Design configurator for mid-rise modular residential buildings

by

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Configurateur de conception pour bâtiments résidentiels modulaires de moyenne hauteur

Bruno LLAVE PONCE DE LEÓN

RÉSUMÉ

L’industrie de la construction fait face à des défis sans précédent en raison de l’urbanisation rapide et de la demande croissante de projets résidentiels durables. La construction modulaire a émergé comme une solution prometteuse pour répondre à la crise mondiale du logement en offrant de l’efficacité, une réduction de l’impact environnemental et des délais de construction plus courts. Cependant, son adoption reste lente en raison des complexités inhérentes et d’un manque significatif de connaissances sur les aspects logistiques, de fabrication et d’assemblage pendant les premières étapes des projets. Cette recherche se concentre sur l’application de la technologie de modélisation de l’information du domaine de la construction (BIM), en particulier l’utilisation de plateformes de configuration basées sur le BIM, comme outil pour combler les lacunes en matière de connaissances nécessaires au développement de projets de bâtiments résidentiels modulaires dans leurs étapes initiales, facilitant ainsi leur adoption.

La recherche vise à comprendre, concevoir et proposer une plateforme de configuration basée sur le BIM pour combler les lacunes existantes en matière d’information sur le transport, la fabrication et l’installation qui limitent l’adoption des méthodologies modulaires. Pour y parvenir, une revue de la littérature académique existante concernant l’utilisation des configurateurs dans la construction a été réalisée, identifiant leurs capacités et les différents domaines d’action dans lesquels ils ont un impact. De plus, cette recherche passe en revue et compare les configurateurs disponibles sur le marché pour identifier les critères permettant de concevoir et de proposer un système de configuration pour un bâtiment résidentiel modulaire, qui sera mis en œuvre dans un cas réel.

La méthodologie de recherche en sciences de la conception (DSR) a été choisie pour son processus itératif et sa rétroaction continue, idéale pour développer des solutions innovantes et pratiques. Cette approche garantit que les solutions soient théoriquement solides et pratiquement applicables, améliorant possiblement l’efficacité et la personnalisation des projets de construction modulaire.

Les résultats de cette recherche indiquent que les plateformes de configuration basées sur BIM ont un potentiel significatif pour améliorer l’adoption de la construction modulaire en facilitant la coordination de l’information, en réduisant les délais et les coûts dans les premières étapes grâce à leur capacité à automatiser la génération d’options de conception et à fournir des informations pour les étapes suivantes du cycle de vie. Elles permettent également de comparer différentes options de conception et de les personnaliser pour répondre aux besoins du projet.

En conclusion, cette thèse vise à contribuer au domaine de l’ingénierie de la construction en approfondissant la compréhension du potentiel des plateformes de configuration basées sur le BIM pour améliorer l’adoption de la construction modulaire à partir des perspectives théoriques et pratiques.

Mots-clés: Construction modulaire; Systèmes de configuration; BIM; Conception computationnelle; Bâtiments résidentiels; Construction hors-site

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ABSTRACT

The construction industry faces unprecedented challenges due to rapid urbanization and the growing demand for sustainable residential projects. Modular construction has emerged as a promising solution to address the global housing crisis by offering efficiency, reduced environmental impact, and shorter construction times. However, its adoption remains slow due to inherent complexities and a significant lack of knowledge regarding logistical, manufacturing, and assembly aspects during the early stages of projects. This research focuses on the application of Building Information Modeling (BIM) technology, specifically the use of BIM-based configuration platforms, as a tool to address the knowledge gaps necessary for the development of modular residential building projects in their initial stages, thereby facilitating their adoption.

The study aims to understand, design, and propose a BIM-based configuration platform to address existing information gaps related to transportation, manufacturing, and installation that hinder the adoption of modular methodologies. To achieve this, a review of the existing academic literature on the use of configurators in construction was conducted, identifying their capabilities and the various fields they impact. Additionally, the study reviews and compares available configurators on the market to identify criteria for designing and proposing a configuration system for a modular residential building, which will be implemented in a real-world case.

The Design-Science Research (DSR) methodology was selected for its iterative process and continuous feedback, ideal for developing innovative and practical solutions. This approach ensures that the solutions are theoretically sound and practically applicable, potentially improving the efficiency and customization of modular construction projects.

The results indicate that BIM-based configuration platforms have significant potential to enhance the adoption of modular construction by facilitating information coordination, reducing time and costs in the initial stages due to their ability to automate the generation of design options and provide information for subsequent stages in the lifecycle. They also allow for the comparison of different design options and customization to meet project needs.

In conclusion, this thesis aims to contribute to the field of construction engineering by deepening the understanding of the potential of BIM-based configuration platforms to improve the adoption of modular construction from both theoretical and practical perspectives.

Keywords: Modular Construction; Configuration Systems; BIM; Computational design; Residential Buildings; Off-site construction

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LIST OF ABREVIATIONS AND ACRONYMS

AEC	Architecture, Engineering and Construction
AI	Artificial Intelligence
BIM	Building Information Modeling
CD	Computational Design
CSCE	Canadian Society for Civil Engineering
DfMA	Design for Manufacturing and Assembly
DSR	Design Science Research
ERP	Enterprise Resource Planning
IoT	Internet of Things
KCN	Keyword Co-occurrence Network
OSC	Off-Site Construction
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
SLR	Systematic Literature Review

INTRODUCTION

The construction industry is facing a major challenge worldwide, trying to meet the growing demand for housing while also aiming for sustainable development. To address rapid urbanization and population growth, the industry is looking for efficient and environmentally friendly housing solutions. Volumetric modular construction, a type of off-site construction (OSC), was chosen as the most appropriate method for this thesis because it offers significant benefits in terms of speed, quality control, and waste reduction. Unlike other OSC methods, volumetric modular construction delivers complete three-dimensional modules, making it ideal for medium-density residential projects. This method minimizes on-site work, which helps reduce disruptions, improves safety, and ensures higher precision through factory-controlled environments. Despite its advantages, combining modular techniques with traditional construction remains challenging, especially during the early design stages, where balancing precision and adaptability is essential.

Building Information Modeling (BIM) is a methodology that has formed a paradigm shift in the way construction projects are managed. BIM goes beyond the three-dimensional representation of the architectural model of a project; it is a complete digital representation of all the information that exists in the project, allowing interaction and integration at every stage of construction. This technology can be especially effective in the field of modular construction because it allows collaborative work within a common data environment, as it centralizes information and allows the creation of information chains that are used at dissimilar stages of the project. This research aims to explore the capabilities of BIM configuration platforms for residential modular construction projects and develop strategies for their effective integration in the contemporary environment. The project aims to establish a framework to effectively utilize BIM to enhance the initial design phases of modular construction by leveraging these concepts.

The main objective of this research is to investigate the impact and improve the use of BIM-based configuration tools in the initial phases of modular residential building design. The study aims to evaluate how BIM can improve accuracy and productivity in the design of modular residential buildings by addressing existing gaps in information related to transportation, fabrication, and installation. These gaps currently hinder the widespread acceptance and application of this off-site construction method.

This research is driven by several important scientific questions: What are the functions provided by commercially available configuration platforms for construction projects? What would be the best design approach for a configuration platform in modular residential projects that would help to minimize the impact of knowledge gaps on the early stages of the project in shipping, manufacturing, and assembly? How a medium-density residential buildings can apply a BIM-based configuration system at the initial stage to enable stakeholders make decisions when adopting modular construction for housing? This research employs a mixed methods approach, integrating qualitative and quantitative research methods to outline the state of the art in the use of these methodologies, to identify the various mechanisms for the development of a BIM configuration platform and to identify how these affects modular construction. The methodology includes case studies, simulations, and comparative analysis to gain data-driven insights and validate theoretical models.

This research aims to contribute to the field of building engineering by improving the understanding of the potential of BIM in modular construction. It intends to address both theoretical and practical shortcomings to promote innovative approaches that have the potential to revolutionize residential construction. The implementation of these strategies may contribute to improve sustainability, optimize efficiency, and promote adaptability to future needs.

This thesis is structured into five chapters, each addressing crucial aspects for understanding, designing, and implementing configuration platforms for modular residential construction projects. Chapter 1 presents a systematic literature review on the use of configuration platforms in off-site construction, using the PRISMA framework to identify and catalog their various functions and features. Chapter 2 focuses on the Design Science Research (DSR) methodology, describing its iterative process of creation, continuous critical reflection, and design cycle, and its application in developing a framework for using configuration platforms in modular residential buildings. In chapter 3, the role of digital configuration platforms in addressing the housing shortage through modular construction is introduced and evaluated, identifying criteria for comparing existing configurators on the market and suggesting areas for future research. Chapter 4 centers on the development of a BIM-based configuration system for the early stages of designing modular residential projects and discusses its potential impact. Finally, Chapter 5 presents the implementation of the workflow in a real case, describing the methodology used, the development and implementation of the framework, and the results and discussions of the pilot project, concluding with insights gained and their implications for future applications.

CHAPTER 1

SYSTEMATIC LITERATURE REVIEW

1.1 Introduction

This chapter of the thesis undertakes a comprehensive literature review of existing commercial configuration platforms used in off-site construction. The primary objective is to systematically identify and catalog the various functions these platforms offer, thereby creating a detailed inventory of features and functionalities. This will help in understanding the current capabilities within the industry and assist in pinpointing areas that require further innovation.

The specific aims of this literature review are twofold. Firstly, to identify topics within the construction field that are particularly related to the concept of configuration platforms at the design stage (Objective 1). This involves analyzing how these platforms integrate with current construction methodologies and their impact on design efficiencies. Secondly, the review aims to propose a general framework for the use of configuration platforms (Objective 2), guiding their implementation and optimization in practical settings.

The methodology chosen for this literature review is structured around the PRISMA framework, ensuring a systematic and transparent approach to data collection and analysis (Page et al., 2021). This method will guide the identification of relevant studies, screening for quality and relevance, and the subsequent synthesis of findings to form a coherent understanding of the topic. By adhering to this structured approach, the review aims to offer robust insights that can support the development and application of innovative configuration systems in off-site construction.

1.2 Methodology

Similar to the snowballing technique, finding new sources of information by looking at the bibliographic references of articles with relevant information about the research question will be conducted. It reviews the references of the paper's bibliographic references. Despite the randomization degree of the results (Heckathorn & Cameron, 2017), this method was used as a first step to explore the relationship between configuration platforms with concepts like Design to Manufacturing and Assembly (DfMA) or Computational Design (CD) to identify applications, linkages, and technologies, relevant to this document. A control chart (Annexe 1) was used to register the resulting information and categorize it according to the topic domains and their posterior use in the SLR.

As a second step, after having developed some understanding of the research domain, and having identified relevant keywords, a SLR was developed to find the most relevant articles to the research topic (Karimi & Iordanova, 2021). The next section will explain the process of finding the data and a qualitative and quantitative analysis of the resulting group of documents. This study employs the SLR approach based on the PRISMA statement. The framework includes both bibliometric analysis and qualitative analysis, and there are three phases: (1) Data collection: finding publications, checking eligibility, screening publications, and selecting relevant publications; (2) Bibliometric analysis: analyzing document content through science mapping co-occurrence method using VOSviewer (keyword co-occurrences, citation relations, co-authorship analysis, identification of influential organization and countries) and (3) Data qualitative analysis: application of content analysis method (the decontextualization, the recontextualization, the categorization and the compilation (Borrego et al., 2014).

1.3 Search strategy

In order to narrow the research, the web Scopus has been used as a database because its scientific journal papers collection is more extensive than others (Manzoor et al., 2021; Waltman, 2016). The concepts of configuration platforms have a wide range of interpretations in different fields, whereby the search has been limited to the engineering field.

The definition of configuration platform and construction has been covered using a list of different concepts to allow a wide range of results. These keywords have been used to conduct a comprehensive search related to the construction field and the configuration platform in order to accomplish the objectives mentioned in the introduction of this section.

The bibliometric search equation was inputted in Scopus denoted below:
TITLE-ABS-KEY ((“*building*" OR “*construction*")

AND

(“*prefabricat*” OR “modular” OR “manufactur*” OR “industrialized”)

AND

(“*configurat*” OR “*platform*”)

AND

(“mass customization” OR “design”)

The PRISMA statement workflow is graphed in Fig. 1.1, and it is divided into three stages. The identification stage is where the first group of documents are filtered on Scopus in order to achieve the eligibility criteria of the search. The documents considered for this process are from 2012 to 2023 to ensure that the most current and relevant information was utilized, reflecting the rapid developments in the field. The documents type selected were articles in final stage, in English, and with the following keywords: Architectural design, Buildings, Building, Office Buildings, Construction, Construction Industry. Then, in the screening stage, the resulting documents (Annex 2) were filtered by their content in titles, abstracts, and keywords. Finally, the science mapping stage is dedicated to quantitative and qualitative analysis. For this step, the list of papers resulting from the snowballing technique were included.

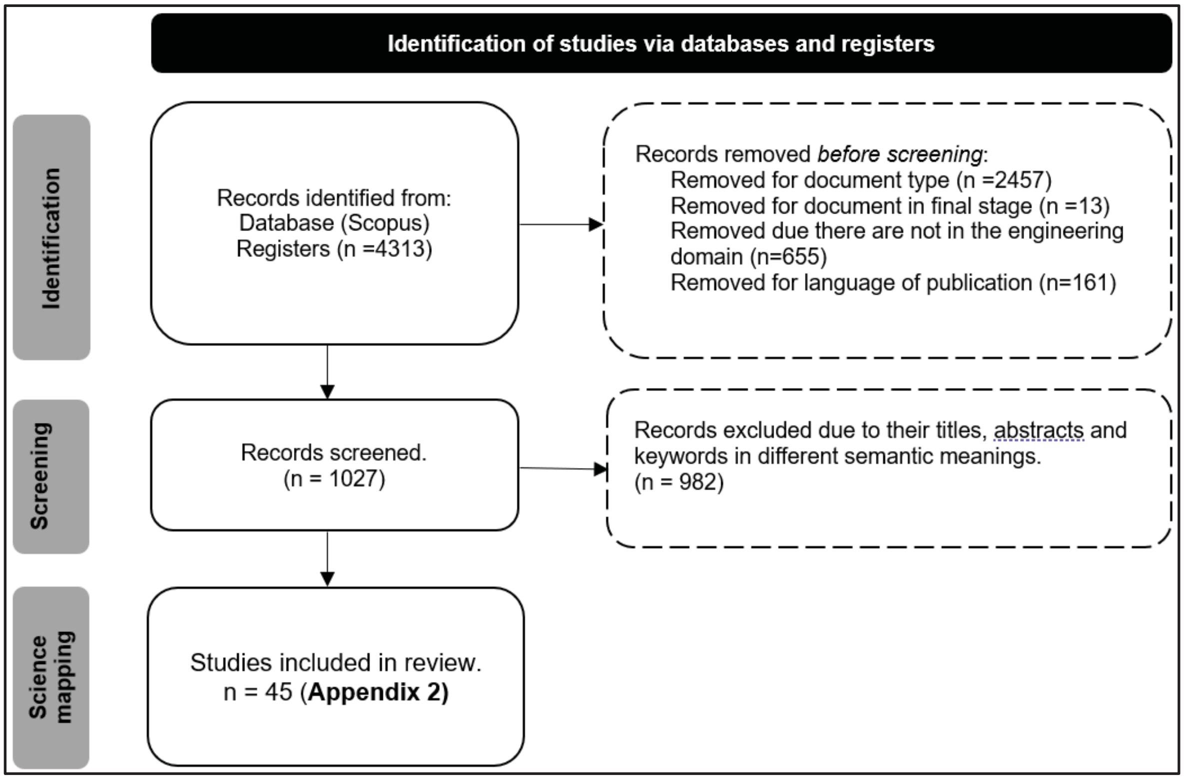


Figure 1.1 PRISMA workflow chart

1.4 Bibliometric analysis

The integration of various technologies such as artificial intelligence, robotics, augmented reality, and others is a frequent and significant topic within the scientific construction community (Wang et al., 2020). Configuration platforms have not had such an adoption level at the time of conducting this research. Probably because its adoption depends on the previous adoption of other technologies, besides affecting the vertical and longitudinal production business structure (Hall et al., 2020).

The uses of configuration platform in the engineering field have been extensively analyzed. However, after the identification stage, of the 1027 publications screened, just around 3% (45 papers) were identified as belonging to the AEC field. Figure 7 shows the proportion of the selected articles against the rest of them. The selection process of the documents was based on the examination of their title or abstract in order to identify information related to the use of configuration platform in the design stage of an AEC project.

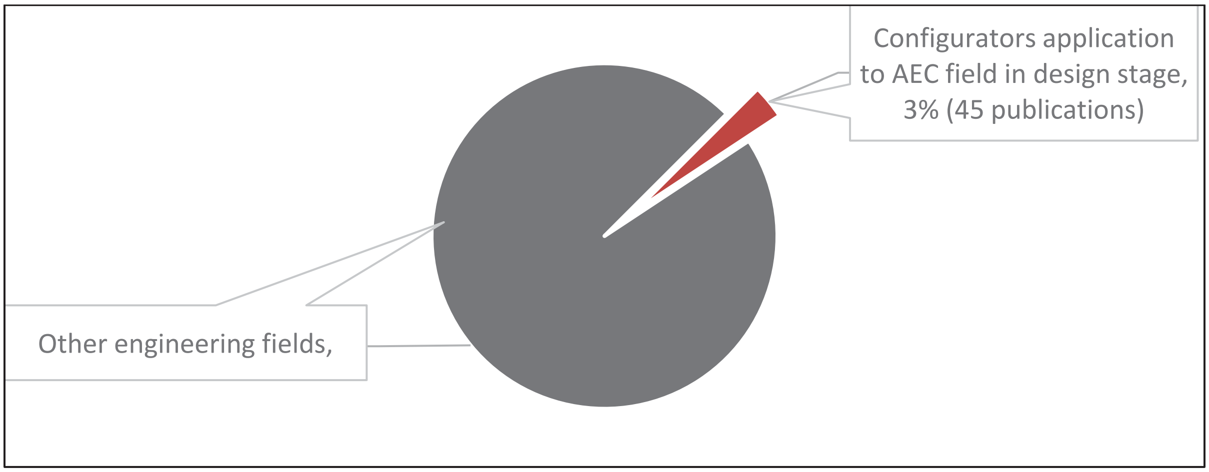


Figure 1.2 Pie chart of results in Screening of the PRISMA process

The following sections are dedicated to performing different bibliometric analyses to provide interpretations from the extracted data.

1.4.1 Keyword co-occurrence network

A Keyword co-occurrence network (KCN) analysis can help framing the research domain because it can identify the relationships between different topics within a research domain. (Radhakrishnan et al., 2017). This KCN was made using VOSViewer to show different colors for each cluster, where the size of the nodes represents the frequencies of occurrence of the respective keywords, the curves of the relationship between keywords, and the lines opacity the degree of connection between concepts. The threshold setting considers a minimum number of 5 occurrences to define clusters for the study.

The results of the study (Figure 1.3), show "architectural design" as the strongest keyword even when it was not used in the search equation. The score of this test is registered in Table 1.1, that shows the relation of the keywords according to their nature in the knowledge domain.

In that regard, it is feasible to identify three distinct categories according to the nature of the concepts. Table 1.2 groups these concepts and the quantitative section describes the overall approach of the reviewed articles about these keywords.

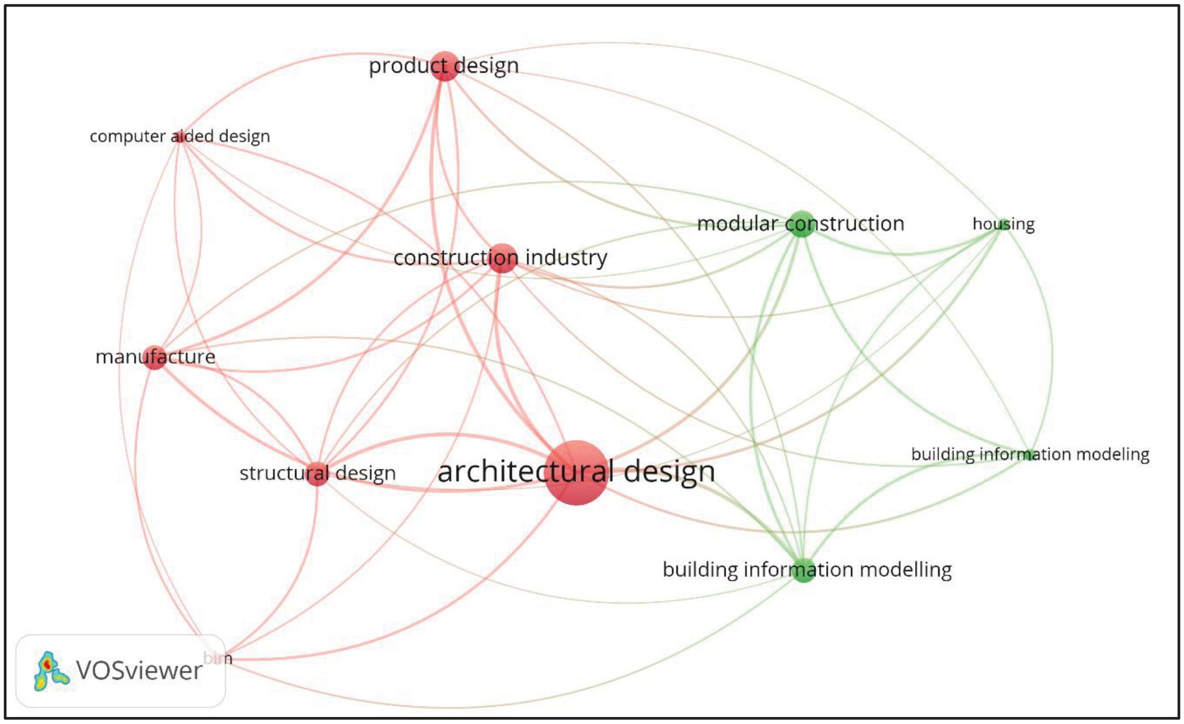


Figure 1.3 Keyword co-occurrence network

Table 1.1 Keyword co-occurrence network score

Keyword	Occurrences	Total link strength
architectural design	26	67
construction industry	12	36
modular construction	11	34
product design	12	34
building information modelling	10	30
manufacture	10	30
structural design	10	30
building information modeling	5	18
housing	5	18
bim	5	17
computer aided design	5	16

Table 1.2 Keyword categories

General concepts	Application domain	Methodology
Construction industry	Architectural design	Building Information Modelling
	Structural design	Modular construction
	Product design	
	Manufacture	

1.4.2 Citation Relations

The citation relations study allows for the identification of the most referenced publications and subsequently the analysis of their impact in the academic domain. Therefore, citation relationship analysis brings indicators of scientific activity. These studies have also helped to clarify the nature, structure, and development of science, as well as signaling the processes in which the science is developed (Vanz and Caregnato, quoted in (Ramos et al., 2012). Furthermore, this study will allow the identification of authors and their organizations which in turn generates relevant content to this domain (Waltman, 2016).

