this way, each vertical panel bay covers the 18 floors of the building with 18 different panels. With this decision and by vertically shifting the panel bays, the outcome became a diverse and unique pattern which is created by only 18 panel types. Figure 6 shows the distribution of these 18 types in different bays, where each number corresponds to a specific panel type.

Constructability Feature and Computational Implementation: The implementation of this feature in the computational algorithm was combined with the implementation of the feature for vertical shift between the panel bays introduced earlier. The typing constructability features can be described in computational design through a function that controls the minimum total number of component types ($f_{min}(\sum t_n)$). This function can be implemented in many different ways. One way is to collect $\sum t_n$ for each design variant and then find the overall minimum, as it was implemented in the OC project.

Certainly, there is a direct relationship between the fabrication costs and the number of component types. Therefore, typing as a constructability feature is a common computational optimization task in many projects. “Minimum window wall types” was another typing feature in this case study which was computationally designed.

4.6. Feature 6: Composition of Façade Panels

Constructability Constraints and Experts’ Knowledge: In repetitive patterns, the composition of the components conveys the context of the design, thereby translating the design’s impression. From a constructability perspective, the position of panels dictates the installation order. As explained earlier, the vertical order of panels in the OC project is determined by the constructability constraints of “minimum panel types” and “inclined straight edges”. However, in this project, like in many projects, panel installation proceeded floor by floor (row by row) rather than bay by bay (Figure 8). Based on experts’ input, minimizing panel variation for each floor enhances the flow of the installation process, as productivity improves when similar components are installed. Therefore, the horizontal order of the panels and, consequently, the order of the panel bays were significant in minimizing horizontal panel variation, and so it was essential to optimize the overall panel positioning to achieve such minimization. As a result, the decision was made to use only 9 different panel types on each floor, even though a total of 34 panels were required to enclose both sides of the building on a single floor.

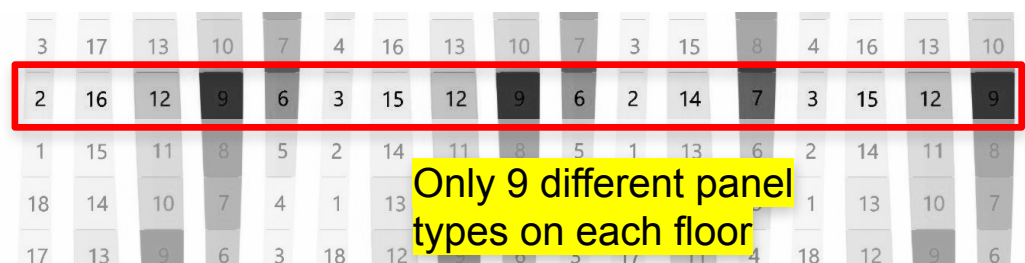


Figure 8. The composition of façade panel types constrained by having the minimum number of types per floor.

Constructability Feature and Computational Implementation: The described constructability constraint above corresponds to the overall panel positioning. Developing suitable features requires considering all components and their composition within the overall design. Consequently, a corresponding constructability feature was integrated into the computational design of the OC project to minimize panel variation on each floor.

These types of constructability constraints are primarily associated with the installation activities and serve to optimize the installation process. Composition features can be defined in computational design by specifying the global positioning of the components, denoted by their global location points ($p_{(x,y,z)}$).

5. New Taxonomy for Constructability Constraints and Features

5.1. Introduction of the New Taxonomy

Using a taxonomy can aid in identifying and describing constructability constraint types systematically. Such taxonomy should be generic, structured, and project-independent. Considering the introduced examples from the case study earlier in this section and the similar examples and constraints from relevant projects, the typical constructability constraints and the associated features can be divided into three different levels:

- **Micro level (component level)**, which includes components and their characteristics (e.g., shape and dimension).
- **Meso level (interrelationship level)**, which concerns relations between two or more components (e.g., distance, intersection, connection).
- **Macro level (contextual level)**, which deals with constraints related to the context of the overall design and requires consideration of the entire architectural concept (e.g., the number of types, and the position of components within the design).