In order to identify the most relevant publications the minimum number of citations was set at 10. In the graphic, the diameter of the nodes represents the number of citations by publication, each color identifies a cluster, and the arcs are the connection between each other.

The result of this study is displayed in Figure 1.4 The influence of these articles can be determined by the number of citations and link strength indicated in Table 1.3.

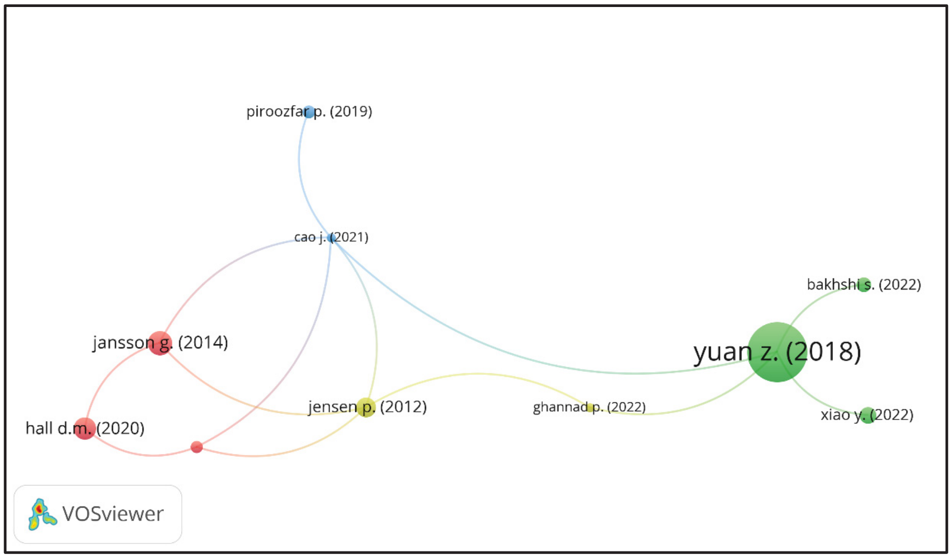


Figure 1.4 Citation Relations networks result

Table 1.3 Citation score

Document	Citations	Links
Cao J. (2021)	28	5
Yuan Z. (2018)	179	4
Jensen P. (2012)	60	4
Wikberg F. (2014)	36	3
Jansson G. (2014)	73	3
Hall D.M. (2020)	67	2
Ghannad P. (2022)	28	2
Piroozfar P. (2019)	38	1
Xiao Y. (2022)	50	1
Bakhshi S. (2022)	45	1
Ezzeddine A. (2021)	35	0
Haghir S. (2021)	14	0
Rezaei Rad A. (2021)	10	0
Baghdadi A. (2020)	32	0
Gravina Da Rocha C. (2020)	10	0
Pantazis E. (2018)	20	0
Potseluyko L. (2022)	17	0
Wang B. (2022)	15	0
Yang B. (2022)	12	0
Reisinger J. (2022)	16	0

According to (Bu et al., 2021) to understand the impact of the publication it is necessary to analyse them from a multidimensional perspective to understand why these works are so cited. Also, (Ramos et al., 2012), indicates that there are two principal reasons to cite an article: 1) for the value of the content related to a specific topic in the domain or its relevance in the general domain, and 2) the prestige of the quoted authors. Hence, it is necessary to analyse qualitatively these results in order to get a comprehensive understanding of the real impact of this result.

1.4.3 Co-authorship analysis

According to (Newman, 2004), "co-authorship of a paper can be thought of as documenting a collaboration between two or more authors, and these collaborations form a "co-authorship network". Co-authorship networks provide a copious and meticulously documented record of the social and professional networks of scientists." Awareness of the existing scientific collaboration networks in any field of research facilitates access to funds, specialties, and expertise; enhances productivity; and assists investigators to reduce isolation (Hosseini et al., 2018).

To perform the study, the minimum number of documents of an author was set at 2 for VOSviewer. In Figure 1.5 the dimension of the nodes is proportionally related to the number of published articles associated with each author, the lines indicate their relationship, the distance of the nodes are inversely related to the closeness of their collaboration and the colors are used to identify different clusters. Table 1.4 presents the co-authorship score table derived from this study.

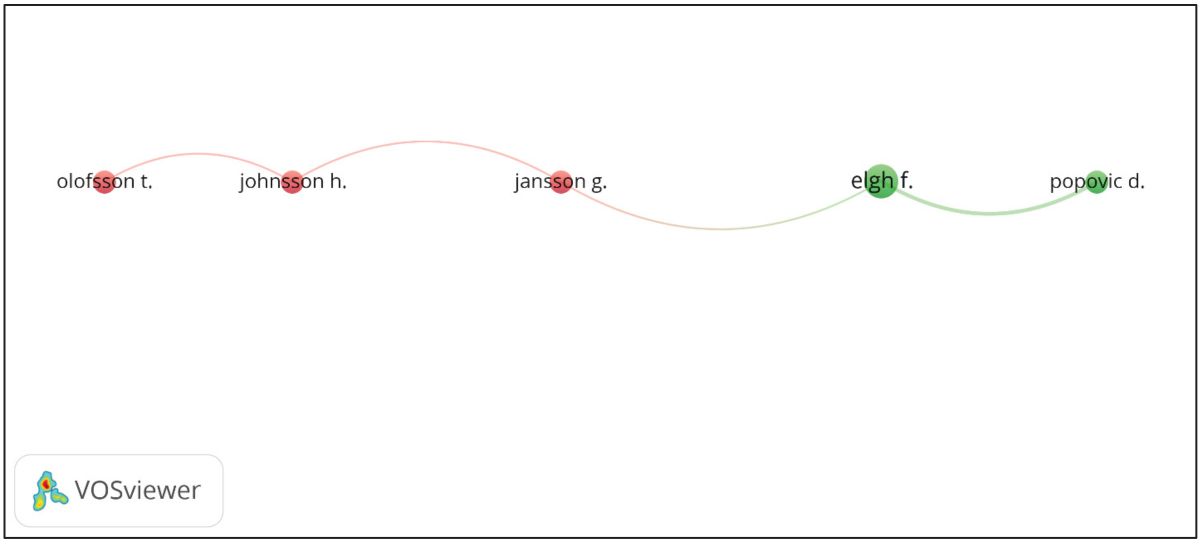


Figure 1.5 Co-authorship analysis network result

Table 1.4 Co-authorship score

Author	Documents	Citations	Total link strength
Elgh F.	3	14	3
Dawood N.	2	62	2
Ghannad P.	2	28	2
Hall D.M.	2	95	2
Jansson G.	2	80	2
Johnsson H.	2	133	2
Lee Y.-C.	3	29	2
Lessing J.	2	95	2
Popovic D.	2	7	2
Pour Rahimian F.	2	62	2
Olofsson T.	2	96	1
Kovacic I.	2	17	2

The analysis of the co-authorship network reveals several important insights:

- Collaboration Patterns: The network visualization indicates that authors with more publications tend to be central nodes within the network, suggesting they play a key role in fostering collaborations. For instance, Elgh F. and Lee Y.-C., both with three documents each, show higher prominence within the network.

- Interdisciplinary Connections: The presence of various clusters in different colors highlights the diversity and interdisciplinary nature of the collaborations. This suggests that researchers are engaging across different domains, thereby enriching the research with a broader perspective.
- Impact of Collaboration: Authors with higher citation counts, such as Johnsson H. and Hall D.M., with 133 and 95 citations respectively, also demonstrate significant link strengths. This indicates that productive collaborations are often associated with higher citation impacts, reflecting the quality and influence of the collaborative work.
- Strength of Links: The total link strength score provides insight into the intensity and frequency of collaborations. Authors like Elgh F., Dawood N., and Lee Y.-C., with higher link strengths, exhibit robust collaborative networks, which may lead to more significant research outputs.
- Isolation and Integration: The analysis helps identify potentially isolated researchers or clusters within the network. These insights can be valuable for fostering new collaborations and integrating isolated researchers into the broader scientific community.

In conclusion, co-authorship analysis serves as a vital tool in understanding the dynamics of scientific collaborations. By mapping out these networks, researchers can better navigate the landscape of their respective fields, identify key collaborators, and enhance the impact of their research through strategic partnerships. The results underscore the importance of fostering strong, interdisciplinary collaborations to advance scientific knowledge and innovation.

1.4.4 Influential Organization

In this section, the articles were analyzed with the objective of identifying the organizations that financed the development of the publications. The results in Table 1.5 were developed considering a threshold with a minimum of 50 citations and just 14 meet the parameters.

Table 1.5 Influential Organization score

Organization	Documents	Citations	Total link strength
Division of structural and construction engineering, Lulea university of technology, Lulea, Sweden	1	73	5
Ncc construction, Sweden	1	73	5
Electronics and communication engineering department, national institute of technology, Hamirpur, India	1	50	4
Guangzhou city polytechnic, Guangdong province, Guangzhou, China	1	50	4
School of computing, engineering & digital technologies, Teesside university, Middlesbrough, United Kingdom	2	62	4
Key lab of smart prevention and mitigation of civil engineering disasters of the ministry of industry and information technology, Beijing university of technology, Beijing, China	1	179	3
Key lab of structures dynamic behavior and control of the ministry of education, Harbin institute of technology, Harbin, China	1	179	3
School of economics and management engineering, Beijing university of civil engineering and architecture, Beijing, China	1	179	3
School of management, Harbin institute of technology, Harbin, 150001, China	1	179	3
Centre for systems engineering and innovation, department of civil and environmental engineering, imperial college London, London, United Kingdom	1	67	2
Construction management, civil and environmental engineering, Lulea university of technology, Lulea, Sweden	1	60	2
Department of civil and environmental engineering, Stanford university, Stanford, ca, united states	1	67	2
Institute of construction and infrastructure management, department of civil, environmental and geomatic engineering, eth Zurich, Zurich, Switzerland	1	67	2
Structural engineering, civil and environmental engineering, Lulea university of technology, Lulea, Sweden	1	60	2

The analysis highlights several key points regarding influential organizations in the field:

- Prominent Contributors: The Division of Structural and Construction Engineering at Lulea University of Technology in Sweden, alongside NCC Construction in Sweden, stands out with 73 citations each and a total link strength of 5. This indicates their significant contribution and influence in the research community, underlining their role in advancing construction engineering research.
- International Diversity: The influential organizations span multiple countries, including Sweden, India, China, the United Kingdom, and the United States. This geographical diversity illustrates the global nature of research collaboration and the widespread support for advancing construction and civil engineering fields.
- High-Impact Research: Several organizations, such as the Beijing University of Technology and the Harbin Institute of Technology in China, show exceptionally high citation counts (179 citations each). This suggests that these institutions are producing high-impact research that resonates widely within the academic community.
- Collaborative Networks: The total link strength scores reveal the extent of collaborative networks. Organizations with higher link strengths, such as the Division of Structural and Construction Engineering at Lulea University of Technology, demonstrate robust collaborative ties, which may facilitate more comprehensive and interdisciplinary research outputs.
- Specialized Contributions: Institutions like the Key Lab of Smart Prevention and Mitigation of Civil Engineering Disasters and the Key Lab of Structures Dynamic Behavior and Control, both in China, highlight specialized research contributions. Their focused expertise in specific areas of civil engineering disasters and dynamic behavior of structures contributes to their high citation counts and influence.
- Academic and Industry Partnership: The inclusion of organizations from both academic institutions (e.g., Stanford University, ETH Zurich) and industry (e.g., NCC Construction) underscores the importance of partnerships between academia and industry. Such collaborations are essential for practical applications of research findings and for addressing real-world challenges in construction and civil engineering.

In conclusion, the analysis of influential organizations reveals the importance of diverse, high-impact research contributions from institutions worldwide. It underscores the value of strong collaborative networks and specialized expertise in driving advancements in the construction and civil engineering fields. The results highlight the critical role of both academic and industry partnerships in fostering innovative research and addressing global engineering challenges.

1.4.1 Influential Countries

The study was conducted for the purpose of identifying the geographical location of the main author's institution. For this analysis, the threshold was defined with a minimum of 3 documents per country. In that regard, the 101 used articles have come from 17 countries and just 7 fulfilled the requirements. In Figure 1.6 and Table 1.6 it is possible to identify that all the listed countries have a high technological development profile.

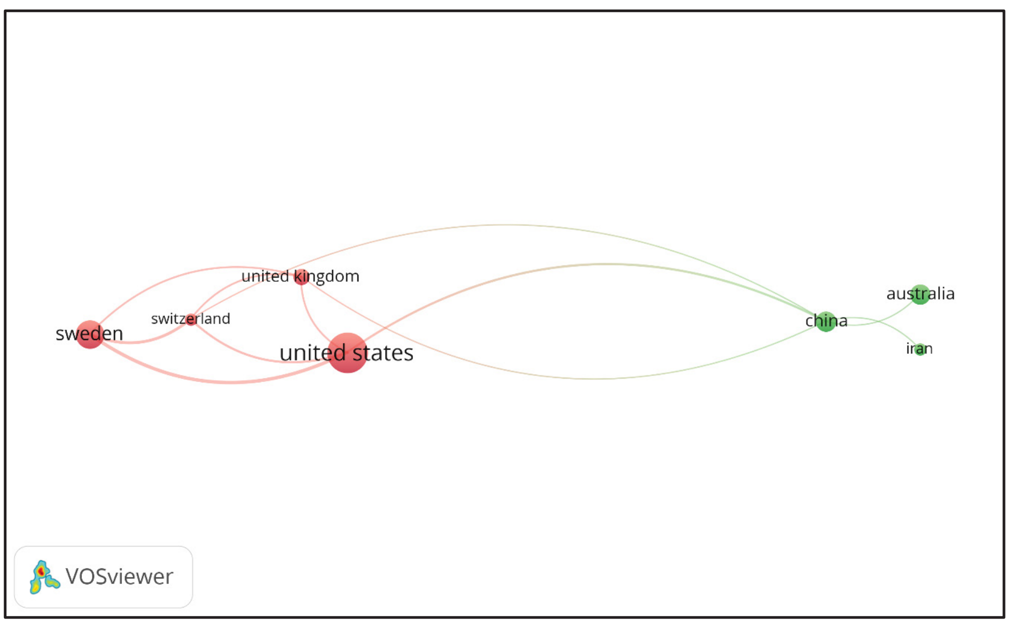


Figure 1.6 Influential Countries network result

Table 1.6 Influential Countries Score

Country	Documents	Citations	Total link strength
United states	10	215	15
Sweden	7	191	14
Switzerland	3	105	11
China	5	265	7
United Kingdom	4	167	7
Australia	5	49	1
Iran	3	91	1

The geographical analysis reveals several key insights:

- Global Reach: The research contributions span across continents, highlighting the global nature of academic research in construction and engineering. This international distribution reflects a wide engagement from technologically advanced nations.
- Leading Contributors: The United States leads with the highest number of documents (10) and a significant total link strength of 15, indicating robust collaborative networks and substantial research output. The high citation count (215) further underscores the influence and impact of research originating from the United States.
- Strong Research Impact: China, with five documents, stands out with the highest citation count (265), demonstrating a significant impact of its research contributions. This suggests that Chinese research in this field is highly regarded and influential.
- Collaborative Networks: Sweden, with seven documents and a total link strength of 14, shows strong collaborative efforts. Its high citation count (191) indicates that Swedish research is both prolific and impactful, benefiting from extensive networking and partnerships.
- Effective Collaborations: Switzerland and the United Kingdom, despite having fewer documents than the United States and Sweden, exhibit high total link strengths and citation counts. This reflects effective collaborations and strong research networks that enhance the visibility and impact of their research.

- Emerging Contributors: Australia and Iran, with five and three documents respectively, show lower citation counts and link strengths. However, their presence in the list indicates growing contributions and potential for increased impact with further collaboration and networking.

In conclusion, the geographical analysis of the main author's institutions highlight the prominent role of technologically advanced countries in contributing to research in construction and engineering. The United States, China, and Sweden emerge as leading contributors with significant research output and impact. The analysis underscores the importance of strong collaborative networks and technological development in producing high-quality, influential research.

1.5 Qualitative discussion

This section shows the result of the content analysis method, through this approach the database is examined to find relevant information for this research. Each fragment of data related to the aim of this study was identified with a code, then the total of codes used was analyzed and grouped into categories according to the perception and the topic abstraction of the researcher (Bengtsson, 2016), Table 1.2 shows the grouped categories: general concept, application domain and methodologies.

As codes are compared and grouped into categories according to the researcher's interpretation based on the level of familiarity with the topic, qualitative content analysis refers to this abstraction as part of the reorganization and re-contextualization of the information on codes and categories (Graneheim et al., 2017). To propose a content analysis study with a controlled degree of abstraction, the codes used were the results from the key-occurrence analysis of the past section. In that regard, this study pretends to describe the different application domains (Table 1.2) in a configuration platform and the identification of different implications of the methodologies of industrialized construction (Table 1.2) that have been identified in the literature. Additionally, to understand how a configuration platform can operate in the construction industry a proposed general framework will be described considering the finding insights.

1.5.1 Application domains in the configuration platform for industrialized construction

According to (Pasetti Monizza et al., 2018), a new paradigm of industrialized construction adopts newest information and communication technologies into the classical industrial processes with the aim of a highly flexible production of customized products and services. In that regard, configuration platform will have an impact in the different application domain of an industrialized construction project stages.

This section proposes a general description of the uses and benefits of configurators in the application domains mentioned previously in Table 1.2 (architectural design, structural design, manufacturing, and product management) and the role of the methodologies identified in the same table (BIM and Modularity).

1.5.1.1 Architectural design in configuration platform for industrialized construction

The nature of an architectural design is based on the client's requirements, a configuration platform brings a framework for the architects to translate the needs of the user into design solutions that can be efficiently manufactured (Jansson et al., 2014). The configuration system supports the designer's interpretation of both the design rules and the constraints of the building system in the different stages of the project (Jensen et al., 2012).

Shen at al. proposes that configuration platforms not only allow clients to make better design decisions based on the data processed by the platform or the view that a graphical interface can offer, they also allow to evaluate the impact of the uses of the building in sustainability aspects or other aspects of the impact of the final building performance (Shen et al., 2021).

According to Jensen et al., the uses of configuration platforms can be applied to design and evaluate entire building systems (Jensen et al., 2012) or to facades (Pantazis & Gerber, 2018), but always using a predefined database of modular construction products. Hall et al. recommend that these products should be developed by a multidisciplinary approach (Hall et al., 2020) and that architects can contribute not only with space studies but also to end-user behavior (Jensen et al., 2012). The flexibility of these modular products will determine the adaptive capability of the final solution.

According to Pantazis & Gerber, (2018) architectural design approach of contemporary building is based on algorithmic design, which denotes the importance of the use of computational resources in the design task. However, architectural design is mostly computer-based but not computing, this is a big opportunity for configuration platforms as a framework with their predefined computational tools and automated capabilities.

1.5.1.1.1 Role of BIM in architectural design oriented to configuration platforms

The integration BIM into architectural design, particularly within configuration platforms, enhances project workflows by enabling more efficient and flexible design processes (Pantazis & Gerber, 2018). Computational design methods support the automation of architectural tasks, optimization of layouts, and exploration of multiple design solutions (Caetano et al., 2020). These approaches help architects and engineers address structural, environmental, and manufacturing constraints. Following is a description of the key findings presented in this section.

- Automated architectural layout design: The use adaptable floorplans through CD's techniques, allows specialist to automate a floorplan solution considering different architectural or structural constraints. According to Jalali Yazdi et al., (2021) it is possible to generate and evaluate a number in terms of architectural objectives such as maximum living space or lighting and minimum energy and translate the results into a BIM model in order to integrate the result to the project workflow.

- Uses of standardized computational design methods (e.g. unified matrix method): The uses of CD's techniques in the construction field have taken relevance in industrial and academic aspects recently. In that regard, Jalali Yazdi et al., (2021) states that some companies have adopted standardized CD's procedures to specific task like structural or architectural layouts, as has been mentioned before. Additionally, the adoption of this practices has open the opportunity to software companies that bring this online CD services, for example Hypar, Testfit and PRISM Cao et al., (2021).
- Integrated solutions considering different data and other specialties: According to Pantazis & Gerber (2018), CD's procedures are multi-agent systems capable to integrate and evaluate data from different specialties to ensure their multiple objectives, for example the clash avoidance between structural and architectural elements.
- Generation and evaluation of multiple design solution: Through CD it I possible to generate different and complex solutions alternative according to the technique or algorithm used for this task (Caetano et al., 2020). In that regard, designer will expand their capacity to explore and optimize design solutions (Pantazis & Gerber, 2018).
- Topology optimization (Baghdadi et al., 2020): According to Pantazis & Gerber (2018), CD's procedure is used to elaborate geometrical architectural modeling which are passed to engineering disciplines to perform analysis in a BIM model. The same authors states that there is an increasing trend to develop algorithms oriented to form optimization considering environmental and manufacturing aspects.

1.5.1.1.2 Role of modular architectural design oriented to configuration platforms

Modular architectural design, when combined with configuration platforms, helps make projects more efficient and manageable. It allows teams to assess important aspects like sustainability and manufacturability early on, ensuring better planning and control over time, cost, and quality (Jansson et al., 2014). By using standardized methods, repetitive processes become easier to manage, and potential issues can be addressed early in the design phase, improving decision-making and project outcomes (Piroozfar et al., 2019). Below is a summary of the key findings from this section.

- Modular architectural product development enables the assessment from the other domain approach (e.g. manufacturability, assembly, or sustainability).
- The Off-Site Construction (OSC) procedures allow a wide planning and control of different edges of a construction project. According to Hossain et al., (2021), the modular architectural product development involves complex interaction between different domains, such as sustainability or manufacturability, whereby it is possible to evaluate the final product from different approaches.
- Brings improvements in controlling and planning time, cost, and quality of the products. According to Jansson et al., (2014), standardization and repeatability of prefabricated methods allow specialist to face the inefficiency of delivery time, cost and quality of traditional methods.
- Standardization of design methods and their assessment. Design can benefit from modularity by standardizing repetitive components (Piroozfar et al., 2019). Meanwhile, the repeatability of standardized procedures allows different benefits for industrialized construction in terms of automation, such as the application of a unified matrix method to optimise the spatial design of modular buildings (Jalali Yazdi et al., 2021).
- Can support the systemic configurative approach. According with Wikberg et al., (2014) stands that “an architectural object is a system of building space and user activity, defined functionally and experientially” (Figure 1.7). In that regard, (ibid.) a complex system can be supported by sub-systems through several levels, those levels of control would be limited by their control actors (city authority, building management, building management, building user organization, and building user).

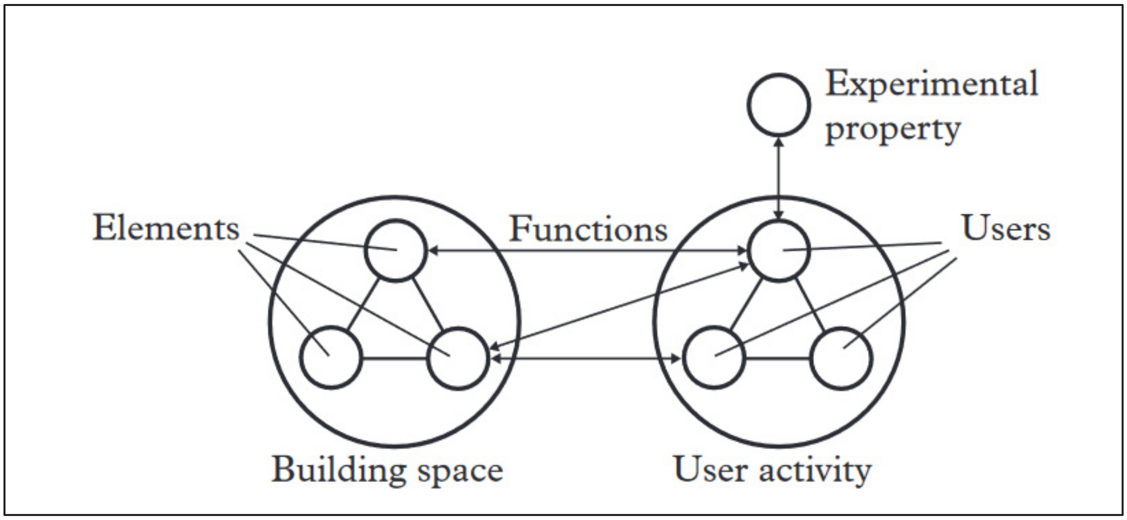


Figure 1.7 Modular architectural object conception diagram.
Taken from Wikberg et al., (2014)

- Enable the evaluation of multiple aspects in the early design stage (Shen et al., 2021). A modular based approach can make building components "functional blocks" embedded with physical parameters, performance functions, and most importantly, "green" design features. This information allows distinct types of assessments in a digital environment to anticipate inconvenience and assist in decision-making.

1.5.1.2 Structural design in configuration platform for industrialized construction

Pantazis & Gerber suggest that the new paradigm of design has increased the complexity of buildings, whereby complex structural challenges can be found in different components of a building, from its structural support to its façade. The use of automated procedures is a frequent practice in specific processes to support engineers along the structural design stage. However, a configuration platform can bring standardized, repeatable, and automated solutions based on the building system's constraints.

Jalali Yazdi et al. proposes that structural constraints of a building system are easily identified and can be used to set computational procedures in a configuration platform framework, in order to automate the design and location of standardized structural building elements (Jalali Yazdi et al., 2021).

1.5.1.2.1 Role of BIM in structural design oriented to configuration platforms

Structural design benefits from a collaborative approach that manages conflicts across domains and allows exploration of multiple design solutions (Pantazis & Gerber, 2018). Computational design (CD) enhances automation by embedding construction and structural rules early in the process, generating optimized solutions tailored to the project's needs (Haghir et al., 2021). Techniques such as topology optimization and automated structural layout design further ensure efficient arrangement of structural elements (Baghdadi et al., 2020; Jalali Yazdi et al., 2021). A more detailed list of the key findings follows.

- Brings a collaborative environment to manage conflicts interdomains. According to Pantazis & Gerber, (2018) the multidisciplinary approach of BIM methodologies allow designers to explore different design solution and manage the conflicting inter-domain objectives of building design.
- Computational design enhances decisions by embedding construction and structural rules and suggestions in the initial phase of the design and thus, enabling automation. Through CD it is possible to develop algorithms framed by the constrains of the selected building system (Haghir et al., 2021). In that regard, it is possible to obtain design options considering several aspects of the construction project, for instance: structural, productionable, or architectural aspects.
- Topology optimization. Different software are used to perform structural analysis. According to Baghdadi et al., (2020) through "topology optimization" it is possible to find the optimal location of the structural elements.
- Automated structural layout design. According to (Jalali Yazdi et al., 2021) in an automated structural layout design procedures, structural elements are arranged and sized in the optimal manner to accomplish the structural objectives.

1.5.1.2.2 Role of modular structural design oriented to configuration platforms

Modular structural design, integrated with configuration platforms, streamlines the alignment of materials, geometry, and structural features to optimize and evaluate design options. This approach supports architectural solutions by working within predefined building systems and project constraints. It also creates a hierarchical structure for modular elements, helping automate the design of complex buildings.

By incorporating manufacturing, transportation, and assembly perspectives early in the process, modular structural design ensures smoother execution (Jensen et al., 2012). Additionally, it establishes clear constraints between components, enabling automated analysis and production workflows (Hossain et al., 2021). Next, it is a summary of the key findings from this section.

- Modular structural products allow for the alignment of material, geometry, and structural characteristics in an automated process to develop, optimize and evaluate design options. According to Liu et al., (2021) CD's techniques research are oriented to simplify the assembly and production chain, through a digital framework to gather all the information needed for the various stages of the project.
- Modular structural products can support architectural solutions in the predefined building system. According to (Popovic, Schauerte, et al., 2021) it is possible to design several architectural or structural solution options into an automated procedure, this design process will be framed by the building systemin and other project limitations that will be mentioned in next sections.
- Provides a hierarchical structure and interaction rules between the modular elements of the building system. According to Popovic et al., (2021) state a hierarchy and interaction between elements of a modular building system, will contribute to automating the instantiation for a specific multi-story modular building using object-based modeling.
- Integrates manufacturing, transportation, and assembly perspectives during the design stage. The uses of the information about structural performance, assembly, manufacturing

or transportation of each construction product can be reviewed, evaluated and managed from the design stage of the project (Jensen et al., 2012).

- Provides attachment constraints to automated procedures. A construction modular product its composed by different elements, the interaction between those elements and their own characteristics define different constrains for the design, use and manufacturing of each module (Hossain et al., 2021). In that regard, the information about structural elements can be used to automate analysis or manufacturing procedures.

1.5.1.3 Manufacturing through configuration platforms for industrialized construction

In OSC methodologies, after the design stage, the manufacturing process begins, which is guided by the finalized product specifications. These specifications culminate in the customer order specification, a critical document that ensures all customer requirements are thoroughly captured and detailed. According to Jensen et al., 2012, it is possible to identify a customer order specification decoupling point for different kinds of production methods (Figure 1.8). In that regard it is possible to identify that Engineer to Order, is the most used method in the traditional construction industry, in which almost no finished products are available before the order is placed. In the Modify to order decoupling point, a generic product structure is configured using technical platforms.

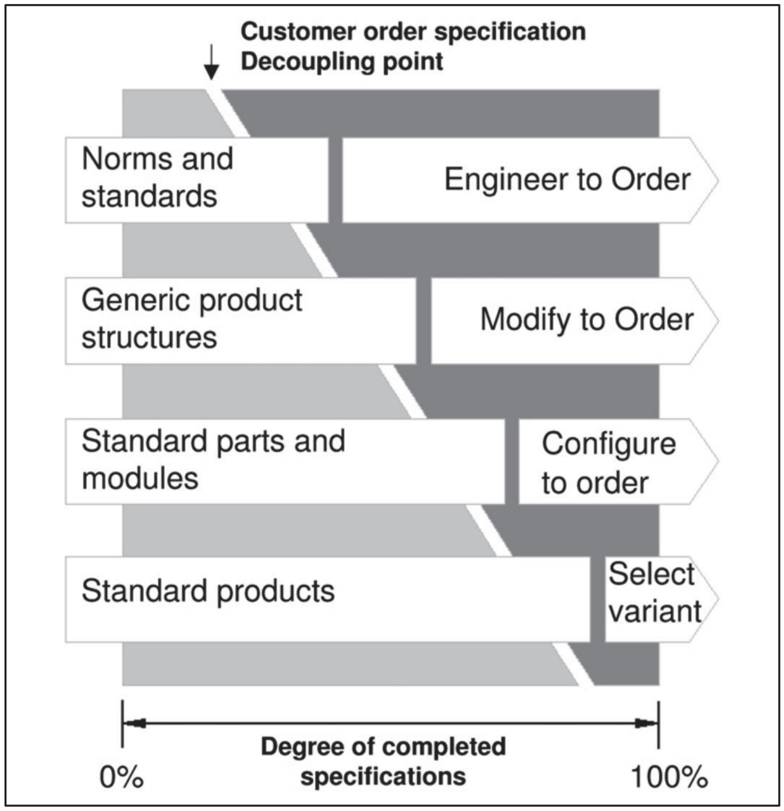


Figure 1.8 Customer order specification decoupling point
for different kinds of production methods.
Taken from Jensen et al., (2012)

Popovic, Schauerte et al. reports that the use of a configuration platform has enabled mass customization in manufacturing industries and could be considered a flexible framework for DfMA methodology, due to its possibility to be adapted to each production design system and its connection with the manufacturing stage (Popovic, Schauerte, et al., 2021). In that regard configuration platforms have a multidimensional impact on the design process, manufacturing, and business flow. The figure 1.9 illustrates the intricate relationships between manufacturing activities, assembly processes, logistics, and the various stages of configuration platforms, highlighting how these elements could interact and support each other throughout the production lifecycle.

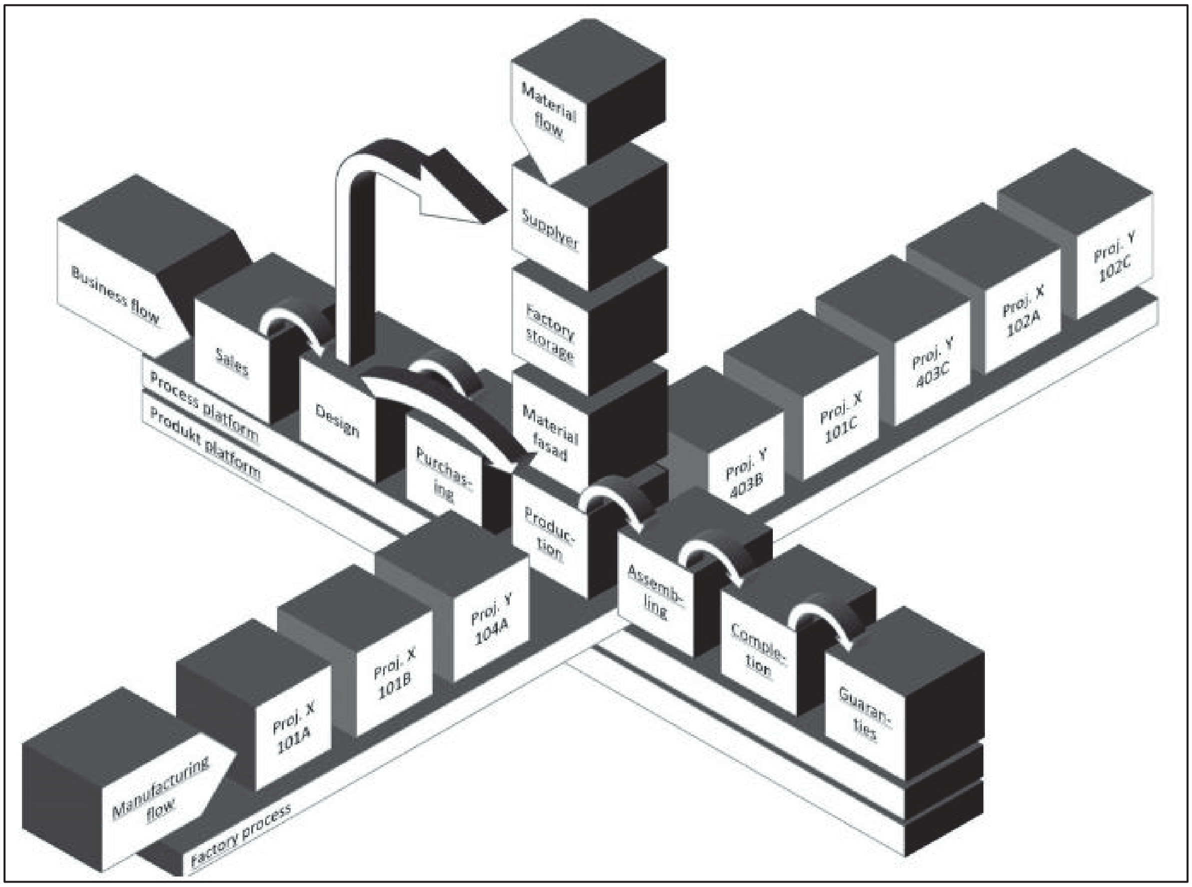


Figure 1.9 OSC project information flow.
Taken from Jansson et al., (2019, p. 49)

1.5.1.3.1 Role of BIM in the manufacturing stage oriented to configuration platforms

The manufacturing stage benefits from the seamless integration of design and production, ensuring products meet specific requirements with precision and efficiency (Pasetti Monizza et al., 2018). Building Information Modeling (BIM) facilitates the transfer of design parameters into manufacturing workflows, aligning production processes with design intent. Additionally, algorithms within BIM models can validate manufacturing procedures, ensuring proper execution (Haghir et al., 2021). Computational design techniques further enhance this process by enabling material optimization, reducing waste, and promoting efficient resource use (Jalali Yazdi et al., 2021). A more detailed list of the key findings follows.

- Enables the information exchange from design parameters to manufacturing parameters. Modular product design process considers manufacturing information and its transferability. A BIM model can provide information of manufacturing, according to the requirement of the element and their manufacturing method these information exchange for manufacturing can be reviewed by a specific algorithm in order to guaranty a correct procedure (Haghir et al., 2021).
- Optimization process reduces material waste. Through CD it is possible to perform different analysis in order to optimize the use of materials and reduce their waste (Jalali Yazdi et al., 2021).

1.5.1.3.2 Role of the use of modular processes in the manufacturing stage oriented to configuration platforms

Modular processes in manufacturing enable the customization of products by translating client requirements into tailored solutions. A Configure-to-Order approach leverages modular components, allowing customers to select from predefined alternatives to assemble a product that meets their preferences. This method ensures flexibility while maintaining control over production standards.

Additionally, modularity enhances manufacturing efficiency by reducing inventory costs and shortening distribution times (Hossain et al., 2021). It also supports mass customization, enabling manufacturers to meet diverse customer demands without compromising productivity. A summary of the key findings from this section follows.

- A Configure to Order approach based on modules makes possible to transfer the client requirements into a customized product. According to Jensen et al., (2012), the standards attached to the elements of modular products are useful to offer customizable option that can be assembled into a desired final product. In that sense, it is important to identify the catalogue of alternatives that can be used for clients to customize a final product that would be assembled with their preferences.

- Manufacturing efficiency can be increased by modularity. A modular approach contributes to reduce inventory cost and distribution time, additionally it is beneficial to satisfy mass customization demand, whereby it increase manufacturing efficiency (Hossain et al., 2021).

1.5.1.4 Product design in configuration platform for industrialized construction

According to Gravina da Rocha et al., (2019) construction products offers a standardized and replicable solution to fill specific needs. Modularity application to DfMA product domain allows conceiving prefabricated elements, considering dimension and physical characteristics to make their scope of uses more flexible. Each modular element can be used to conform to assembled volumetric elements with a defined degree of personalization according to their building system and selected manufacturing process. The automation of this customization process was enabled by the use of a product configuration platform (Popovic, Elgh, et al., 2021).

The life cycle of a construction product starts in its design where it is possible to identify two stages predefinition and product specification. At the same time, these can be divided into the following four stages: (1) conceptual design, related to the final geometry configuration of the proposal; (2) parametric design, oriented to set the design constrains to generate design options different specialties involved in the project; (3) configuration, where the final characteristic of the final products is set and evaluated and (4) detailed design stage, used to create and transfer information to downstream stages (idim). These stages could be related to the description of configuration platform types exposed by Cao et al., (2021) in order to identify the stage of product development in the different use of configuration platforms (Figure 1.10). This typology will be explained in the next section.

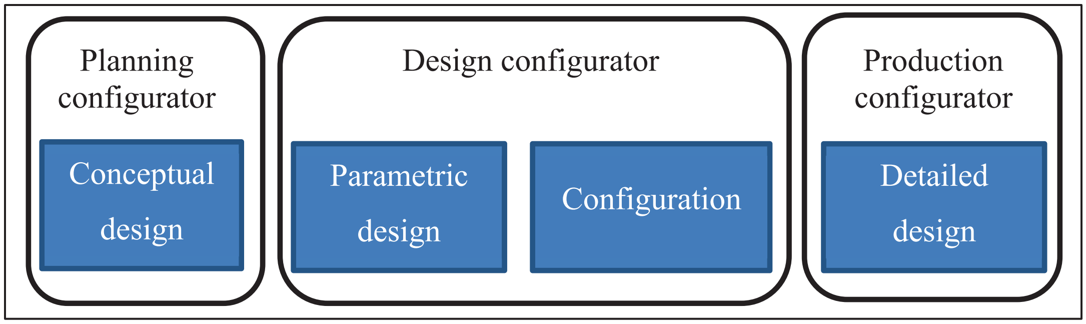


Figure 1.10 Types of configuration platforms according to the level of product requirement specification stages.
Created by the author.

The flexibility of the solutions is supported by the balance between the commonality and exclusiveness of the resulting products (Wikberg et al., 2014). Whereby, the level of granularity of the modular products that will be used in the configuration platform will allow different degrees of customization.

1.5.1.4.1 Role of BIM in the product design stage oriented to configuration platforms

The product design stage benefits from centralized information management, allowing for smoother configuration processes and alignment with the desired final product (Popovic, Schauerte, et al., 2021). Digital technologies like Building Information Modeling (BIM) support this process by managing technical aspects and providing clients with visual insights into design development. Additionally, the integration of computational design methods enables the generation and evaluation of design options, enhancing the workflow (Koeleman et al., 2019). Collaboration among stakeholders is also a key element, as BIM facilitates coordination across different phases of the project lifecycle (Piroozfar et al., 2019). A more detailed list of the key findings follows.

- Communication information technology, as BIM, allows the configuration process. The use of digital technologies as a communication tool allows to centralize the information during the product specification stage, in order to set up the desire final product (Popovic, Schauerte, et al., 2021). In that sense, a BIM model can be adopted as a platform for that configuration process in order to manage technical aspect and allows clients to understand graphicly the development of the process.