Figure 9 shows the developed taxonomy for constructability constraints, including their required parameters for feature-based modeling and computational implementation. This taxonomy is developed in alignment with the work of [13,15,65] on constructability and feature-based modeling.

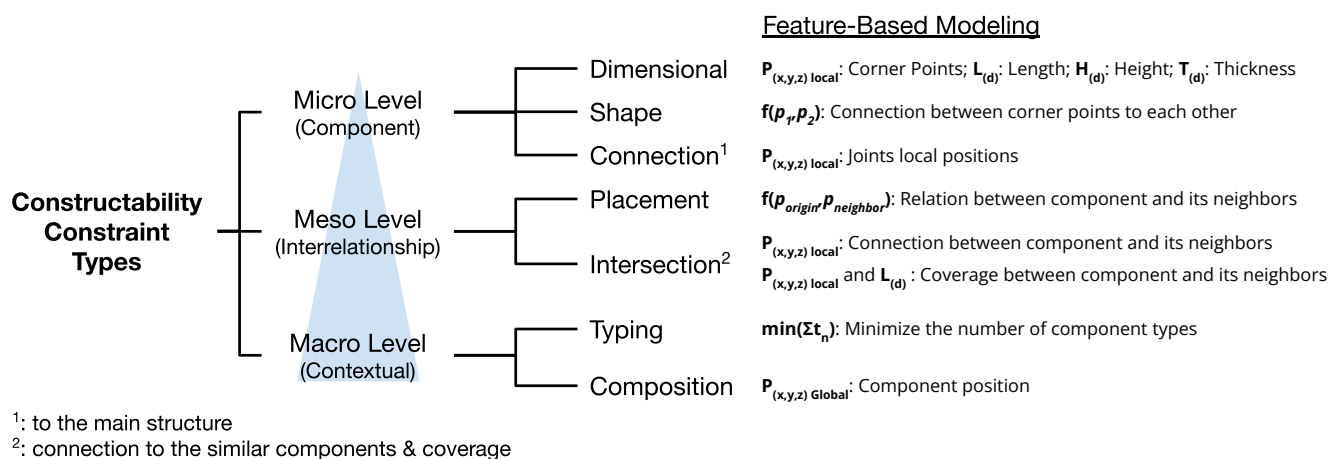


Figure 9. Taxonomy for classification of typical geometric constructability constraints and features.

When analyzing and categorizing constructability constraints, it is crucial to differentiate between the cause (i.e., the design intent) and the effect (i.e., the constructability constraint). This distinction is necessary because sometimes the design intent might belong to a different level of taxonomy than the relevant constructability constraint. An example here is the “inclined straight edge” feature considered in the selected case-study project. In this project, the original design intent was to have a pattern with curved vertical elements across multiple floors. According to the new taxonomy, this design intent can be classified at the “Macro Level”, as it considers the overall pattern of the façade panels. However, experts strongly advised against curved edges for these panels, as they are expensive to fabricate and not easy to install. As a result, a constructability constraint was determined to design façade panels with inclined straight edges. This constraint pertains to the “shape” of the building components, classified at the “Micro Level”. Hence, each façade panel in a bay received a distinct angle of inclination as its feature.

The new taxonomy can broadly classify most constructability constraints and features of prefabricated façades, independent of projects. The three subsequent tables provide examples from renowned projects and their respective constructability constraints, showcasing this flexible adaptability. In selecting these examples, special attention was paid to ensure that all had sophisticated design intents challenging construction and varied in scale, occupation purpose, and levels of complexity.

5.2. Validation of the New Taxonomy Through External Project Examples

Cross-referencing methodology was employed to validate the elements of the new taxonomy. Four computationally designed projects with complex façade designs were selected for this purpose, and geometric constructability constraints for each project were identified from publications analyzing them as case studies. Each of these projects is briefly introduced separately below, followed by a correlation of the identified geometric constructability constraints with the levels and constraints of the new taxonomy, as summarized in Tables 1–3.