- Enables the use of computational design methods in the configuration process. The digitization supports the use of different technologies in order to generate or manage the information of a project (Koeleman et al., 2019). Whereby, the use of specialized techniques to generate and evaluate design option are integrated to the flow work.
- Support the collaborative work between a project's stakeholders. According to Piroozfar et al., (2019), a basic premise of BIM methodology is the collaboration between different stakeholders at different phases of the project life-cycle.

1.5.1.4.2 Role of modularity in the product design stage oriented to configuration platforms

Modular product design enables flexibility by allowing kit-of-parts components to be combined into new volumetric elements, with computational design (CD) methods supporting this process (Hossain et al., 2021; Cao et al., 2021). It also helps manage constraints in manufacturing, supply, and assembly by using configuration platforms to transfer information between stages (Gravina da Rocha et al., 2019). Furthermore, modularity aligns with prefabricated building systems, ensuring smooth workflows across project phases (Jensen et al., 2012). A more detailed list of the key findings follows.

- Modular kit of parts products can be mixed and merged to create new modular volumetric elements. The flexibility level of configuration process it is determined by the granularity of the modular design (Hossain et al., 2021). According to Cao et al., (2021) "Kit-of-parts are pre-engineered and pre-designed digital models representing fabrication-ready components". In that regard, CD's procedures can be used to combine the elements of kit-of-part in order to obtain the information to elaborate a DfMA project.
- Manufacturing, supply, and assembly aspects can be constrained for modular product design. According to Gravina da Rocha et al., (2019), there are several studies about the implication of modularity in manufacturing, supply and assembly chains. In that regard,

configuration platforms could be used as a framework in order to transfer the information between stages.

- Can be oriented to support specific building systems. There are different building systems oriented to prefabricated construction projects workflow (Jensen et al., 2012). Whereby, it could be possible to integrate a configuration platform as a workflow to transfer product demands through distinct stages of a project.

1.5.2 Functional capabilities of configuration platforms in industrialized construction

As stated by Jansson et al., (2014) configuration platform could be considered a collection of assets (i.e. components, processes, knowledge, people and relationships) and it is oriented to customize the product without sacrificing flexibility. In that regard Cao et al., (2021) propose a framework where the modular elements which compose the final products are predefined in a manufacturing kit-of-parts. The authors describe Kit-of-parts as pre-engineered and pre-designed digital models representing fabrication-ready components.

Cao et al., (2021) suggest that this database of elements can generate different product solutions to the client's necessities using configuration rules that can be defined in the project level or product level information. This author states that there are three topologies of configurators which are described below (Figure 1.11):

- Typology 1 - Planning configurator: The targeted products could be a conceptual building model created by architectural firms in early planning. The major objective of applying the configurators is to generate diverse development plans, such as site plans, building profiles, and floor plans. These development plans are evaluated by decision-makers in order to make a final selection Cao et al., (2021).
- Typology 2 - Design configurator: This is used to support the project design phase. In this scenario, architects, engineers, and sometimes fabricators are involved and collaborate on

configurators. The targeted products could be a detailed building model configured with predefined modules, such as timber panels. The major difference between typology 1 and 2 lays in the generated outputs. For typology 2 configurators, the low-level detail web plans are converted to BIM models in authorized design applications Cao et al., (2021).

- Typology 3 – Production configurator: It represents configurators that support construction projects at the project production phase. Engineers and fabricators usually adopt DfMA principles in the early design stage before the manufacturing process Cao et al., (2021).

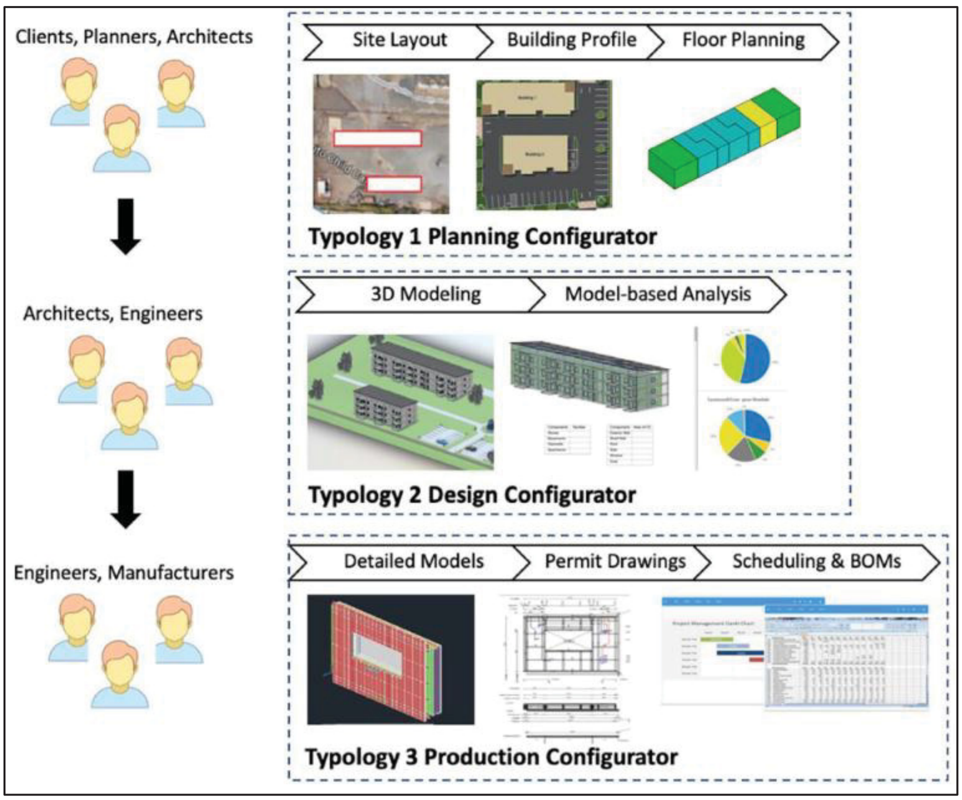
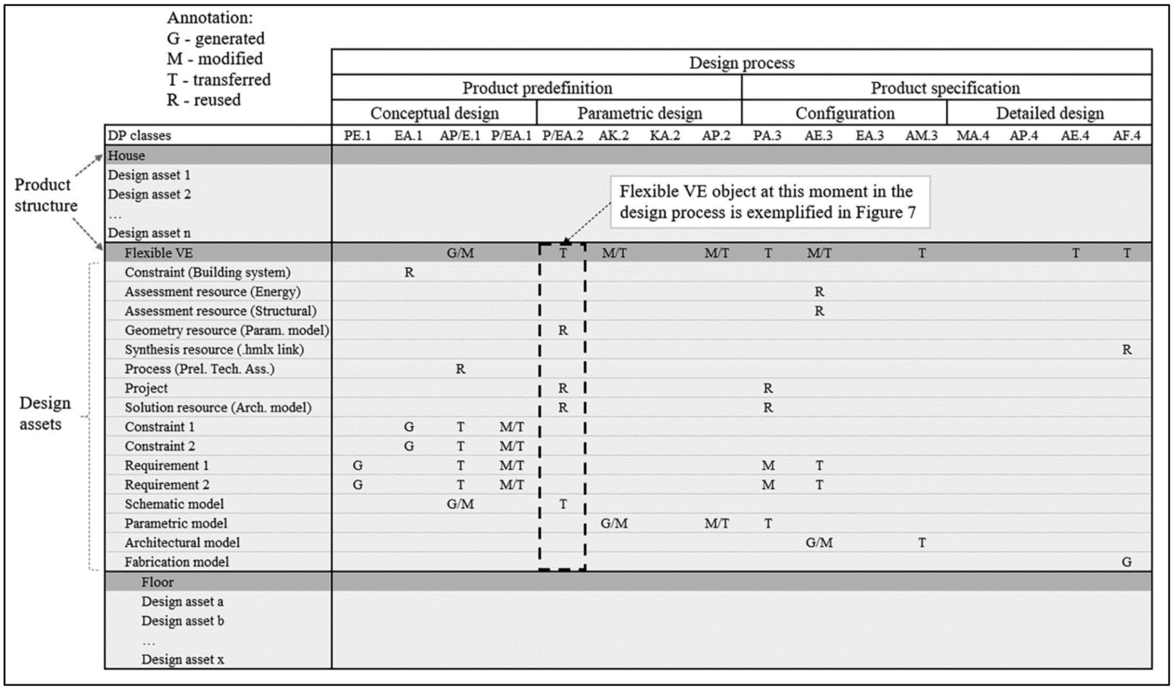


Figure 1.11 Types of configuration platforms.
Taken from Cao et al., (2021)

In agreement with Popovic et al., (2021) the configuration rules along the design process in a construction product configuration platforms can be of different kinds, but those which define the physical constraints are the rules of the selected building system. Figure 1.12 shows an example of information exchange to define the rules in configurators depending on different stages of the design process.



	Design process															
	Product predefinition								Product specification							
	Conceptual design				Parametric design				Configuration				Detailed design			
DP classes	PE.1	EA.1	AP/E.1	P/EA.1	P/EA.2	AK.2	KA.2	AP.2	PA.3	AE.3	EA.3	AM.3	MA.4	AP.4	AE.4	AF.4
House																
Design asset 1																
Design asset 2																
…																
Design asset n																
Flexible VE			G/M		T	M/T		M/T	T	M/T		T			T	T
Constraint (Building system)		R														
Assessment resource (Energy)										R						
Assessment resource (Structural)										R						
Geometry resource (Param. model)					R											
Synthesis resource (.hmlx link)																R
Process (Prel. Tech. Ass.)			R													
Project					R				R							
Solution resource (Arch. model)					R				R							
Constraint 1		G	T	M/T												
Constraint 2		G	T	M/T												
Requirement 1	G		T	M/T					M	T						
Requirement 2	G		T	M/T					M	T						
Schematic model			G/M		T											
Parametric model						G/M		M/T	T							
Architectural model										G/M		T				
Fabrication model																G
Floor																
Design asset a																
Design asset b																
…																
Design asset x																

Figure 1.12 Example of information exchange content throughout the design process for the flexible Volumetric Elements (VE).
Taken from Popovic et al., (2021)

1.6 Conclusion

This section will conclude the chapter by presenting the key research findings in relation to the objectives stated for this study, as well as a reflection of its value. Additionally, this section will describe some limitations and propose opportunities for future work based on the thesis research proposal.

This research has the objective to identify topics of the construction field related to the concept of the configuration platform in design stage of construction projects, for this purpose a SLR was performed to identify the most relevant articles in the field. Additionally, this research seeks to interpret how configuration platforms work and propose a general framework to configurate modular construction products, according to its product typology and level of development.

The literature review has shown that, different application domains and methodologies have been identified to be used with configuration platform; a general description of product management, architecture, engineering, and manufacturing domains have been developed as well as the roles of BIM and modular methodologies applied to construction and product design fields. Additionally, a general configuration system framework was developed considering existing information and its inductive analysis (Figure 1.13). This framework, taken from Popovic, Elgh, et al., (2021) and edited by the author of this thesis, allows to identify the task in each application domain, the level of product design development related to each type of configurators and the tasks required according to the type of platform or level of product design. This states a multidisciplinary framework that specifies the relationship between different stages of the product, defining the path to exploring communication plans that can support the workflow and the automation of the procedures. Opening the possibility to the study of other factors related to the proposed framework.

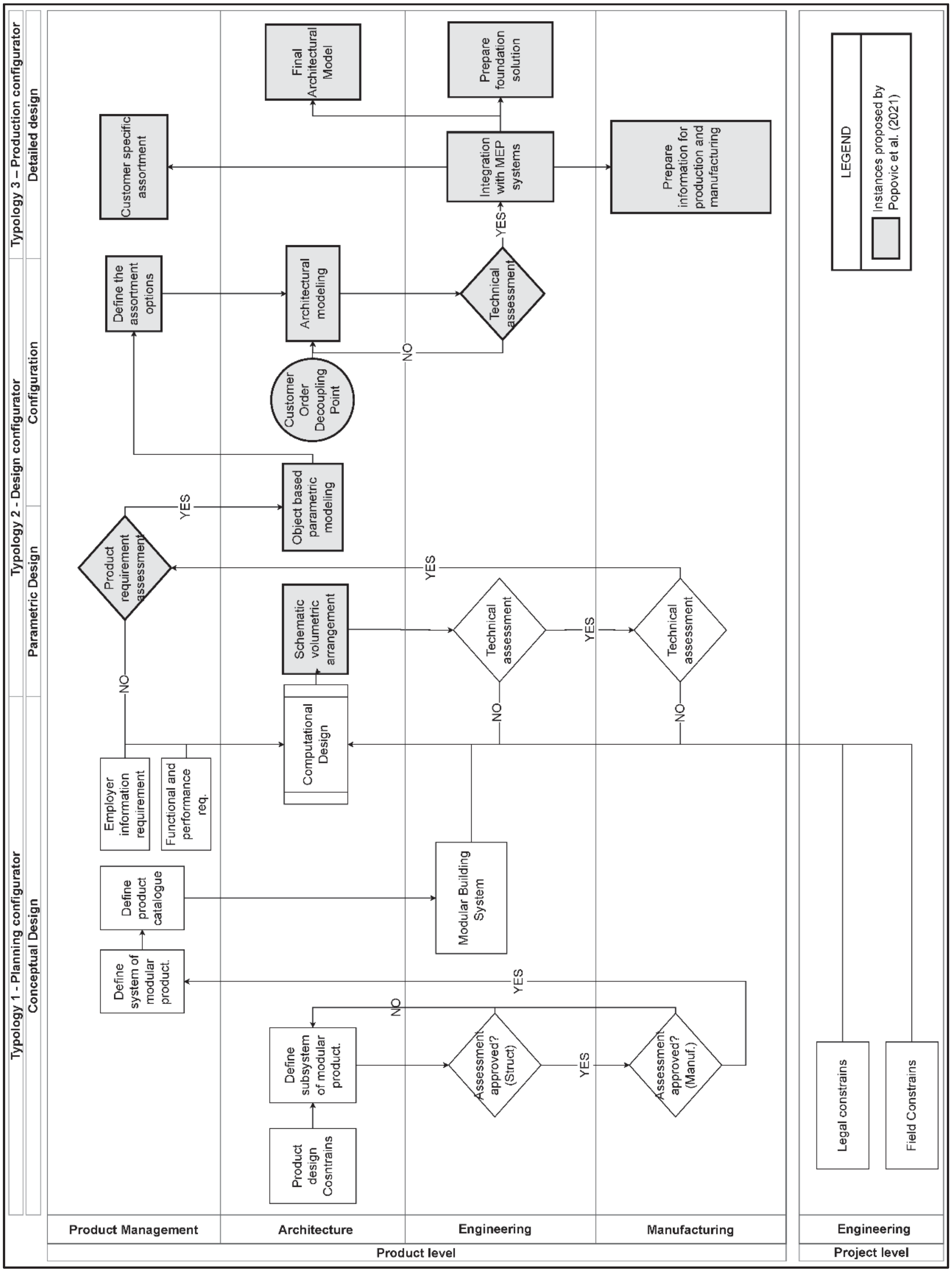


Figure 1.13 The configuration platform workflow described is developed according to the types of configuration platforms and the product's level of development. Adapted from Popovic et al., (2021).

Configuration platforms do not belong to a coherent body of knowledge, making it difficult to organize the literature review. Despite that, previous studies describe BIM as the most ideal methodology to exchange information, support collaborative work and use computational design procedures for optimization processes in the product design stage. There are few studies of configurators based on BIM content (Cao et al., 2021) and their use to support the development of modular design from a multidisciplinary approach, such as sustainability, cost, materials or manufacturing (Hossain et al., 2021; Jalali Yazdi et al., 2021). In that regard, Jensen et al., (2012) state that the designer's interpretation of the design rules, the constraints of the building system and other aspects of a OSC project can be supported by configuration systems.

Studies focused on configuration platforms with a multi objective optimization approach can be very beneficial to help specialists in early stages of OSC projects, due to designers have a low understanding of manufacturing and assembly aspects (Langston & Zhang, 2021). According to (Jensen et al., 2012), "it is the role of the configuration system to support the designers" interpretation of both the design rules and the constraints of the building system in the different views."

In addition to that, designers can use a variety of CD tools to accomplish specific tasks thanks to the availability of multiple tools, however most of the time those tools are not connected between each other and that makes it hard for the designers to evaluate multiple criteria synchronously in their projects (Pantazis & Gerber, 2018). As it has been mentioned, future work could be oriented to the study of the process which supports the application of the presented framework (Figure 1.13). Through BIM methodologies and computational design tools, it is possible to implement the proposed framework in order to explore more deeply the communication scheme, identify computational design methods that can contribute to the proposed framework, and then develop them to finally evaluate them (Cao et al., 2021). Another suggestion could be to explore the existing platforms and method capable to support the proposed workflow.

In spite that configuration platform is a multi-agency optimization process that can be applied to many aspects of the construction field, this research has been oriented to the design stage of construction projects. In addition, the methodologies used have a degree of subjectivity due to the researcher's bias attached to the interpretation.

The next chapter represents a general description of the main application domain in the use of configuration platform for construction and proposes a flexible workflow for its application to support future research.

CHAPTER 2

OBJECTIVES AND METHODOLOGY

Design Science Research (DSR) was selected as the methodology for this study due to its effectiveness in developing innovative and practical solutions. DSR's iterative process and focus on refining solutions through continuous feedback make it ideal for creating a robust framework for configuration platforms in modular residential construction. This approach ensures that the solutions are both theoretically sound and practically applicable, enhancing the efficiency and customization of modular construction projects. In this chapter, the approach of DSR will be examined by detailing its objectives and explaining why it is suitable for this study.

The DSR method focuses on creating practical and innovative solutions to real-world problems, while simultaneously relying on a solid scientific foundation. Its goal is to merge theory and practice to develop and evaluate artifacts, systems, or processes that meet specific needs. This approach is characterized by an iterative creation process, continuous critical reflection, and a design cycle that allows for the progressive refinement of the proposed solution (De Sordi, 2021).

The DSR method is ideal for this project because it promotes the creation of concrete solutions tailored to the real needs of the sector. The literature describes six steps for the development of this research approach, which are depicted in Figure 2.1.

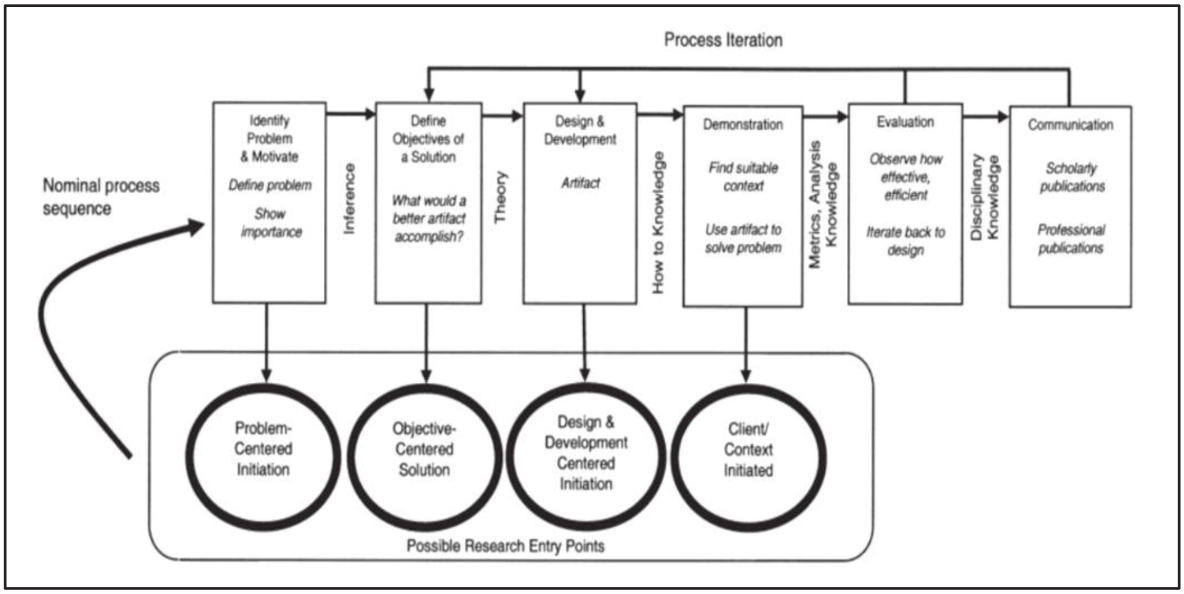


Figure 2.1 DSR Methodology Process Model.
Taken from Vom Brocke et al., (2020)

This approach is especially relevant for developing a framework for a configuration platform aimed at the construction of modular residential buildings, as an artifact in research. To develop such an artifact, an in-depth study is required on previous research regarding the use of configuration platforms in construction, as well as an analysis of existing platforms, the needs of the industry with respect to these configuration systems, and the practical validation of the proposed innovations. The following sections describe the different stages named in Figure 2.1 related to this research.

2.1 Phase 1: Identify problem and motivation

2.1.1 Motivation

The housing crisis represents a growing global challenge, and OSC stands out as a promising solution to this problem, offering significant advantages over traditional construction methods. These advantages include faster construction times, cost reductions, and minimized environmental impact. These benefits are essential not only to accelerate construction processes but also to make them more sustainable and economical.

The main motivation for this research lies in contributing to the development and improvement of OSC adoption. By exploring and improving the use of this innovative practice, this work aims to promote the acceptance of configuration platforms for implementing residential modular construction projects. This, in turn, could play a crucial role in mitigating the housing crisis by providing viable and efficient alternatives that meet urgent housing needs.

This study seeks to delve deeper into how BIM-based configuration systems can optimize the initial design of modular construction projects, thereby improving delivery times and the overall efficiency of the construction process. Promoting this practice as a possible solution to the housing crisis.

2.1.2 Problem context

The use of OSC is gaining popularity in the architecture, engineering, and construction sectors due to its advantages in terms of planning, economy, environment, and planning. However, unlike traditional methods, this approach must address many aspects of the project from the initial stage, so it is especially important to successfully manage the criteria of logistics, manufacturing, and assembly, because the lack of knowledge in these aspects is one of the main reasons for not using this constructive methodology.

The integration of digital technology, specifically BIM, enables a perfect connection between design limitations in the early stages and subsequent manufacturing and assembly processes. In addition to the management of information in a common and standardized data environment.

The world is currently experiencing a housing crisis that has been exacerbated by rising immigration and market inflation. This situation highlights the urgent need for new construction methods, such as OSC.

2.1.3 Research Problem

The industry division and the lack of technical knowledge among the developers in relation to collecting and manufacturing system result in a big void in the adoption of OSC practices. This is still happening notwithstanding the fact that OSC solutions are known to be effective in solving housing problems.

2.2 Phase 2: Define objectives

2.2.1 Main Research Objective

The study aims to create a digital platform that can be used for the design stage of a modular construction project for residential buildings. The main goal of this platform is to address the knowledge gaps in logistics, manufacturing, and installation which hinder the uptake of off-site construction. In addition, it provides a shared data environment for all involved stakeholders in early construction phases besides being a tool for creating different design options automatically based on sustainability and cost criteria so that better decisions can be made during this period. This project seeks wider adoption of prefabricated methods towards ecological housing units characterized highly efficient systems within building sector that are more respectful to our surroundings.

2.2.2 Research Questions

1. What are the functions provided by commercially available configuration platforms for construction projects?

2. What would be the best design approach for a configuration platform in modular residential projects that would help to minimize the impact of knowledge gaps on the early stages of the project in shipping, manufacturing, and assembly?

3. Describe how medium-density residential buildings can apply a BIM-based configuration system at the initial stage to enable stakeholders make decisions when adopting modular construction for housing?

2.2.3 Research Tasks/Specific Objectives

1. Review of Literature: Conduct a review of the current off-site construction commercial configuration platforms in order to identify and classify their functions while making a list of features they have.

2. Conceptual Model Designing: Create a conceptual model for configuration platform meant for modular residential buildings with emphasis on interface design, data integration methods and user interaction models development.

3. Real case Implementation: Use the proposed BIM-based system for configuration during a case study to evaluate its application at early stages of medium density residential project and measure its efficiency.

2.2.4 Hypotheses

1. Efficiency of configuration system: Configuration platforms assist in decision making processes, project visualization, and stakeholder interaction.

2. Platform configuration: When developing a customised configuration platform for modular residential projects, logistics, production, and assembly modules must be connected. This will help designers in the initial stages of the project.

3. BIM System Impact: The implementation of BIM-based configuration systems from the initial phases of design improves the level of information accuracy where one can select project requirements either from real-time data or possible outcomes.

2.3 Phase 3: Artifact design and development

In this research project the solution’s design and development procedure is methodically structured using the Design Science Research (DSR) approach. The DSR methodology requires an endeavor to adhere to principles like focusing on specific needs, simplicity in execution, effective integration of components as well as continuous innovation. It is constituted by an iterative cycle that involves conceptual modeling which progresses into more detailed designs which allow for adjustments along the way.

As De Sordi, (2021) observes, using an instantiation artifact in research enables one to practically analyze the proposed solution. This practical evaluation becomes important because it offers a chance of establishing whether the developed artifact serves as an effective answer to the studied problem or not. When this artifact is implemented, it becomes possible for people to directly see how well it works while at the same time being able to gauge its impact within real situations thereby giving tangible proof on both efficiency and suitability towards initially stated requirements.

2.4 Phase 4: Demonstration

The designed artifact undergoes a test to ascertain its capability and efficiency in the demonstration stage of the DSR method. This is a critical point at which it is possible to see how specific problems are managed by the artifact in a controlled environment thus linking theory with practice (De Sordi, 2021).

All components of the artifact will be assessed as one unit including procedures of usage, required inputs, and obtained outputs. Through development of a real-world application, this testing shall take place. In this stage, not only is technical feasibility tried but also different adjustments made on such areas of design that may have failed to meet their aims are corrected in readiness for later natural environment assessments.

2.5 Phase 5: Evaluation

According to DSR, Naturalistic evaluation requires the artifact to be used under real conditions, by real users with real problems. It is important for the artifact to be tested within the context it was designed for (De Sordi, 2021).

During this stage, the assessment focuses on specific criteria such as how functional the prototype is; its typical usage among users; appropriateness of use environments was already established before but now being considered again based on certain indicators like those mentioned earlier. Analysis should show whether there might have been any need for adjustments or enhancements to made at design and development phases so that they can match up with what is expected from them the success of solving identified problems heavily depends upon these reviews being done iteratively thus making sure relevance plus effectiveness thereof are achieved.

2.6 Phase 6: Communication

During the communication phase of DSR, it is important to cater for the needs of two main audiences: the practitioners who will use the artifact and the academic researchers interested in the subject of study. When dealing with the former, the communication should be clear and concise on the operationability of the instrument, its advantages as well as user instructions. This will make it possible for people to use these devices in their professional environments thus enabling creativity and adoption of modern technologies (De Sordi, 2021).

On the other hand, when it comes to the academic society, the information must be passed in a more structured and elaborate manner which is common with scholarly publications. Such should encompass detailed descriptions about designing an artefact alongside its development process plus evaluations or evidence showing that indeed this method works effectively. These facts are necessary because they will help other researchers understand what has been done so far in relation to their work thereby encouraging further studies and knowledge expansion within that area. It should be noted that for solutions to be both theoretically sound and practically viable, a dual approach that encompasses both aspects must be adopted.

For some of the work reported in this chapter, brief accounts are contained in conference publications that describe stages in writing subsequent sections. For this project, some documents describing the development of subsequent chapters are part of conference publications that will be briefly described next.

2.6.1 Article 01: Digital Configuration Platforms for Residential Modular Construction projects: A Comparative Study

This article's content is found in Chapter 3 of this document. It compared and assessed different digital setup platforms in the market so as to understand how best they can be used for developing a residential modular building project. The authors undertook a qualitative content analysis which helped them discover what these setup platforms do before producing their evaluation criteria. According to the study, it was possible to find out various design solutions by subjecting distinctive designs that meet modular design requirements into configurators.

2.6.2 Article 02: BIM-based configuration system for an early design stage of modular residential projects

The content of this article is in the fourth chapter of this thesis. Its main goal is to verify the assumption that the use of BIM-based configuration platforms may facilitate overcoming the lack of knowledge which prevents a wider implementation of OSC methods. It contains information on the research approach, architectural solutions, as well as criteria for designing a workflow system for configurating buildings in the context of the general model. The paper presents conclusions and restrictions of BIM based configuration platforms established during the study along with some ideas for their future enhancement.

2.7 Conclusion

The chapter on Objectives and Methodology outlines the research framework for developing a configuration platform tailored to modular residential construction. The use of Design Science Research (DSR) provides a structured and iterative approach to create innovative solutions, ensuring alignment between theory and practice. This methodology emphasizes continuous refinement through feedback, enhancing both the practicality and effectiveness of the proposed framework.

The research aims to address critical knowledge gaps in logistics, manufacturing, and assembly, which hinder the broader adoption of off-site construction (OSC). Through the integration of Building Information Modeling (BIM) and computational design, the proposed platform will facilitate better decision-making during the early design stages of modular projects, contributing to more sustainable and efficient construction processes.

Ultimately, this project seeks to demonstrate the value of a BIM-based configuration system in overcoming industry challenges and promoting modular construction as a viable solution to the ongoing housing crisis. The chapter also outlines the research phases, from problem identification to artifact evaluation and communication, providing a clear path for achieving the study’s objectives.

The next chapter presents a study submitted to the 2024 International Society for Computing in Civil and Building Engineering Conference. It explores how digital configuration platforms can address the growing demand for affordable, sustainable housing by evaluating their ability to support modular construction projects effectively.

CHAPTER 3

DIGITAL CONFIGURATION PLATFORMS FOR RESIDENTIAL MODULAR CONSTRUCTION PROJECTS: A COMPARATIVE STUDY

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This chapter of the thesis presents a contribution made to the conference of International Society for Computing in Civil and Building Engineering 2024. It states that there is a growing global need to build affordable, eco-friendly, high-quality housing quickly. Industry is finding solutions in the industrialized construction field, which is generating tools to meet the needs of the global housing crisis. Modular construction methods are a promising asset to help face this crisis. In this study, the authors compare and evaluate different digital configuration platforms available on the market to understand to what extent they would satisfy the needs to develop a residential modular building project. The researchers employed a qualitative content analysis approach to identify the functions of configuration platforms and then generate evaluation criteria. The study found that the analyzed configurators can consider modular design criteria to find and evaluate various design solutions. However, they need help to automate the generation or incorporation of information chains. Such digital information chains would allow the correct data exchange between the various project stages, thus linking the production lines upstream and downstream.

3.1 Introduction

The construction industry has made considerable progress in improving productivity by adopting digital tools such as Building Information Management (BIM) methodologies and automation tools for various management, design, and manufacturing tasks. However, our society has also been facing a housing crisis that is becoming more severe with time. This housing problem affects everyone, and many countries are turning to industrialized construction methods as part of the solution. Countries like Sweden have already embraced industrialized construction methods, which have enabled them to produce more than 70% of their housing using industrialized methods and many other countries promote the adoption of these practices to shorten their housing crisis (Ferdous et al., 2019).

Modular construction is an industrialized off-site construction method that involves prefabricated modular components manufactured off-site and then transported to the construction site for assembly. This construction method has become popular in recent years because it offers many benefits, including reduced construction time, lower costs, improved quality control, sustainability and many other advantages (Benjamin et al., 2022; Razkenari et al., 2020; Sonego et al., 2018). To develop a modular construction project, designers could use digital configuration platforms that allow them to design and customize modular buildings to meet the specific needs of their clients. These platforms use advanced algorithms and artificial intelligence (AI) to create detailed 3D models of the building components (Ghannad & Lee, 2022; Lee et al., 2023). By doing so, the platform can bridge the knowledge gap between construction specialists and the manufacturing and assembly knowledge required to adopt the modular approach in the industry (Razkenari et al., 2020; Yuan et al., 2018).

In the last decades, industrialized construction has changed paradigm through its digitization. That brought to light the concept Industry 4.0, which is a new production model based on computer-controlled trends including robotics, AI , Internet of Things (IoT), automation, and others (Hall et al., 2020). Nowadays, configurators can create information chains to connect the design stage with the rest of the project's stages. It means that, if it is needed, every single element of the final configuration could be provided with the required information to go through the entire product's life cycle in an automated way and industrialized construction methods could take advantage of this (Yuan et al., 2018).

The scientific literature indicates that using Configuration platforms, or configurators, could enhance the adoption of modular construction methods (Benjamin et al., 2022; Cao et al., 2021; Ghannad & Lee, 2022; Jensen et al., 2012; Piroozfar et al., 2019). Such configuration systems use predefined building configurations that can be customized using different criteria to generate and evaluate distinctive design solutions. These criteria would be used to frame the customization rules that are based on different editable parameters which will define the features of the final product, such us the number of levels of the building, the modules dimensions, the carbon footprint value of a specific element, among others. The design of configurators is not standard, and its level of detail is based on the granularity level of the product decomposition and the purpose of the use of the configuration platform in the project lifecycle (Bryden Wood et al., 2021; Hossain et al., 2021; Jensen et al., 2015). In that regard, there is evidence in previous studies of the use of building configurators to automate the generation and evaluation of design solutions and then to prepare and transmit substantial information for the subsequent stages in the project life cycle, such as manufacturing or assembling information (Benjamin et al., 2022; Cao et al., 2021; Ghannad & Lee, 2022; Piroozfar et al., 2019).

In this study, we will compare and evaluate different digital configuration platforms available on the market to understand to what extent they would satisfy the needs to develop a multistorey residential modular building project. We will examine each platform's features, advantages, and limitations, orienting the evaluation to their use in a residential modular project. This research aims to contribute to the growing knowledge of modular construction and digital design and provide valuable insights for builders, architects, and engineers interested in adopting this innovative construction method.

The paper will be organized as follows. In the first section, we will provide an overview of the modular construction advantages that can contribute to satisfying the increasing dwelling demand and the role of digital configuration platforms in industrialized construction. In the second section, we will review the existing literature on configuration platforms for construction projects and identify the key features and functions that academia has registered to generate the criteria for comparison. In the third section, we will present the results of our research, including a detailed comparison of the different platforms based on the evaluation criteria. In the fourth section, we will discuss the implications of our findings for the practice of modular construction. In the last section, we provide the conclusions and recommendations for future research.

3.1.1 Modular building systems in addressing the housing shortage.

Modular construction systems allow for constructing different building floors in a factory, even before earthworks commence on the final building site. The construction of the modules in a factory means that the manufacturing tasks would be performed in controlled environments that guarantee more safety in controlling the atmospheric conditions. In some countries, this type of consideration could shorten delivery times. In addition, this work environment offers more safety against work accidents (Arashpour, 2019; Jensen et al., 2012). It makes it more feasible to incorporate labour with manufacturing experience from other industries, which would help to compensate for the lack of labour that comes with increasing housing production to meet demand (Bryden Wood et al., 2021; Hall et al., 2020). For more specialized tasks, it would be possible to improve workers' performance through digital tools such as configuration platforms (Ghannad & Lee, 2022; Piroozfar et al., 2019; Yuan et al., 2018).

Working within factories also impacts the project's sustainability as it provides better waste control and allows a better analysis of the carbon footprint involved in the process (McKinsey Global Institute, 2017; Sonego et al., 2018; Vestin & Säfsten, 2021). Other factors that contribute to the improvement of environmental sustainability of modular methodologies are that they will enable us to think about the disassembly of its parts and their use, leaving the possibility of generating a circular economy (Hossain et al., 2021; Sonego et al., 2018).
Modular construction offers greater control in development times that could be between 30% and 50% shorter and provides an advantage over traditional methods in terms of cost control and guarantees better quality control (McKinsey Global Institute, 2017), which could result in a better return on investment in a shorter period. These advantages could contribute to taking advantage of the limited budget governments face to satisfy the housing demand.

Using this construction method can lead to high production rates that meet clients' needs through standardized products. However, standardization can sometimes result in excluding specific and unique client needs. Research shows an inverse relationship between customization and productivity/cost (Bryden Wood et al., 2021). To overcome this challenge, some industries have adopted a Mass Customization business strategy to deliver various products while using standardized components that meet customer requirements (Ghannad & Lee, 2022; Jalali Yazdi et al., 2021). Mass Customization is not only a production chain differentiator, but it can also provide environmental and social sustainability benefits.

Avoiding waste caused by product changes made after occupation by users can increase the perceived value and sense of ownership (Rocha et al., 2015).

Different studies have identified difficulties in the design stage of modular construction projects, the problems in this stage can causing a significant setback in the project, this is why this stage is more time-consuming and costly than designing a conventional house. (Bryden Wood et al., 2021; Ghannad & Lee, 2022). Another fact that contributes to set the importance of this stage is the lack of experience of an architect in designing and proposing modular solutions. (Ghannad & Lee, 2022). For this initial stage, it is crucial to ensure that the design phase of a modular project is precise enough to establish a design freeze at the outset. As modular construction methods require tasks to be executed simultaneously, there is minimal room for design modification.

The adoption of highly automated construction systems is currently limited by the high investment required to implement automated factories for these processes and the need for more qualified personnel (Langston & Zhang, 2021; Qi et al., 2021). About qualified personnel, there is a knowledge gap among experienced personnel about the assembling, manufacturing, and transportation constraints that should be taken into consideration from the beginning of modular projects. This study considers that configuration platforms could assist specialists by limiting their design activities within the rules that would make it possible to develop the project with the selected modular system (Cao et al., 2021; Ghannad & Lee, 2022) The following section discusses the issue of configuration platforms within industrialized construction.

3.1.2 Configuration platforms for the industrialized construction

Traditional construction methods, with a project-based approach, solve each project, for which the contractor considers the details of each stage from design to construction of the project (Bryden Wood et al., 2021). These traditional methods and solutions are often unique and unrepeatable, and the short interaction times between those involved make it difficult to develop practices, procedures and designs that can be reused on different projects (Jensen et al., 2015).

The configurators in the construction are based on the concept of configurable products, whereby a building project using a configurator becomes a product-based project where the final product is the building product. These configurators define the product's architecture based on a set of characteristics, options and constraints of the different systems that compose it (Jensen et al., 2015). The characteristics define the product's physical, functional, aesthetic or performance properties and can be selected by the user within a range of possibilities. Options are the alternatives available for each feature, and constraints are the rules that limit the possible combinations among the options. In other words, a configuration system, often called a configurator, makes it possible to define, manage and control the features of a final stage of a product or at a particular stage of its life cycle (Benjamin et al., 2022).

The use of configurators has resulted from the industrialization of construction since it allowed the integration of different tools and methodologies in other industries (Cao et al., 2021; Jensen et al., 2015). Their service makes it possible to obtain a customized result that fits the client's needs by repetitively using the products in a company's catalogue while maintaining the distinctiveness of client choices (Jansson et al., 2019; Jensen et al., 2015). Past research has indicated that Building Information Modeling (BIM) methodologies can be employed as a fundamental tool to develop this technology (Cao et al., 2022; Piroozfar et al., 2019). Additionally, software designed for the gaming industry can be used to create a user-friendly visual interface that facilitates interaction during the design process, ultimately leading to greater customer satisfaction with the end product (Potseluyko et al., 2022).

However, this research considers that a configuration platform for industrialized modular construction projects should not only consider the active components of the catalogues, such as volumetric modules, kit-of-parts or interfaces, but also consider the processes, knowledge, and established relationships between the stages of its life cycle that are developed before, during or after the design stage (Jansson et al., 2019; UK Research and Innovation et al., 2023).

In this way, a configuration platform in modular construction can not only fulfill a function in the design stage by providing various design options but also by standardizing, automating, and controlling information exchange for other stages, providing the possibility to develop a cyber-physical environment for the manufacturing stage (Maskuriy et al., 2019). Thus, the platforms centralize this information into a shared data environment to help the construction field's fragmented production and supply chains (Hall et al., 2020; Jensen et al., 2015).

Modular construction requires high coordination between design, manufacturing, logistics and assembly teams (Wilson et al., 2019). Today, configuration platforms can automate the search for design solutions with a digital fabrication and self-assembly approach (Liu et al., 2021). Previous study has identified three types of configurators (Cao et al., 2021). The first type is the Planning Configurator, which is used to find volumetric arrangements; the second is the Design Configurator type, which is used for evaluating solutions and creating a BIM model based on the selected option. The third type can transfer information to other stages of the production or management chain; it is called the Manufacturing configurator.

Configuration platforms are a scalable solution to implement various forms of industrialized construction, and the UK government has recently promoted their use to enhance the benefits in the industry (Bryden Wood et al., 2021). Platform use can help achieve an economy of scale, provide optimized design solutions, increase productivity, efficiency and predictability, improve quality control, minimize rework risk, and reduce waste and carbon footprint (UK Research and Innovation et al., 2023). Different publications agree that configurators are a means for adopting industrial construction methods with standardization of construction products and procedures (Bryden Wood et al., 2021; Cao et al., 2021; UK Research and Innovation et al., 2023); this becomes a tool to take advantage of the benefits of industrialized construction methods against the housing crisis.

3.2 Methodology

This study employed an inductive methodology to systematically establish criteria for evaluating the roles of configurators in construction projects. Utilizing a "snowball" literature review, supported by both backward and forward snowballing methods, the process began with a core set of articles and expanded through their cited references (Anane et al., 2023b). The gathered data underwent meticulous qualitative content analysis approach to identify configurators roles (Bengtsson, 2016). Preliminary evaluation criteria were derived through a second cycle of researcher-guided categorization. Additionally, insights from specialized literature of configuration platforms for Off-Site construction methods (Bryden Wood et al., 2021; UK Research and Innovation et al., 2023) and the configurators categorization proposed in a previous study (Cao et al., 2021) were considered to enhance the criteria. This iterative approach aimed to provide a nuanced understanding of configurators in construction projects and establish a reliable evaluation framework.

3.3 Identification of the list of criteria

3.3.1 Functions of configuration platforms for modular construction projects

The new paradigm of industrialized construction incorporates the latest information and communication technologies into cyber-physical environment, which allows to automate industrialized processes to achieve highly flexible production of customized products and services. In this context, configuration platforms have an impact on the different application domains of industrialized construction and the literature shows that they can be used at distinct stages throughout the project life cycle (Maskuriy et al., 2019).

The uses of configuration platforms can be applied to design and evaluate different systems of a building (Jensen et al., 2012; Pantazis & Gerber, 2018), however, these platforms must always use a predefined database of modular construction products. The flexibility of these products will determine the adaptive capability of the final solution. Table 3.1 shows other more specific uses of configurators addressing modular construction projects.