5.2.1. The Eight Spruce Street Project in New York [35,37,66–68]

Also known as New York by Gehry, this project is a 76-story residential skyscraper designed by Frank Gehry and completed in 2011. Renowned for its undulating stainless steel façade and complex structural design, the project utilized advanced computational design approaches to achieve precise geometric control. This ensured seamless integration of the over 10,000 unique stainless steel panels, reducing fabrication and installation errors.

Computational tools aligned the façade's complex geometry with the structural frame, minimizing conflicts between architectural intent and engineering feasibility. Leveraging BIM, the design team oversaw the off-site prefabrication of façade panels, streamlining on-site assembly and reducing construction time. BIM also facilitated rapid exploration of design iterations, balancing aesthetics with constructability and cost constraints.

The constructability challenges addressed in this project highlight the innovative approaches required to realize its extraordinary architectural vision. According to [35,37,66–68], the Eight Spruce Street project faced several geometric constructability challenges, including the requirement for the window sill in the façade panels to maintain a specific distance from the finished floor. Additionally, the size of the aluminum frame panels was limited, and both fabrication and transportation faced constraints due to size limitations. The project also dealt with the complexity of curvy and sharply angular curtain walls, which necessitated the use of embedded aluminum brackets to attach the curtain wall to the main structure. Furthermore, the façade components required connections through rivets, and a significant effort was made to reduce most of the curtain wall panels from free-form shapes to single-curved geometries. Finally, the design ensured that the façade gave the impression of the building being wrapped in a silky fabric.

Beyond the geometric aspects, other constructability challenges included the use of reinforced concrete and the integration of outrigger walls to ensure lateral stability, both of which fall under structural considerations. Aligning the undulating façade with the structural frame posed another structural challenge. From a project management perspective, the development, design, and construction processes required careful coordination, alongside addressing significant financial challenges associated with the project [69–71].

5.2.2. The Galaxy Soho Project in Beijing [36,72,73]

This project, designed by Zaha Hadid Architects, is renowned for its complex, curvilinear architecture. The building's fluid, non-repetitive forms required advanced 3D modeling and precise fabrication techniques. Achieving a seamless appearance necessitated custom-fabricated materials, increasing both cost and construction time. These complex-

ities made integrating design and construction processes essential to effectively address project challenges.

Computational design approaches played a pivotal role in overcoming constructability challenges associated with the building's flowing architecture. Advanced parametric modeling tools were used to develop the intricate geometry, ensuring design precision and structural feasibility. A fully automated BIM process enabled comprehensive virtual evaluations of the building's components and assemblies. Additionally, specialists focused on the geometric rationalization of the façade components to maximize value while maintaining artistic intent, optimizing the complex curves and surfaces for efficient and budget-conscious construction.

According to [36,72,73], the Galaxy Soho project in Beijing faced several geometric constructability challenges primarily due to the complex geometry of its sheet-metal components. One key challenge was avoiding expensive forming techniques for the fabrication process while ensuring the intricate shapes of the sheet metals could be accurately bent and formed. Additionally, the connections between the sheet metals and their attachment to the main structure required meticulous planning and execution. Another challenge involved reducing the variety of cone types used in the design, which helped streamline the fabrication and assembly processes without compromising the architectural intent.

Beyond the geometric aspects, the project required close collaboration between designers and builders to address the inadequacy of traditional construction methods, a significant project management challenge. Material selection, particularly for the exterior cladding, needed to strike a balance between achieving the desired aesthetic goals and adhering to the capabilities of local manufacturing processes. Moreover, producing accurate prototypes was essential to ensure the precise fabrication and seamless installation of the building's unique components, further emphasizing the importance of advanced fabrication techniques [74–76].

5.2.3. The Palazzo Italia in Milan [37,77,78]

Designed by Nemesi & Partners for Expo 2015 in Milan, this project is notable for its innovative design featuring a unique geometric texture evoking the random interweaving of branches, creating a dynamic “urban forest” concept. Furthermore, advanced sustainable technologies were employed in this project to achieve near-zero energy consumption and reduce air pollutants.