Table 3.1 Role of configuration platforms in modular construction projects

Role of configuration platforms regarding the architectural design domain	**References**
Provides automated layout design.	(Ghannad & Lee, 2022; Jalali Yazdi et al., 2021)
Allows standardized computational design methods (e.g. unified matrix method) and their assessment.	(Cao et al., 2021; Ghannad & Lee, 2022; Jalali Yazdi et al., 2021; Piroozfar et al., 2019)
Generates integrated solutions considering different data and other specialties.	(Ghannad & Lee, 2022; Hall et al., 2020; Pantazis & Gerber, 2018)
Generates and evaluates multiple design solutions.	(Cao et al., 2021; Jalali Yazdi et al., 2021; Liu et al., 2021; Pantazis & Gerber, 2018)
Allows to optimize the building topology.	(Baghdadi et al., 2020; Liu et al., 2021; Pantazis & Gerber, 2018)
Brings improvements in controlling and planning time, cost, and quality of the products.	(Jansson et al., 2014)
Allows for the use of a product-based project approach.	(Hall et al., 2020; Jensen et al., 2015; Liu et al., 2021; Popovic, Elgh, et al., 2021; Wikberg et al., 2014)
Enhance the client requirement management providing a graphic user interface to improve client participation and design management functions.	(Cao et al., 2021; Ghannad & Lee, 2022; Jensen et al., 2012)
Provides a hierarchical structure and interaction rules between the modular elements of different building systems.	(Ghannad & Lee, 2022; Haghir et al., 2021; Jalali Yazdi et al., 2021; Popovic, Elgh, et al., 2021)

Table 3.1 Role of configuration platforms in modular construction projects

Role of configuration platforms regarding the architectural design domain	**References**
Allows for the integration of manufacturing, transportation, and assembly constraints during the design stage.	(Cao et al., 2021; Ghannad & Lee, 2022; Jensen et al., 2012; Yuan et al., 2018)
Enables the information exchange from design parameters to manufacturing parameters.	(Ghannad & Lee, 2022; Haghir et al., 2021; Jensen et al., 2015; Yuan et al., 2018)
Enables different streams of client final decisions in the supply chain.	(Cao et al., 2021; Hall et al., 2020; Jensen et al., 2015)
Increases manufacturing efficiency and optimizes the material waste.	(Bryden Wood et al., 2021; Cao et al., 2021; Jalali Yazdi et al., 2021)
Contributes to better quality and environmental control	(Cao et al., 2021; Hall et al., 2020; Yuan et al., 2018)
Enables visualization, management, evaluation, and optimization of the design options in the configuration process.	(Koeleman et al., 2019; Popovic, Elgh, et al., 2021)
Allows the collaborative work between a project's stakeholders.	(Cao et al., 2021; Ghannad & Lee, 2022; Piroozfar et al., 2019)
Provides automated design configurations.	(Cao et al., 2021; Ghannad & Lee, 2022; Popovic, Elgh, et al., 2021)
Enhances adoption of mass customization strategies according to product architectures.	(Ghannad & Lee, 2022; Jensen et al., 2012; Wikberg et al., 2014)

3.4 Empirical Results - evaluation of the configurators available on the market

The evaluation process consisted of three stages. The first stage was the selection process, where commercially available platforms were compared to other web-based applications.

These platforms had a software architecture based on a front-end, back-end, and a database, and functioned similarly to other web-based applications. The front-end uses a graphic user interface to allow users to input data, the back-end processes the data, and the database stores the information (Cao et al., 2021). This criterion is essential to be considered in the selection because this type of software structure centralizes the information and allows the different parties involved to manipulate the data obtained, as well as the rules that can prevent errors at the top of the production chain from affecting those at the bottom (Cao et al., 2021; Jansson et al., 2019). Another criterion considered was the adaptability of the configurator to modular construction methods (Jansson et al., 2019) and that it is not a mere marketing platform for a certain type of prefabricated construction products. To identify which configurators to study, we reviewed construction technology and innovation publications and searched for potential subjects on professional web search engines like LinkedIn. After that, we filtered them based on the criteria mentioned above. During the second stage, we aimed to develop criteria for comparison. To achieve this, we carefully considered two sources of information. Firstly, we analyzed and identified the functions outlined in Table 3.1 of the previous section through literature review. Secondly, we considered the information required into each stage of an off-site construction project, as it was detailed in previous work (Rochat, 2024). We then analyzed the data obtained and formulated general concepts to compare the selected platforms. This allowed us to synthesize the information obtained from scientific literature and the industry's needs, and to develop a set of criteria for comparison. In the final stage, we evaluated trial versions of the platforms and evaluated them based on the functions they provide. During this final stage, we identified software functions that were not available in all selected configurations, these functions were included as a comparison criterion. To illustrate the results of our comparison criteria, Table 3.2 was formulated, which highlights specific criteria to distinguish differences discussed in the next section.

Table 3.2 Evaluation of selected configurators for modular residential buildings

Configurators type	**Source of the criterion**	**Criteria**	**Test Fit**	**Skema**	**Autodesk Forma**	**Architec tures**
Planning configurator	Software function comparison	Geolocation.	Yes	Yes	Yes	No
	Information required by the industry	Enables designers to create and edit modules.	Yes	Yes	No	Yes
	Information required by the industry	Allow to import modules from another software.	Yes	Yes	No	Yes
	Software function comparison	Allows to customize each module.	Yes	Yes	Yes	No
	Software function comparison	Allows users to create building configurators.	No	No	Yes	No
	Software function comparison	Generates different residential building configuration options.	Yes	Yes	Yes	No

Table 3.2 Evaluation of selected configurators for modular residential buildings

Configurators type	Source of the criterion	Criteria	Test Fit	Skema	Autodesk Forma	Architec tures
Planning configurator	Software function comparison	Allow to edit residential building configuration	Yes	Yes	Yes	Yes
	Literature review	Provides field information on the location of the project (i.e. Sound score rating, vegetation, wind directions, and others).	No	No	Yes	No
	Literature review	Geometry optimization.	Yes	Yes	Yes	Yes
	Literature review	Provides designers with tools to create and edit the building's conceptual shape.	Yes	Yes	Yes	Yes

Table 3.2 Evaluation of selected configurators for modular residential buildings

Configurators type	**Source of the criterion**	**Criteria**	**Test Fit**	**Skema**	**Autodesk Forma**	**Architec tures**
Design configurator	Literature review	Evaluate various design options.	Yes	Yes	Yes	Yes
	Literature review	Evaluates sustainability indicator.	Yes	Yes	Yes	No
	Information required by the industry	Evaluates cost indicator.	Yes	Yes	No	Yes
	Software function comparison	Generates a BIM model with all the information of the selected option.	No	Yes	No	Yes
	Software function comparison	Allow to editing the components or parameters of the modules to optimize the evaluation.	No	Yes	No	Yes

Table 3.2 Evaluation of selected configurators for modular residential buildings

Configurators type	**Source of the criterion**	**Criteria**	**Test Fit**	**Skema**	**Autodesk Forma**	**Architectures**
Design configurator	Literature review	Allows the integration of different databases for the elaboration of indicators or the review of databases to check values.	No	No	No	No
Manufacturing configurator	Literature review	Allows the integration of other information management software to centralize the information and make it accessible to other stakeholders.	Yes	Yes	Yes	Yes

Table 3.2 Evaluation of selected configurators for modular residential buildings

Configurators type	**Source of the criterion**	**Criteria**	**Test Fit**	**Skema**	**Autodesk Forma**	**Architectures**
Manufacturing configurator	Literature review	Allows the exchange of parametrized manufacturing information.	No	No	No	No
	Literature review	Provide detailed manufacturing drawings.	No	No	No	No
	Information required by the industry	Generates manufacturing scheduling and BOM.	No	No	No	No
	Information required by the industry	Generates assembling scheduling.	No	No	No	No
	Information required by the industry	Modules weight	No	No	No	No

3.5 Discussion

The analyzed configurators can provide modular design solutions automatically but cannot propose complete solutions for modular building projects. In that regard, they can consider modular design criteria to find and evaluate unique design solutions. However, they cannot automate the generation or incorporation of manufacturing information. The digital information chains allow for the correct data exchange with stages after the design stage, which link upstream and downstream in the production lines. In some previous studies, a configuration system was implemented in a Design for Manufacturing approach; the result is a powerful tool that enables designers to create products that are optimized for both manufacturing and assembly processes (Piroozfar et al., 2019; Yuan et al., 2018). This approach has the potential to significantly improve the efficiency and effectiveness of the design process, leading to better products and reduced costs. Besides, it enables a virtual space for the interaction of suppliers and customers (Bryden Wood, 2023). Table 3.3 shows the percentage of compliance with the criteria established for each type of configuration platform oriented to multistorey residential modular buildings.

Table 3.3 Percentage of compliance with the criteria established for each type of configuration platform oriented for residential modular buildings

Configurators type	**Test Fit**	**Skema**	**Forma**	**Architectures**
Planning configurator	80%	80%	80%	50%
Design configurator	50%	83%	33%	67%
Manufacturing configurator	17%	17%	17%	17%

The literature indicates that configurators generate a reduction in the development time of a project (Cao et al., 2021), which is an excellent benefit for residential projects, especially considering that the Canada is going through a sever housing crisis and buildings should be designed and built with a sense of emergency but without compromising quality and sustainability. The construction industry is slow to adopt some technologies, often because adopting one depends on adopting another earlier (Hall et al., 2020), however initiatives in countries such as the United Kingdom are encouraging the use of configuration platforms to enhance the adoption of industrialized methodologies to address challenges such as the housing crisis (Bryden Wood et al., 2021).

Previous research has suggested that using a product-based project approach in construction can involve breaking down a building into different systems whose design can be automated or configured (Ghannad & Lee, 2022; Jensen et al., 2015). However, these studies did not consider that not all configuration systems are suitable or available. A wide variety of configuration systems can provide greater customization, but this can also result in more suppliers being involved. This consideration may offer an opportunity to explore the use of configuration platforms in construction, creating a new niche market and virtual space for a fragmented supply chain to work together more efficiently (Bryden Wood, 2023).

3.6 Limitations and future research

It is important to note that the evaluation criteria used in this research are general and do not provide a detailed analysis of the capabilities of any specific software analyzed. For instance, while all configurators can export a BIM model file of the project, not all of them provide sufficient information to continue with the design tasks in a BIM-enabled modeling environment. Whereby future research could be oriented to the exploration or development of best practices for data exchange standards regarding a BIM-based configurators for modular construction.

Although some of the evaluated platforms can be used to some extent to provide specific information that can be relevant at the manufacturing stage of the project, the lack of studies on standards for the transfer of information needed at the manufacturing stage limits the ability to evaluate this aspect. Future research could focus on developing manufacturing information standards that the industry would need to transfer to this stage by integrating external databases containing industry standards that can adapt the result according to the manufacturer requirements. In that regard it could be possible to evaluate up to what extend BIM configurators could provide a holistic solution for manufacturing stage of a Modular Residential project.

The evaluation carried out in this study was performed by analyzing the functions available in the frontend of the applications. Therefore, the functions available in the backend of the applications, where different interactions with the available databases can be generated, were not considered. For future studies, to include different databases in the analysis could help identify platforms that not only address design and manufacturing challenges but also contribute to the construction of more sustainable and cost-effective housing. And investigate the potential of configuration platforms to support the development of universal social housing, focusing on cost-effective and sustainable solutions. This direction could address broader societal challenges related to housing affordability and accessibility.

Furthermore, it should be kept in mind that this evaluation is subjective and limited by time. Therefore, it is important to consider including triangulation, surveys with specialist or other validation methods in future studies.

3.7 Conclusion

The study's findings indicate that the current configurators can assist designers up to the design phase by automating design tasks and evaluating the generated options based on several predefined design criteria relevant to a modular design. However, the study also found that these configurators need further development in transferring manufacturing information, which is a challenge for their use in an automated modular construction process.

It is worth noting that evaluated configurators can interface with BIM software such as Autodesk Revit, which can recognize and storing manufacturing information. Despite that. purpose of this research is to determine the extent to which configurator platforms are utilized in each stage of an off-site construction project, and not to evaluate the specific capabilities of the BIM software.

The results of this paper suggest that the current market supply of modular configuration software cannot yet be integrated into an automated, modular housing scale production system.

This configuration systems could enhance the time and cost performance from the early stage of a OSC project and could provide a common data environment for industry standards.

CHAPTER 4

BIM-BASED CONFIGURATION SYSTEM FOR AN EARLY DESIGN STAGE OF MODULAR RESIDENTIAL PROJECTS

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This chapter is part of the publication presented in the annual conference of the "Canadian Society for Civil Engineering," where this study proposes the use of a configuration platform (also called configurator) to guide users in customizing final products based on design requirements and available manufacturing options. Such platforms provide construction consultants with the necessary tools and information to design a construction product (a building) that aligns with the characteristics of a specific building industrialized system. Configuration systems are an application of artificial intelligence and have exciting potential to streamline design choices, evaluate them, and ensure compliance with regulatory standards. Modular construction is perceived as an alternative solution to the housing crisis due to its benefits of cost, production time, environmental impact, and high quality. This article aims to assess the hypothesis that BIM-based configuration platforms can help fill the knowledge gap that limits the adoption of off-site construction methodologies. The study elaborates on the method used, the architecture, and the criteria that served as guidelines for the proposal of a configuration system workflow used into a general study case. The findings and limitations of BIM-based configuration platforms are discussed, and proposals for future research are suggested.

4.1 Introduction

Integrating technology in construction has significantly transformed traditional methods, offering more efficient and sustainable solutions (Chen et al., 2021; Wang et al., 2020). One significant technological advancement is the development of configuration systems, which streamline the design, production, and assembly of modular structures with precision and flexibility. These systems, often considered applications of artificial intelligence, assist in decision-making processes and ensure compliance with regulatory standards (Haug et al., 2012).

Modular construction presents itself as a viable alternative to address global challenges such as the housing crisis, offering benefits in terms of cost, production time, environmental impact, and quality (Chen et al., 2021; Wang et al., 2020). This paper addresses the need for more tools to assist designers in adopting modular integrated construction systems, particularly in the context of Building Information Modeling (BIM) based configuration platforms. BIM technology has enabled the digitization of construction project information, facilitating computational design procedures and automating processes (Anane et al., 2023a). This makes it possible to generate information necessary for decision-making and automated processes or create simulations that allow the characteristics of the building in question to be evaluated.

Despite advancements in BIM technology, existing BIM configuration platforms do not generate models directly applicable to other stages of the project lifecycle, presenting a significant gap in the adoption of off-site construction methodologies (Cao et al., 2021). This study explores how BIM-based configuration platforms can fill this knowledge gap, particularly concerning integrating off-site construction methods into the design and manufacturing processes.

Furthermore, the paper aims to investigate the potential of BIM platforms in addressing the identified gaps in the literature regarding off-site construction and BIM integration. By examining the capabilities and limitations of BIM platforms, the study seeks to contribute to future research directions, including the automation and optimization of design elements, carbon emission analysis, and the integration of various phases in the lifecycle of off-site construction projects (Wang et al., 2020).

This article proposes a BIM-based configuration platform to help bridge the knowledge gap limiting the adoption of off-site construction methodologies. To this end, the following section will explain the literature review and the identified gaps, following the objectives and method used to elaborate this research; after that, the comparison of commercial configurators will show how the criteria to elaborate the proposal was shaped. The following section elaborates on why volumetric modules were the selected OSC method. The architecture of the proposed configurator will be explained, and finally, the discussion and conclusions will be finalized.

4.2 Literature review

To conduct a case study, an extensive search was conducted on digital databases, including Scopus and Direct Science. The primary objective was to delve into the utilization of configuration platforms for modular construction projects and the integration of BIM methodology in this domain. The snowball technique was employed to identify and analyze relevant articles on these subjects.

Previous studies have identified the future direction of research on the application of BIM in the OSC field and the responsiveness of a BIM-based configuration system in OSC has been recorded (Wang et al., 2020). The findings have been organized and summarized in Table 4.1, which provides directions for the development of the configuration platform that will be the artifact of this research.

Table 4.1 Responsiveness of BIM-based information platforms to the areas identified for future research on the application of BIM in the OSC field

Futures research directions about application of BIM on OSC field	**Responsiveness of BIM based configuration platforms**
BIM-based automation improves coordination of prefabricated elements, with AI (Artificial Intelligence) aiding assembly processes.	BIM-based platforms automate the design process considering the limitations of the building system, client, and project requirements (Cao et al., 2021; Piroozfar & Piller, 2013).
Establishing BIM standards and integrating with technologies like sensors enhances data exchange efficiency in OSC projects.	A predefined configurative system establishes its common data environment, which can be utilized in database design and automated processes. These standards are beneficial across various stages of OSC projects (Ezzeddine & García de Soto, 2021).

Table 4.1 Responsiveness of BIM-based information platforms to the areas identified for future research on the application of BIM in the OSC field

Futures research directions about application of BIM on OSC field	**Responsiveness of BIM based configuration platforms**
BIM should expand to manage OSC aspects such as procurement and safety.	Integrating different configuration instances enables the management of diverse sources of information and outcomes, a crucial consideration in BIM platform design (Ezzeddine & García de Soto, 2021).
AI integration in BIM aids in complex data processing and decision-making.	The configurative system is a form of AI that uses complex rules to make design decisions like humans. Integrating various AI systems can promote Industry 4.0 practices and cyber-physical systems.(Cao et al., 2021; Hall et al., 2020).
Recycling strategies for prefabrication materials are essential for sustainability.	BIM platforms optimize resources and enable element info management for creating digital twins even after integration into buildings (Pasetti Monizza et al., 2018).
BIM utilization across the OSC life cycle needs streamlining.	They allow the generation of information for the manufacturing, assembly, and transportation stages while considering the design limitations inherent in each stage (Anane et al., 2023a; Cao et al., 2021; Piroozfar & Piller, 2013; Zhai et al., 2019).
More case studies are needed to assess BIM's impact and develop evaluation models.	These platforms can optimize and evaluate indicators and integrate standardized evaluation systems. Further research is needed. (Cao et al., 2021).

Table 4.1 Responsiveness of BIM-based information platforms to the areas identified for future research on the application of BIM in the OSC field

Futures research directions about application of BIM on OSC field	Responsiveness of BIM based configuration platforms
Integrating technologies like RFID with BIM should align with OSC processes for maximum benefit.	The effectiveness of integrating RFID technology in configuration platforms for digital modeling is not well-documented. BIM configurator could potentially be used to integrate this technology (Cao et al., 2021).

4.3 Objectives and research method

The study aims to simulate the use of a BIM configuration system for a modular residential construction project to help modular system users consider aspects of fabrication, assembly, and transportation from the early design stages of the project. Therefore, an artifact was then developed to carry out a case study that would provide information on the capabilities and requirements of BIM configuration platforms and their application in OSC projects. Previous studies with similar approaches (Piroozfar & Piller, 2013; Zhai et al., 2019) have demonstrated the effectiveness of addressing the logic of design, data collection and evaluation, and qualitative analysis techniques in this type of research.

The next chapter will explain the criteria considered in developing this proposal. These criteria are the product of a qualitative analysis that establishes the proposal's capabilities based on a comparison of existing data from academic and contemporary industrial sources.

4.4 Comparison of commercial configurators

To carry out this study, an exhaustive comparison of the various configuration platforms available on the market and their viability within OSC projects was carried out (Llave & Iordanova, 2024a). This comparison was based on an extensive literature review to identify the functions of BIM configuration platforms in construction projects of distinctive characteristics. In addition, several commercially available software was evaluated and compared based on their integration into the lifecycle of an OSC project. Finally, industry requirements, such as engineers, architects, and contractors, for adopting OSC methodologies were considered. Table 4.2 lists the criteria that resulted from this process and that have been considered for the elaboration of this project.

Upon carefully examining various configuration platforms available in the market, it was determined that none of the existing platforms were designed to meet all the criteria established for the intended purpose. Consequently, proposing a configuration system specifically tailored to this task became necessary.

Table 4.2 Criteria to elaborate a BIM-based configuration workflow for modular construction

Configurators type	**Source of the criterion**	**Criteria**
Planning configurator	Software function comparison	Geolocation.
	Information required by the industry	Enables designers to create and edit modules.
	Information required by the industry	Enables designers to import modules from another software.
	Software function comparison	Allows to customize each module.
	Software function comparison	Allows users to create building configurators.
	Software function comparison	Provides users with different residential building configuration options.

Table 4.2 Criteria to elaborate a BIM-based configuration workflow for modular construction

Configurators type	**Source of the criterion**	**Criteria**
Planning configurator	Software function comparison	Allow to edit residential building configurations.
	Literature review	Provides field information on the location of the project (i.e. Sound score rating, vegetation, wind directions, and others).
	Literature review	Geometry optimization.
	Literature review	Provides designers with tools to create and edit the building's conceptual shape.
Design configurator	Literature review	Evaluate various design options.
	Literature review	Evaluates sustainability indicator.
	Information required by the industry	Evaluates cost indicator.
	Software function comparison	Generates a BIM model with all the information of the selected option.
	Software function comparison	Provides users the option of editing the components or parameters of the modules to optimize the evaluation.
	Literature review	Allows the integration of different databases for the elaboration of indicators or the review of databases to check values.