The pavilion's external “branched” envelope, composed of over 700 unique panels, necessitated advanced computational design approaches. These ensured each panel could be precisely fabricated to fit together seamlessly, despite their complex shapes. Computational design strategies transformed this ambitious architectural vision into a tangible structure, highlighting the critical role of digital tools in modern construction.

According to [37,77,78], this project presented several geometric constructability challenges associated with its complex design. The prefabricated pieces required adherence to specific dimensions, ensuring their seamless integration into the overall structure. Geometry refinement was necessary to optimize the steel weight, reducing the material used while maintaining structural integrity. Additionally, the project incorporated adjustable connections to facilitate assembly and improve adaptability during construction. Another significant challenge involved reducing the variety of angular component types to simplify fabrication while preserving the design's intent. The building's unique branched façade pattern, evocative of a forest, added an additional layer of complexity to the geometric considerations.

Apart from geometric concerns, the project faced challenges related to material innovation and project management. Innovative materials were employed to reduce air pollutants, aligning with the building's sustainability goals. The integration of photovoltaic glass into the roof design exemplified the intersection of aesthetic and environmental considerations. Furthermore, the project's complexity necessitated an integrated design process, fostering seamless collaboration among architects, engineers, and construction teams to address the intricate demands of the design and construction phases.

5.2.4. The Zahner Factory Expansion in Kansas City [37,79,80]

Completed in 2011 and designed by Crawford Architects, this project is recognized for its innovative façade inspired by metal oxidation patterns. The goal was to create a large, column-free assembly space with clear height for material movement, seamlessly connecting it to the existing factory floor. The design transformed an underutilized area into a transparent, functional space showcasing Zahner's ability to produce highly engineered forms.

The design's key components are vertically oriented fins, commonly used as structural backups behind organic façades manufactured by Zahner. Additionally, a glass panel system was implemented in this project to provide transparency between the factory's activities and the surrounding neighborhood, while offering ideal northern light to the assembly space. Computational design approaches were pivotal in addressing constructability challenges, particularly concerning the building's complex façade.

According to [37,79,80], the Zahner Factory Expansion project faced several geometric constructability challenges, particularly related to its innovative façade design. Custom-made aluminum panels were developed in the form of vertical fins, requiring careful attention to both design and fabrication. Optimizing the spacing of these fins was essential to maintain structural integrity while achieving the desired visual effect. Additionally, the fins were composed in a manner that created a wave-like impression, adding a dynamic and visually striking element to the building's exterior.

In addition to geometric challenges, the project encountered issues related to fabrication and project management. Efficient fabrication and assembly of the panels were critical to ensuring that the intricate design could be realized within the project's constraints. The effective integration of structural and aesthetic elements posed another significant challenge, demanding close collaboration among stakeholders. Moreover, prefabrication was prioritized to minimize on-site adjustments, streamlining the construction process and reducing potential delays.

Tables 1–3 summarize the cross-referencing of the new taxonomy's levels and constraints with the geometric constructability constraints identified in the selected projects. As shown, all identified constraints align with the new taxonomy's categories, supporting the validation of its structure.

With this validation, the new taxonomy can now serve as a control measure in the computational design process. By using the new taxonomy, computational designers can systematically review its levels to ensure that all related geometric constructability constraints are addressed. Moreover, computational designers will be able to incorporate necessary experts' knowledge and develop the corresponding constructability features, thereby streamlining their workflows more effectively. The next section focuses on applying a refined approach using the validated taxonomy.

Table 1. Validation of the new taxonomy’s micro level through external project examples.

Micro Level	
Taxonomy’s Geometric Constructability Constraints	Observed Geometric Constructability Constraints
Dimensional Constraints	Eight Spruce St.: - Stack at window sill: 14” above finish floor - Aluminum frame panels: 2” min. and 7” max width - Considering the fabrication and transportation constraints, a size of 2.5 × 4 m was sufficient
	Galaxy SOHO: The geometry of sheet metals ensures that the fabrication process does not cause additional costs due to the expensive forming techniques
	Palazzo Italia: Typical dimension of 4 × 4 m and 20 cm thickness
Shape Constraints	Zahner Factory Expansion: The custom-made aluminum panels in form of vertical fins are computationally designed (<i>Dimensional and Shape</i>)
	Eight Spruce St.: Curvy and sharply angular curtain walls
	Galaxy SOHO: The sheet metals are bent and formed
Building-Component Connection Constraints	Palazzo Italia: The unit geometries are calculated so that the overall steel weight is optimized
	Zahner Factory Expansion: The custom-made aluminum panels in form of vertical fins are computationally designed (<i>Dimensional and Shape</i>)
	Eight Spruce St.: 14,000 embedded aluminum brackets are used to attach the curtain wall to the main structure
	Galaxy SOHO: The connection of sheet metals is computationally designed
	Palazzo Italia: 5800 adjustable connections

Table 2. Validation of the new taxonomy’s meso level through external project examples.

Meso Level	
Taxonomy’s Geometric Constructability Constraints	Observed Geometric Constructability Constraints
Relational Placement Constraints	Zahner Factory Expansion: The optimized distance between fins
Intersection Constraints	Eight Spruce St.: Connecting the façade components with rivets

Table 3. Validation of the new taxonomy’s macro level through external project examples.

Macro Level	
Taxonomy’s Geometric Constructability Constraints	Observed Geometric Constructability Constraints
Typing Constraints	Eight Spruce St.: 90% of curtain wall panels were reduced from free-form to single-curved
	Galaxy SOHO: - Reduction in cone types by 30% Palazzo Italia: - Reduction in angular component types (30%)
Composition Constraints	Eight Spruce St.: Façade gives the impression that the building is wrapped in a silky fabric
	Galaxy SOHO: - The layout of the sheet metal panels is computationally designed Palazzo Italia: - Branched pattern in the façade that should mimic a forest Zahner Factory Expansion: - The composition of fins should give the impression of waves

6. Conceptual Approach for Knowledge-Based Computational Design Using the New Taxonomy for Geometric Constructability Constraints

Building on the identified geometric constructability features (Section 4) and the proposed taxonomy (Section 5.1), the following section introduces a new systematic approach for integrating experts’ knowledge into computational design process. To provide readers with a clearer understanding of the proposed changes, the current common computational design process is first discussed before presenting the refined conceptual approach.

6.1. Current Computational Design Approach

Figure 10 illustrates the typical computational design approach when dealing with unique designs using UML Activity Diagram notation. In this approach, when the design team is confronted with a complex design with challenging geometric constructability conditions, their common practice involves reviewing and analyzing the design concept to identify potential constructability issues. This analysis usually includes internal iterations within the organization but often excludes engaging external practitioners due to project contract models and other project-related circumstances that hinder such engagement. Following the internal design review, the computational designer formulates an algorithm that is applied to the building information model of the project (sometimes only a parametric model is available). It is at this stage that the iterative process with project stakeholders begins, who are responsible for making decisions regarding various design options and their constructability. This approach was also observed in the OC project.