Table 4.2 Criteria to elaborate a BIM-based configuration workflow for modular construction

Configurators type	**Source of the criterion**	**Criteria**
Manufacturing configurator	Literature review	Allows the integration of other information management software to centralize the information and make it accessible to other stakeholders.
	Literature review	Allows the exchange of parametrized manufacturing information.
	Literature review	Provide detailed manufacturing drawings.
	Information required by the industry	Generates manufacturing scheduling and BOM.
	Information required by the industry	Generates assembling scheduling.
	Information required by the industry	Modules weight

4.5 Configuration tools for modular construction

Configuration tools are resources that can assist companies in adopting an industrialized construction business model (Cao et al., 2022; Popovic, Schauerte, et al., 2021). Therefore, in this experiment, criteria that fit the capabilities and limitations of the case study were considered. This section will be devoted to describing some of the criteria that guide decisions related to the modular methodology selected for this case study, as well as the general criteria used to select the software used in the experiment.

4.5.1 Defining OSC method

For this experiment, using volumetric modules or Modular Integrated Construction (MiC) systems was considered appropriate because they simplify decomposing a building into different subsystems since each module can be considered a self-supporting and even autonomous element (Wuni & Shen, 2020). This approach also guarantees the repeatability of the elements, which, from an industrial manufacturing perspective, ensures better quality control, better activity planning, and better streamlining of production lines (Pasetti Monizza et al., 2018).

This OSC method has been used in residential buildings, offices, and hospitals. A prominent example of its efficiency and quality to date is the Leishenshan hospital in Wuhan, China. This project covered a total construction area of 79,000 m2 and was completed in just two weeks (Chen et al., 2021), demonstrating the potential of this methodology to meet the immediate need for residential buildings.

One barrier to adopting this methodology is the difficulty of customizing modular solutions in the construction field, even though the industry has found a way to reduce the monotony and deteriorated aesthetics of modular design (Razkenari et al., 2019). BIM platforms facilitate the customization of products and services, translating customer requirements into modular design solutions (Piroozfar & Piller, 2013).

4.6 Proposed BIM-based configuration workflow

According to the literature, several configuration platforms are available in the market. However, it has yet to be verified that they are specifically designed to be used throughout the entire lifecycle of an OSC project (Cao et al., 2021). For this reason, it was considered pertinent to develop a customized workflow using the BIM software available on the market. This approach allows setting the configuration rules and laying the groundwork for future research and improvement using this framework.

BIM software is not only limited to building modelling during the design stage, as it contains information that can be leveraged at various stages of the project lifecycle, especially in OSC projects, where BIM helps to provide the same functions and, in addition, generates chains of information that connect the manufacturing stages, assembly and supply with the design stage (Cao et al., 2022; Jensen et al., 2015; Zhai et al., 2019). Therefore, the interoperability of the software has been a crucial criterion in its selection.

Another relevant aspect was the degree of integration with computational design techniques for information modelling and the creation of parametric elements that allow the automation of functions (Pasetti Monizza et al., 2018). Thus, it would be feasible to establish the rules that will direct the workflow of the configuration system.

Considering the criteria mentioned above and their application in numerous studies, Autodesk Revit and its extension Dynamo for Revit are the most suitable software for this purpose.

This case study aims to demonstrate that a BIM platform could facilitate the adoption of MiC and highlight the benefits of this methodology for efficiently addressing the housing shortage. The next section will look at the functions of the configuration platform and the criteria that have shaped it.

4.6.1 Configuration system architecture

Previous studies on configuration platforms have shown that digital tools with a backend and frontend-based software structure, where various databases act as containers of rules for the various configuration systems that interact with each other, are effective for these operations (Cao et al., 2021). In the backend, the data obtained can be used for various purposes, such as the automation of robotic processes in automated production lines (Anane et al., 2023a) or the optimization of various categories of information, such as the geometric representation that can be used for the execution of product manufacturing activities (Pasetti Monizza et al., 2018).

In addition, criteria can be established to find data to support decision-making, such as the carbon footprints of each product, to optimize the result of the building's carbon analysis (Sonego et al., 2018).

On the other hand, the frontend is the interface connecting the platform's users, where information on entering and exiting the platform is received (Zhai et al., 2019).
To develop this proposal, the development of a configurative system through a workflow that fits the capabilities of the software and the time limit to develop this work was considered. Figure 4.1 shows the workflow and the sections whose explanation will be detailed in what follows.

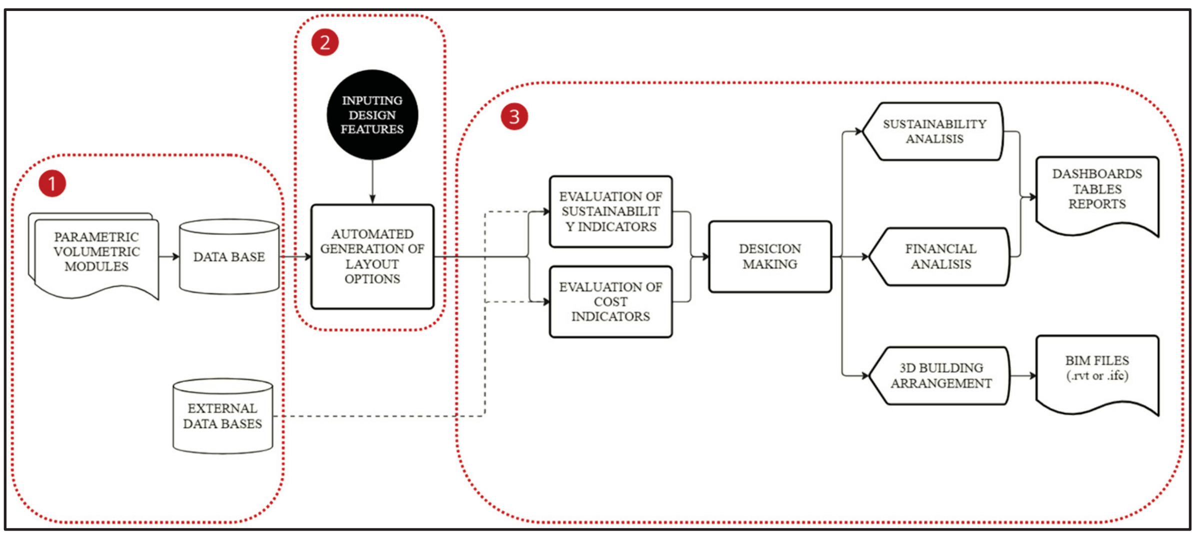

Figure 4.1 BIM-based configuration system workflow

As shown in Figure 4.1, the first section of the workflow deals with the database containing libraries of parameterized elements responsible for their geometric representation, as well as other databases that contain information on their non-physical aspects, such as indicators for sustainability, economics, or supplier comparison analysis.

The second part will address how to generate the building geometry using standardized computational design techniques and customize architectural proposals according to parameters determined by the project and the client.

Finally, the last section will address system information management, decision-making, and the outputs obtained from this workflow.

4.6.1.1 Section 1 - The Parametric Elements Database

Subdividing complex systems into less complex components is one of the foundations of the concept of modularity (Jensen et al., 2015; Wuni & Shen, 2020). When using MiC, each module is considered to have its own structural, architectural, and MEP (Mechanical, Electrical, and Plumbing) system, which should be integrated as part of a single system once the building is completed.

Through a meticulous process of module decomposition, designers can generate multiple design variants for a single component. This approach facilitates the selection of the best variants to create the desired final product (Zheng et al., 2021). In Figure 4.2, a left column displays various categories of data available in the database. These categories are a product of volumetric module decomposition. The central section of the image shows different examples of the elements of each category and indicates their belonging to elements of other categories. On the right side of the image is a brief description of the information in each category of the proposed database.

Using the elements in the database makes it possible to create a comprehensive digital model of the building, which can be used to evaluate design options based on various indicators. The proposed database does not contain information about these indicators, whereas external databases were included to provide information about the selection of optimal materials for the project, carbon footprint reduction, cost optimization, and supplier analysis (Bryden Wood, 2023).

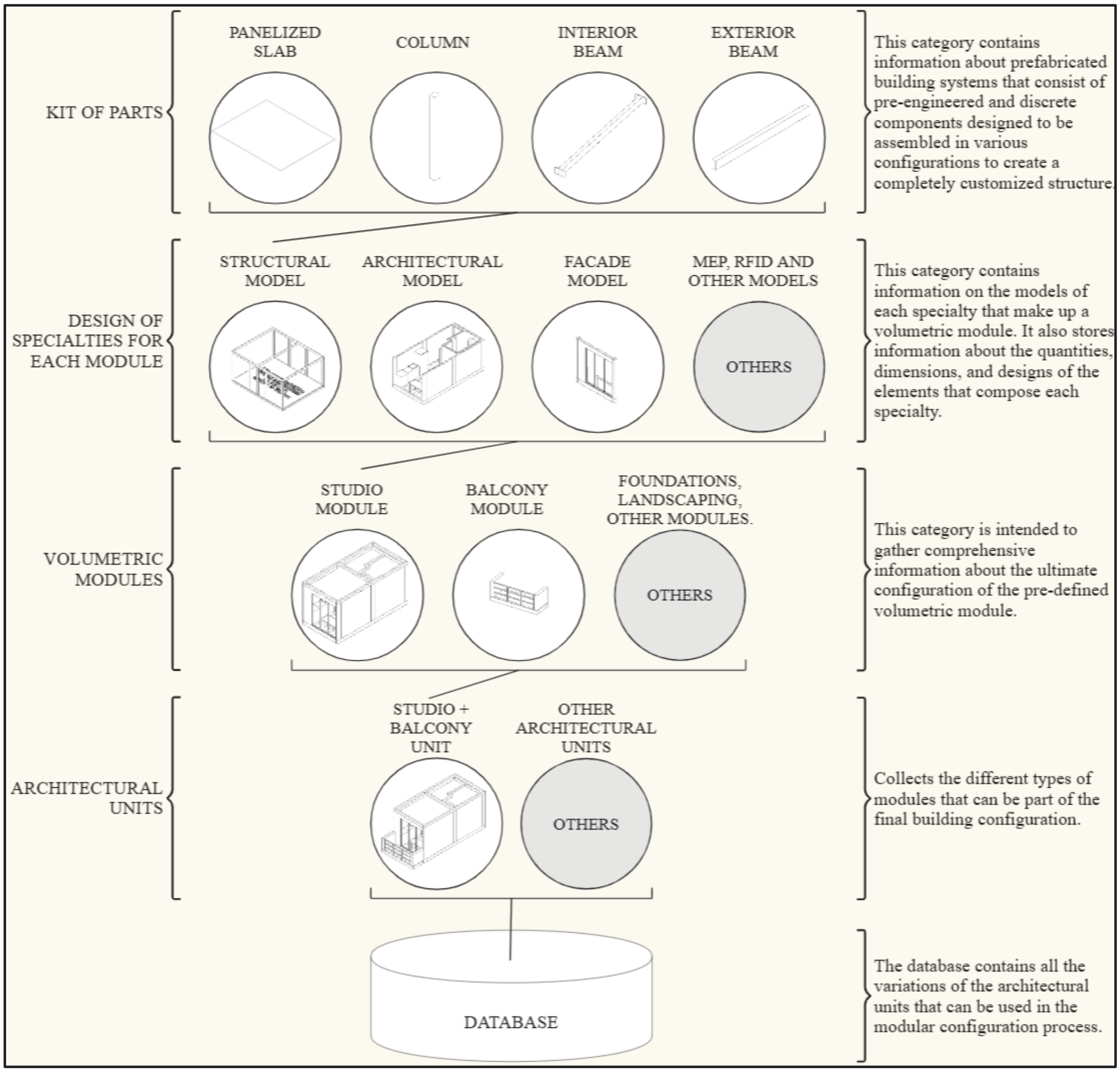

Figure 4.2 Data categories based on volumetric modules decomposition

This database used a parametric family to create an adaptive component representing the BIM structural model. This element can be adapted to any module dimension added to the database, changing element quantities and dimensions in its kit of parts, demonstrating that design automation is possible considering the structural rules of the chosen building system. Due to the complexity of the task, the models of the other specialties have yet to be automated, so it is necessary to manually edit the existing or new architectural models.

The transportation legislation allowing them to be transported to the assembly location must constrain the final dimension of each volumetric module.

4.6.1.2 Section 2 - Automated Design and Configuration Rules

The figure 4.3 depicts the algorithm's sequence to create the building's geometry. The design automation process starts by drawing the central axis of the building. Then, the algorithm generates a two-dimensional matrix to house the virtual containers. These virtual containers will hold different architectural units like apartments, circulation areas, and others that will make up the building. Finally, the algorithm replicates the two-dimensional matrix vertically to create the desired number of floors specified by the client. This way, the final geometry is generated with the maximum possible number of containers using the chosen module dimensions.

The automated process for generating the building's geometry is a variation of the unified matrix method used in some previous publications (Sharafi et al., 2017).

Apart from the above information, the client must specify the number of architectural units that will be part of the configuration process. Another configuration option is the building's façade. The current proposal provides the flexibility to include or exclude balconies in the apartment units.

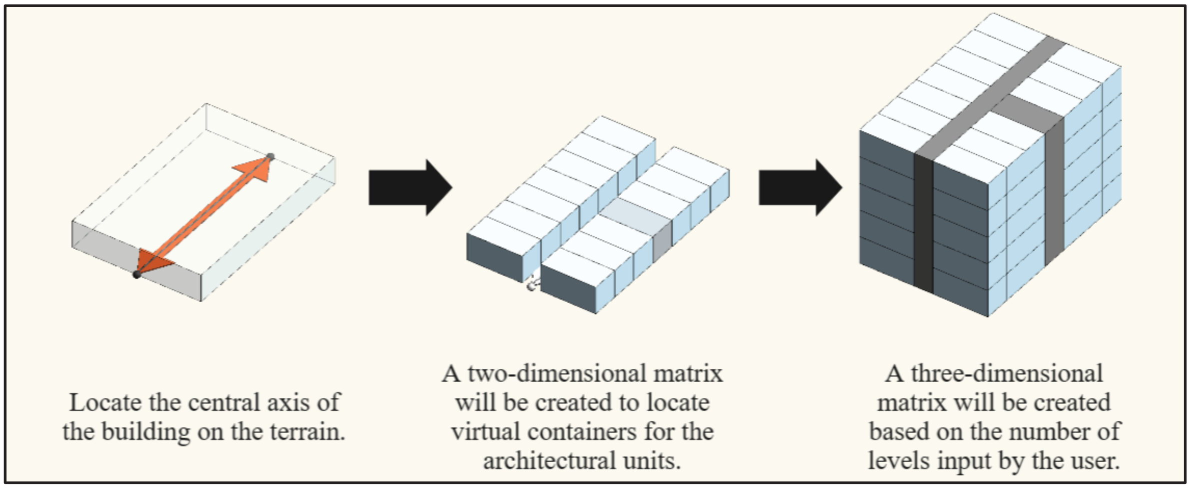

Figure 4.3 The algorithm's sequence to create the building's geometry

4.6.1.3 Section 3 - Information management, decision-making and outputs

Information acquisition occurs after defining the desired features of the product, allowing users to compare between different options once these are established. This process not only uses the information generated in the automated process described above, but also leverages information from databases geared to contain non-physical data of the elements. In this way, comparative tables can be created with different indicators according to the needs of the stakeholders.

In this part of the workflow, it is also possible to visually compare the first preview of the project, allowing untrained users to use BIM models to understand better the aesthetic changes that some decisions might generate.

Once the desired model has been selected, the available information can be used to generate comparisons of indicators, quantify elements, and create data useful for its manufacture and management at the distinct stages of the project.

4.7 Discussion

The discussion section aims to analyze the findings and final reflections, contrasting them with the information in the literature on similar applications or related theories in this field.

While shaping the final design through the selection of different modules is an approach used in previous studies (Cao et al., 2022; Piroozfar & Piller, 2013; Zhai et al., 2019), this paper highlights that allowing configurations for each more minor component within the modular system allows for a greater level of detail in the customization of the final product. It was also noted that the approach used with the unified matrix is limited by the number of predefined configurations available for the building, and no records have been found of the comparison of different computational design techniques that could be used in the same type of project.

Several publications support the idea that using configuration platforms helps transition to Industry 4.0 (Pasetti Monizza et al., 2018). However, little development has been found in open-source proposals that use Industry Foundation Classes (IFC) standards, which allow the use or development of residential building configuration systems that can be configured according to each project's different constraints.

4.8 Conclusion

This paper presents the use of a configuration platform for a multi-family housing complex that uses a modular construction system. Its purpose is to provide designers with design criteria that consider the constraints imposed on the manufacturing, assembly, and transportation stages of construction products within the residential building. In addition, it allows the user to customize the result and generate information according to the client's and the project's specific needs.

Expanding the configuration options requires greater specificity in the architecture of the products included in the database. To gather more information about their performance within the configuration system, additional studies using various computational design techniques are suggested.

It has been found that using BIM-based configurative systems in modular projects is effective and supports future research directions proposed in the literature. The need for further research on BIM platforms and their application in Off-Site Construction (OSC) is highlighted, in using these methodologies to evaluate projects and integrating technologies like Radio Frequency Identification (RFID) into these workflows.

Regarding the limitations of this project, Dynamo, a visual programming platform, was used to generate the connection with the database, the automation algorithm, and the feature configuration space in the same interface. There are no records of different methods used to create custom configuration flows for construction projects other than through these visual programming platforms. However, developing a standalone application could enhance the capabilities of the proposal.

Additionally, due to the limited time available for the proposal, future research will focus on validating and developing the proposed workflow.

CHAPTER 5

APPLICATION OF THE CONFIGURATION PLATFORM IN A REAL-WORLD MODULAR RESIDENTIAL PROJECT

5.1 Introduction

The integration of digital configuration platforms enables builders to design and customize modular buildings precisely, using advanced algorithms and AI to generate detailed 3D models (Ghannad & Lee, 2022; Lee et al., 2023). This strategy helps bridge the gap between design and manufacturing, assembly, and transportation knowledge, essential for the modular construction process (Razkenari et al., 2020; Yuan et al., 2018). Additionally, the rise of Industry 4.0 has introduced a new era of production characterized by robotics, AI, and automation, enhancing the connectivity across all project stages, and facilitating a comprehensive lifecycle approach to building projects (Anane, 2022; Hall et al., 2020; Vestin & Säfsten, 2021).

This study examines the application of the proposed BIM-based configuration framework that helps bridge the gap between design and manufacturing, assembly, and logistics knowledge for modular construction, with a focus on the early design stages. Utilizing the modular construction project PD2023-005 from the *Système électronique d'appel d'offres* database (*Secrétariat du Conseil du trésor*, 2023), it assesses the proposed configuration platform's effectiveness in streamlining design, manufacturing, and transportation considerations, aiming to identify the optimal design solutions for project needs.

5.2 Literature review on the methods of evaluation of configuration systems

To conduct the method of evaluation of the implementation, previous studies related to the evaluation of prefabricated building configuration systems in different contexts (as identified by the SLR in Chapter 1) were reviewed. Table 5.1 shows a synthesis of the findings in the literature.

Table 5.1 Documents analyzed related to evaluation of configuration systems for prefabricated construction projects

Article Title	**Author**	**Main Findings**	**Specific Evaluation Details**
Automated Modular Housing Design	Ghannad and Lee (2022)	Explores automated housing design using a module combination algorithm. Finds efficiency in design processes and customization options.	Algorithmic simulation and analysis of design outcomes.
Product Configuration in Construction	Ghannad and Lee (2022)	The article proposes a conceptual framework for a cross-phase product configurator unified through a manufacturing kit-of-parts. The configurator supports a low-to-high level of detail of kit-of-parts and integrates product platforms across multiple building phases.	The research develops a configurator prototype using three-tier architecture
Product Platform Alignment in Industrialized House Building	Jensen et al. (2015)	Investigates mass customization in construction through modularization. Highlights the potential for increased product flexibility without significant cost increases.	Survey and interviews with engineers and project managers to validate modularization strategies.

Table 5.1 Documents analyzed related to evaluation of configuration systems for prefabricated construction projects

Article Title	Author	Main Findings	Specific Evaluation Details
BIM-Based Interactive Environments in Construction	Ezzeddine and García De Soto (2021)	Analyzes the connectivity of teams in modular construction projects. Suggests that improved connectivity leads to better project outcomes.	Network analysis and surveys to measure team dynamics and project outcomes.
Platform Use in Systems Building	Popovic et al. (2021)	Discusses product platform alignment in industrialized house building. Emphasizes the importance of aligning platform strategies with market demands for successful customization and efficiency.	Expert interviews and review of project documentation for qualitative assessment.
Configuration Platforms for Design Customization	Jansson et al. (2014)	Focuses on the use of product platforms in systems building. Identifies key factors affecting platform use in construction, such as the balance of commonality and distinctiveness.	Triangulation with experts to validate findings and detailed case study analysis.

Table 5.1 Documents analyzed related to evaluation of configuration systems for prefabricated construction projects

Article Title	**Author**	**Main Findings**	**Specific Evaluation Details**
Configuration platform for customisation of design, manufacturing and assembly processes of building façade systems: A building information modelling perspective	Piroozfar et al. (2019)	The paper investigates how configuration principles can address challenges in applying Building Information Modelling (BIM) in the Architecture, Engineering, and Construction (AEC) industry. It focuses on developing a customizable façade system using BIM to enable modularisation and mass customisation.	Case study evaluates how BIM enhances modularisation, standardisation, and collaboration in façade design and construction.
Connectivity in Modular Construction Projects	Cao et al. (2021)	Studies cross-phase product configurators in modular building projects. Reveals configurators can enhance coordination across different construction phases.	Simulation for process validation, surveys, and interviews with participants for practical insights.