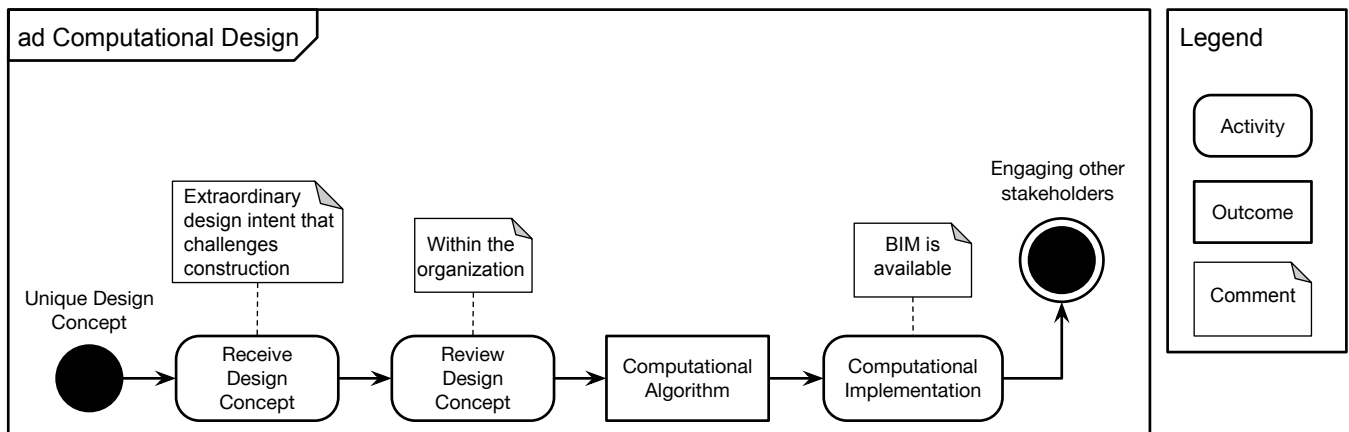


Figure 10. Current computational design approach without engaging external expert knowledge.

6.2. Refined Computational Design Approach Using the New Taxonomy

In the approach described above, stakeholders lack upfront practitioners' input in their decision-making process, which may lead to significant drawbacks during project implementation. Furthermore, the examples in Section 4 highlight that complex geometric design conditions can cause different constructability constraints, affecting the fabrication and installation process of the building components. These examples also show how developing suitable features in design models can convey the necessary practitioners' knowledge into the computational design process, addressing constructability constraints during the design. The examples provided were the practical motivation for the research team to develop a conceptual systematic approach for knowledge-based computational design using geometric constructability features, as shown in Figure 11, using UML Activity Diagram notation.

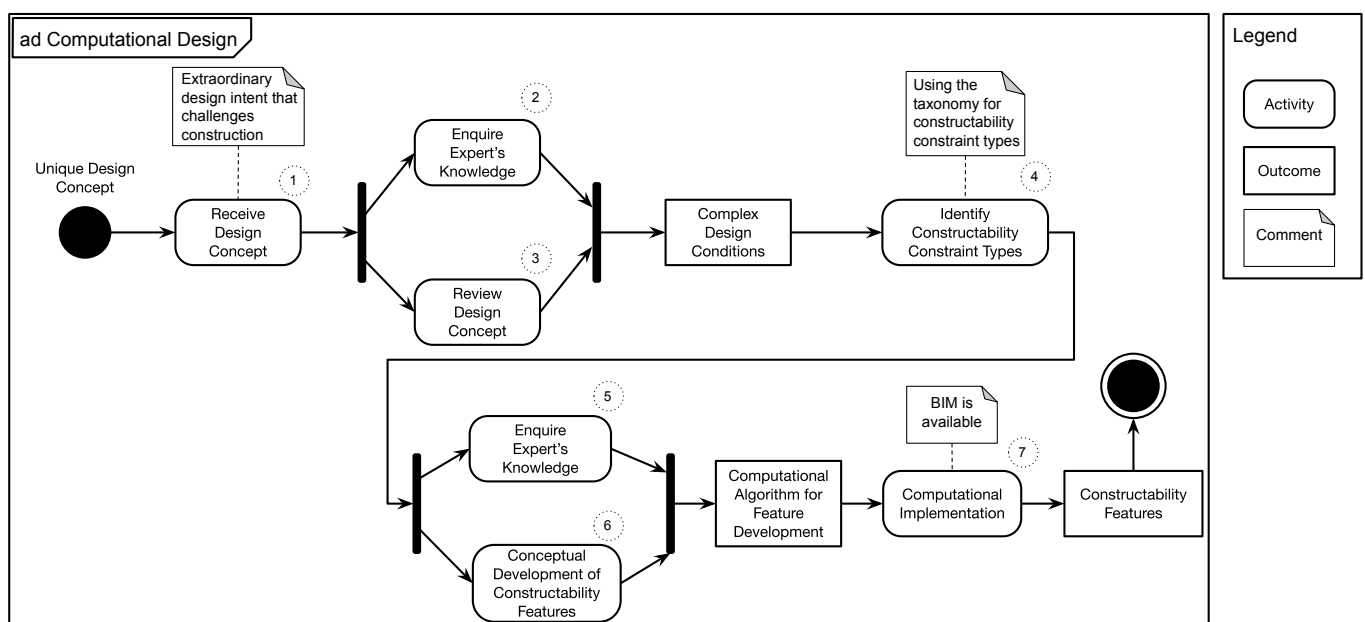


Figure 11. Conceptual approach for knowledge-based computational design using constructability features.

In this approach, the computational designer relies on the consultation of practitioners in reviewing the design concept and identifying complex geometric design conditions that can cause constructability challenges (activities 2 and 3). Using the identified complex geometric design conditions from the previous steps, the designer can determine the

relevant types of constructability constraint that arise from those complex design conditions (activity 4). This activity uses the new taxonomy for geometric constructability constraints and features that is introduced in the previous section.

By employing the new taxonomy, computational designers can systematically go through its levels to ensure that all related geometric constructability constraints are captured.

Next, the computational designer involves the practitioner's knowledge in developing the required geometric constructability features, creating the suitable computational algorithm (activities 5 and 6). After this stage, the designer can computationally implement the developed algorithm using BIM (or sometimes a parametric model) as an information source (activity 7). In this way, constructability features can be computationally implemented considering the expert's knowledge.

6.3. Validation of the Refined Computational Design Approach by Cross-Referencing Existing Research

The primary objective of the presented conceptual computational design approach in this section is to address the lack of a structured method for integrating constructability knowledge at the micro, meso, and macro levels into the computational design process.

The proposed activities in this approach are designed to minimally disrupt common computational practices, introducing minor yet effective enhancements to the existing methods familiar to practitioners, which are anticipated to make its adoption more appealing by aligning with current workflows.

While the idea of more frequent and early engagement of domain experts in the design process is not novel, the new taxonomy introduced in this research sets this approach apart from the common computational design methods currently used in the industry. Therefore, validating the refined computational design approach involves two main pillars: first, the validation of the new taxonomy, as presented in the previous section, and second, the validation of the proposed activities for integrating experts' knowledge, which is discussed in the remainder of this section.

The cross-referencing methodology is employed to validate the proposed new activities outlined above. Existing research highlights that engaging downstream experts during the design process, such as builders, manufacturers, and field trades, is particularly feasible for projects involving prefabricated elements [3,41,81]. However, this engagement requires the implementation of appropriate collaborative project delivery methods [41,82] and the establishment of collaborative infrastructure, particularly through BIM platforms [41,83,84]. The importance of collaborative construction practices was further emphasized in all four external projects introduced in the previous section. Thus, it can be concluded that the early involvement of downstream experts during the design process is a valid assumption.

Conversely, the lack of such necessary collaborative construction practices for effective practitioner engagement can create notable inefficiencies. This was partially the case in the OC project, which led to multiple constructability challenges on site, as observed by the research team and raised by the practitioners during the interviews conducted. The main two reasons frequently mentioned in these interviews were:

1. A traditional delivery model that did not allow practitioners to freely and frequently exchange with one another.
2. A lack of maturity in the project team, with the exception of the design team, in terms of using BIM.

Examples of the missing constructability features mentioned by the practitioners in the OC project are:

- The placement of the connections on the panels could have been optimized further with the sufficient engagement of the manufacturer. In fact, the manufacturer modified the suggested placements to facilitate the fabrication process, leading to issues during the installation.
- The arrangement of the connections on each panel had a high variance, resulting in confusion on site when choosing the right panel, as panels of the same type could have different arrangements of connections.
- The order of the placement of the panels on the trucks could have been organized to follow the installation sequence, avoiding unnecessary crane and crew time on site.

7. Conclusions and Future Works

This paper has outlined a conceptual approach that leverages knowledge-based computational design to enhance the constructability of prefabricated façade panels. Through a case-study project, it demonstrates how feature-based modeling can effectively navigate geometric design complexities, uniting aesthetics with construction realities.

This research advances the state of the art by proposing a novel taxonomy and a conceptual approach that systematically integrates domain experts' constructability knowledge into computational design processes. Unlike existing methods, which often focus on isolated aspects of constructability, this approach provides a comprehensive framework that bridges the gap between design intent and construction feasibility. By validating the taxonomy across diverse architectural projects, the study demonstrates its versatility and potential for broad application. Furthermore, the proposed framework highlights a pathway for leveraging feature-based modeling in addressing geometric constructability challenges, setting the foundation for future innovations in integrating computational design with practical construction knowledge.

Given the scarcity of applications using feature-based modeling to integrate expert knowledge for constructability in the design process, a reverse reasoning process was adopted, deriving solutions from analyzing past cases. To this end, a series of constructability constraints from an ethnographic case study was presented, and for each identified constraint, domain expert input and the implementation of the respective constructability feature in computational design were discussed. As a result of this investigation, a new taxonomy with three levels was introduced to capture domain experts' knowledge on typical constructability constraints and the associated features. The new taxonomy's three main levels are: component (micro), interrelationship (meso), and contextual (macro).

Furthermore, to validate the details of the new taxonomy, a cross-referencing methodology was employed using various examples from projects with complex architecture. This validation also showcased the taxonomy's broad applicability in classifying geometric constructability constraints and features of prefabricated façades, independent of specific project details.

Ultimately, a refined conceptual approach for knowledge-based computational design was proposed, incorporating the new taxonomy for geometric constructability constraints and features, thus enabling a systematic integration of domain experts' knowledge. This refined conceptual approach was then validated through cross-referencing its key elements with the existing body of knowledge.

It should be noted that this research has certain limitations, primarily due to its reliance on a single case study, which restricts its ability to comprehensively address all aspects of constructability knowledge. To clarify this limitation, a theoretical two-dimensional framework of constructability constraints was presented, that also can be used as a roadmap for future research.

Another limitation is that the research team joined the project after its computational design was completed. While the team had access to project documents, meetings, and project participants, there was no opportunity to elevate this study to an action research project.

Different constructability issues and their resulting impacts are not equal. Additionally, incorporating expert knowledge into the computational design process and developing respective model-based features require additional organizational and financial efforts. For instance, in the case of the OC project, there was an opportunity to optimize the positioning of the hooks on top of the façade panels to allow the panels to be lifted and brought to the workers at the main structure in an upright position by the crane. The impact of this constructability feature would have been a smoother installation process and a significant saving in construction time on site. On the other hand, implementing Feature 5 and optimizing the number of panel types in this project through shifting from fully customized panels to a limited number of standardized types resulted in massive savings in the project budget. This shows that, while both examples address important aspects of constructability, their impacts on the project are not equivalent. Therefore, due diligence is necessary when reviewing constructability issues to carefully select which ones need to be addressed and what computational features need to be created. In this regard, a weighting system for constructability issues to prioritize their importance for a construction project might be necessary. This requires further investigation, which the research team envisions exploring in future work. Moreover, looking ahead, the research team aims to expand this work to include constructability constraint types from the presented framework that were not covered in the current research.

Additionally, the research team plans to expand upon the current conceptual approach. The operationalization of this work will be piloted in a future project to further validate the conceptual framework and assess its effectiveness in a real-world scenario. By doing so, the team anticipates demonstrating significant advancements in the efficiency of design and construction processes, particularly in off-site construction, where the benefits of prefabrication combined with BIM can be fully realized. This future work will not only reinforce the practical value of the current approach but will also set the stage for a new paradigm in integrating computational design and constructability within the architecture, engineering, and construction industry.

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Conflicts of Interest: The authors declare no conflict of interest.

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