In conclusion, the case studies presented in the table 5.1 utilize insights from a comprehensive review of existing literature on prefabricated building configuration systems. The analysis, detailed in Table 5.1, synthesizes findings from various studies, highlighting the effectiveness and potential of different configuration approaches in modular construction. Key studies, such as those by Ghannad and Lee (2022), Jensen et al. (2015), and Popovic et al. (2021), focus on advancements in automated design algorithms, mass customization, and product platform alignment, respectively. This synthesis provides a solid foundation for evaluating BIM-based configuration systems in real-time scenarios, addressing important gaps in technical knowledge among designers in the prefabricated construction industry.

5.3 Methodology

This study aims to demonstrate that utilizing configuration platforms can simplify the adoption of modular methodologies in the initial phases of design. In that regard, it employs a qualitative approach to the development and evaluation of a BIM configuration platform, through real-world project implementation of the artifact via a software prototype. Supported by the Société de l'Habitation du Québec, which provided crucial information for the implementation of the artifact in a real-world context. The implementation case focused on the PD2023-005 project, consisting of the construction of a 51-unit modular residential building in Chicoutimi, Quebec.

Advanced tools such as Autodesk, Revit and Dynamo were used for the development of the software prototype of the artifact for the modeling and manipulation of information within a BIM approach. This process allows the automation of the configuration, ensuring compliance with the specific criteria of the construction system, manufacturing, assembly, and transport. In addition, databases are integrated to facilitate the evaluation of environmental and cost indicators during the configuration process.

The evaluation of the framework is conducted through triangulation with experts, allowing several researchers to analyze the information collected and offer different perspectives within the project individually. This reduces the risks of experimental biases, such as observer bias.
In conclusion, the methodology adopted in this study provides a structured approach that not only supports the development of innovative solutions in the field of modular construction, but also establishes a framework for their systematic and rigorous evaluation. This methodology

is critical to ensure that the framework is not only theoretically sound, but also effective in real construction environments.

5.4 Software Prototype Development and Implementation

This section provides a detailed and graphical explanation of the prototype development and implementation process. The first subsection elaborates on the development of the software prototype. It begins with the initial conception of the workflow that enables the creation of the configuration system and ends with a detailed explanation of each consideration taken to create the proposal. The next subsection is dedicated to implementing the artifact in a real-world case.

5.4.1 Development of the software prototype

To develop the configuration prototype, it was necessary to delve into the conception of modular architectural products. A construction product offers a standardized and replicable solution to meet specific needs (Gravina da Rocha et al., 2019). Even a building could be conceived as a product composed of other products (Jansen, 2012), which is known as a product-within-product approach. In the field of product design knowledge, this can be understood as a definition of modularity, where a module is a self-contained collection of elements that can be managed as a single entity.

The application of modularity in the field of construction products makes it possible to design prefabricated elements that make up the kit of product parts. Each modular element can be used to form assembled volumetric elements with a defined degree of customization, depending on your selected construction system and manufacturing process. The automation of this customization process is enabled through the use of a product configuration platform (Popovic et al., 2021).

The literature identifies three types of configuration platforms applied to construction: planning configurator, design configurator, and production configurator (Cao, 2021). These platforms can be used at different stages of the modular construction project lifecycle. The rules that define configuration processes are related to the stages of the product life cycle, its modularity and level of granularity (Janssen, 2012).

Although the configuration platform prototype proposed in this study is designed for the initial stage of residential modular building design, the modular construction methodology implies that production criteria must be considered from the outset. Therefore, it is proposed to include manufacturing and logistics criteria from the beginning of the process to inform the configuration process. This will allow for results that could be used by a production setup configuration platform, based on the classification by Cao et al (2021), mentioned above.

For the development of the prototype, it is proposed to use an adaptation of the workflow proposed by Popovic (2021) made by the author. Figure 5.1 illustrates the different stages of the framework that compose the configuration system, the fields of knowledge from which these criteria come and the type of information that is provided, according to the classification of configurators identified in the literature. In the image 5.1, Popovic's proposed steps employ geometries with a gray background color, while the author's additional or edited steps employ geometries with a white background color.

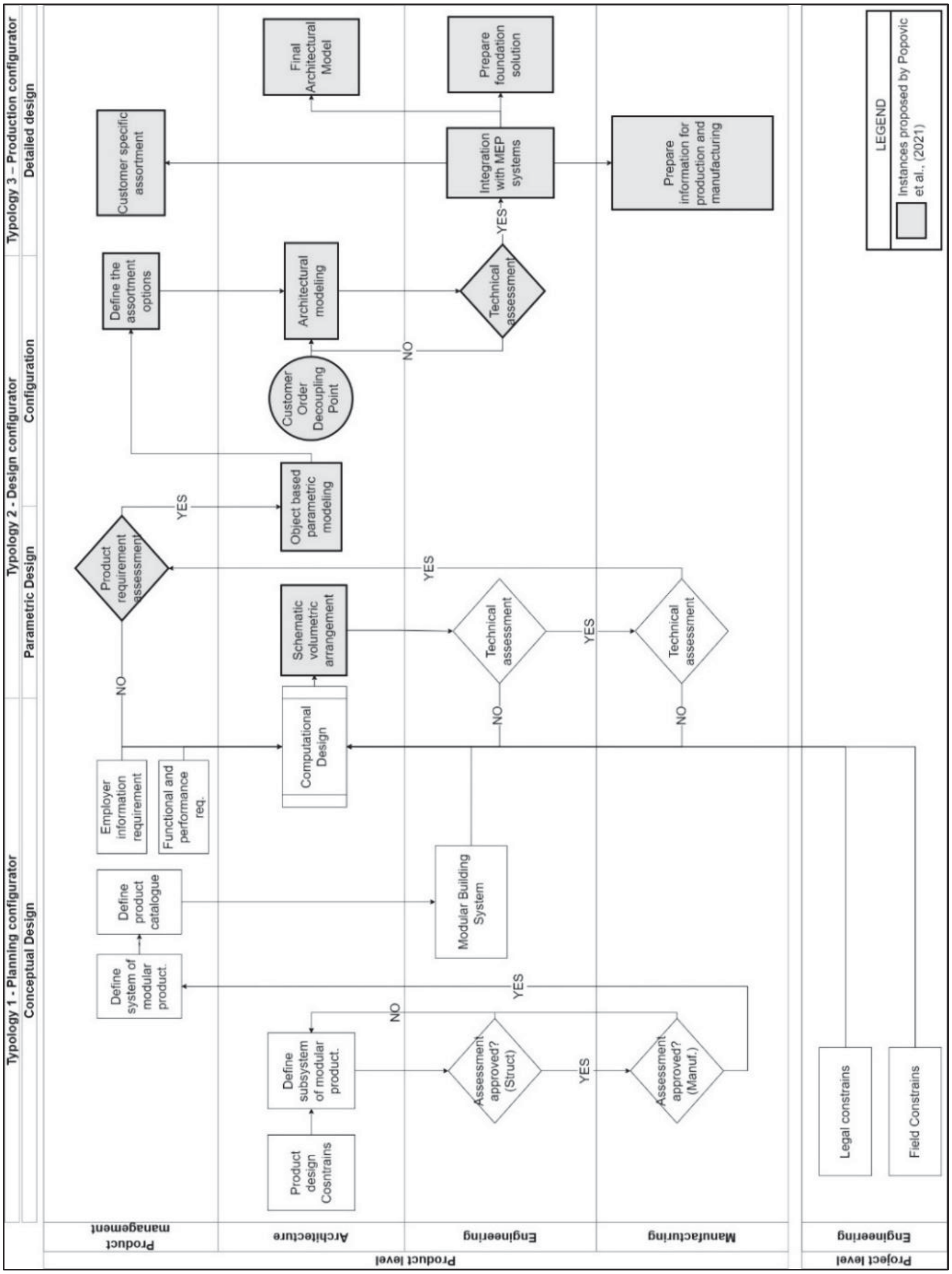

Figure 5.1 Adaptation of the workflow proposed by Popovic (2021) for a configuration system

Since the primary objective of this study is to demonstrate that the use of configuration platforms can facilitate the adoption of modular methodologies in the early stages of design, some steps that have not been identified as part of a planning or design configuration platform are omitted. In addition, the steps related to the different technical evaluations proposed in the framework are also omitted, as they are considered not to contribute to the testing of the hypothesis of this study.

Image 5.2 shows the elements considered in the elaboration of this artifact. Workflow stages that are part of another type of configurator are considered in prototyping because, as mentioned above, information from manufacturing and logistics processes from later stages of the production chain are used as primary criteria in the initial stages. Therefore, it is natural to have the information that allows you to continue with the post-design stages.

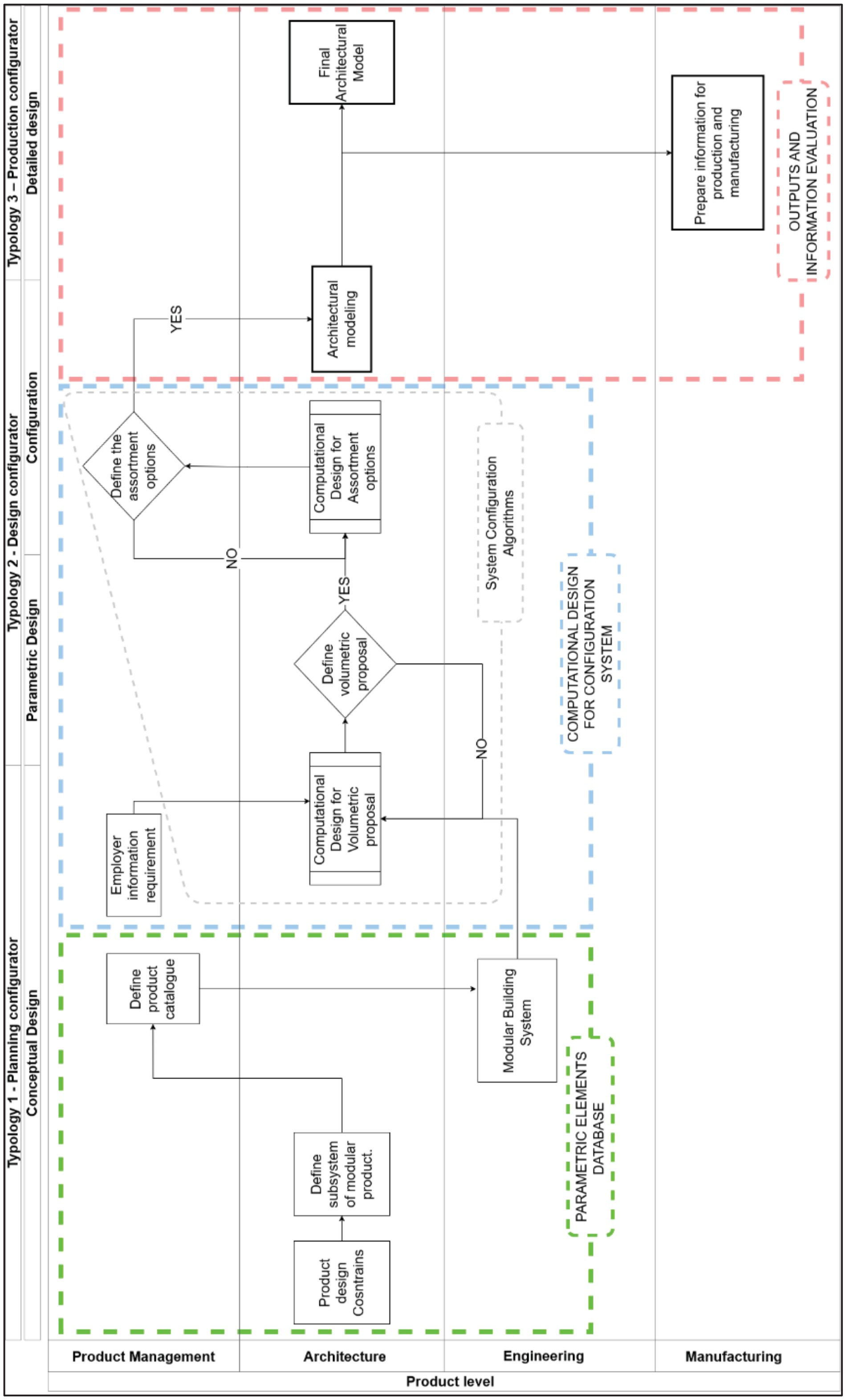

Figure 5.2 Workflow considered necessary for the development of the configuration platform

Figure 5.2 groups the different stages considered within the workflow for the development of the prototype of the configuration platform software. The following sections will explain in detail the content of each stage and the strategy used to incorporate it into the proposed configuration system.

5.4.1.1 Parametric elements database

The parametric database section focuses on the development process of the construction product that will be used in the modular artifact construction system. Considering that a construction product offers a standardized and replicable solution to address specific requirements (Gravina da Rocha et al., 2019), this section will explain the conception of the product catalog for volumetric modules, following the stages in Figure 2.

5.4.1.1.1 Product design constrains

The design constraints for a modular construction project can have different sources, depending on the different stages of the project's life cycle, its stakeholders, or even limitations specific to the construction site and its legislation (Jansen, 2012). To develop the configuration system prototype, only a few constraints were considered to validate the hypothesis of this study.

One of the limitations is that the modules need to meet specific dimensions to guarantee their transportability. In that regard, the product's ability to automatically adapt to these constraints has been proven using a parametric system in the digital representation of the construction product's structural system.

One of the constraints was the ability to set specific dimensions of modules as a logistical constraint. In this way, the BIM model of the structure of the volumetric module will always contain elements that meet the engineering and design criteria necessary to adapt to the selected construction system through the use of a "kit-of-parts". The "kit-of-parts" is a pre-engineered and pre-designed system of components of a product (Cao, 2021). The configuration level of these elements is determined by their level of granularity (Hossain, 2021), so for this prototype a parametric BIM model was created that is capable of adjusting the dimensions and quantities of the structure based on the overall dimensions of the module.

The ability to transfer information to the downstream production stages of the product life cycle was also an initial constraint, as manufacturing criteria must be considered from the first stage of the project. In the prototype, for example, a structural system of cross laminated timber with steel connections was used. Accordingly, rules were included in the BIM parametric system that allow relevant information to be obtained for production, such as the types of elements to be manufactured and the ability to obtain drawings for their manufacture.

5.4.1.1.2 Define subsystem of modular product

For the configuration system prototype, the hierarchy of subsystems that make up a building was simplified. The BIM model of the residential building taken as an example, was considered to be the finished product and to be composed of different subsystem design modules (Wuni & Shen, 2020). From this, it is possible to infer that a building can be considered a complex system and its elements are its modules. In addition, this same concept can be applied to modules, and it is possible to continue this cycle until singular elements such as individual modules are obtained. Figure 5.3 provides a graphical reference to the hierarchy of the different subsystems considered in the development of the prototype.

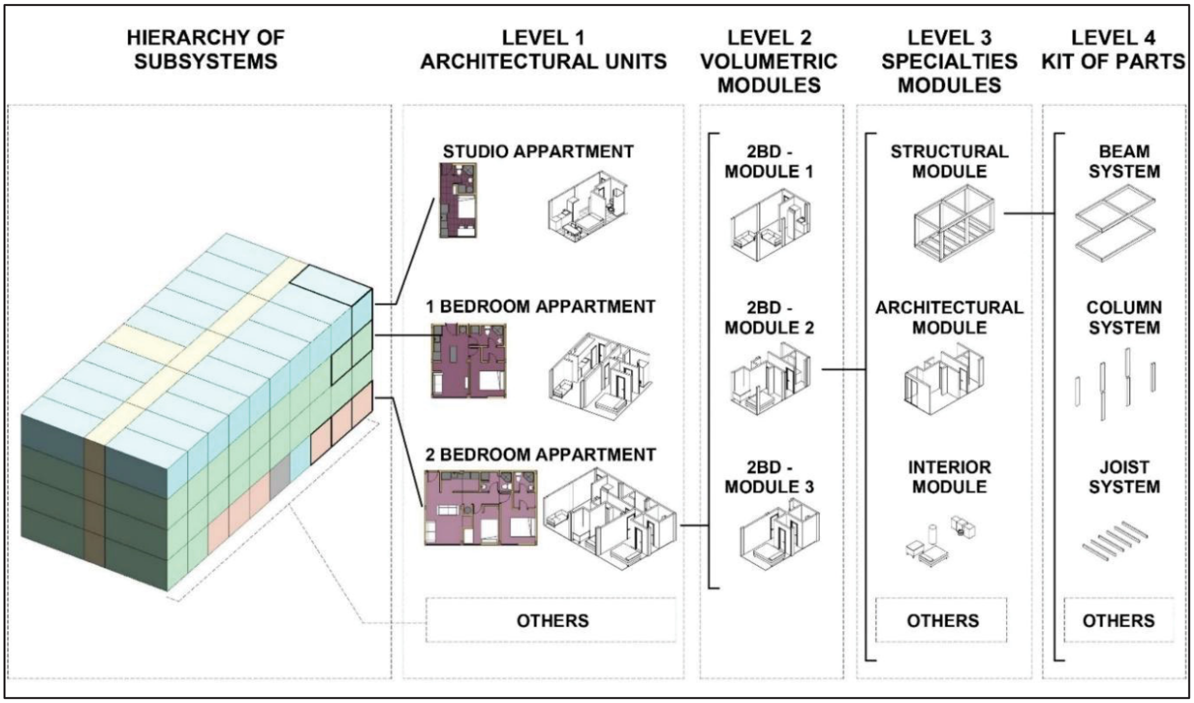

Figure 5.3 Hierarchy of subsystems for product decomposition

At the first level of this hierarchy are the sets of volumetric modules that make up an architectural unit. These architectural units form the catalogue of products designed to meet the architectural requirements of the project. The following section will develop the elaboration of this catalogue.

On the second level, there are the volumetric modules that make up the different architectural units. For example, housing units can be composed of more than one volumetric module.

The third level is composed of the systems of the different specialties that are part of each volumetric module. At this level, only the specialties of architecture and structure were considered. As mentioned in the previous section, parametric models of structure consider a kit of parts capable of adapting to the nature of each architectural unit. In this way, the results of the structural design for the housing and circulation modules are different, but they use the same kit of parts, demonstrating the flexibility of the proposal.

Finally, the last level is dedicated to the kit of parts of each subsystem. As a proof of concept, only the kit design of parts of the structure model with the aforementioned characteristics was included.

5.4.1.1.3 Define product catalogue

The elaboration of the catalog of this prototype was developed to partially meet the architectural requirements of a residential building. This catalog considers the use of modules for the apartment units, a hall for the main entrance, balconies, the upper roof of the building, and horizontal and vertical circulation. The goal is to achieve different levels of configuration and customization of the final product, and to provide a tool that allows those involved in a residential construction project to adopt modular practices.

However, Bryden Wood (2021) state in the literature that to identify the different types of architectural units necessary to meet the requirements of residential buildings, an analysis of commonalities between different existing projects or a study of the building codes that determine the necessary spaces that make up a building is required.

The commonality analysis is carried out by creating a database of projects with the same typology, such as residential buildings, then identifying the architectural spaces that make up the project, their square footage, and other characteristics. Finally, the spaces that are part of most projects and their common characteristics are identified, such as the average square footage. This way, a list of spaces that make up a catalog of necessary architectural units for a modular residential project is obtained.

Regarding the study of building codes, the standards in these documents usually specify the quantity and characteristics of types of architectural spaces that make up a residential building. Therefore, it is suggested to study the codes to ensure that the product catalog meets the required standards.

5.4.1.2 Computational design for configuration system

This section explains how this prototype generates and evaluates design options through computational design (CD). CD techniques are applied to BIM models by manipulating the parameters of the elements that make up the digital model, since the characteristics of the BIM elements are represented by parameters. In this way, it is possible to integrate parametric design techniques and other computational design techniques into a BIM framework. This allows users to generate different design solutions, evaluate and optimize them in an automated manner, to find the solutions that best suit the project requirements.

It is important to understand the taxonomy of CD procedures in order to identify their potential applications. In this sense, this study aims to identify and briefly describe the different DC techniques identified in the literature. In the book by Bolpagni et al. (2022), parametric design is described as a set of rules that generates design solutions from defined inputs. Generative design is based on a collection of rules and inputs that produce different results, which are evaluated and ranked according to a specific set of objective criteria. There is a second layer of techniques that use concepts and mixed techniques from those mentioned above. Algorithmic design uses an algorithm that optimizes the result until a defined result is obtained, while evolutionary design uses evolutionary algorithms aimed at solving multiobjective optimization problems (Caetano et al., 2020).

The following subsections describe the considerations for collecting customer information to execute the configuration process. Next, a subsection dedicated to the configuration system algorithm will be developed, where the different layers that make up the configuration algorithm will be explained and how, through the application of a parametric design approach, the prototype of the configuration platform could be developed. This subsection provides a brief introduction and then elaborates on the computational design strategy and approval for generating building volume and defining assortment options.

5.4.1.2.1 User information requirements

Continuing with the premise of simplifying the design process of a residential building, this prototype considers basic information about the project, such as the location, and some requirements of the project, such as the dimensions of the modules to be used, the mix of apartments, the number of levels of the building and some customization options, such as the criteria in which the architectural units will be grouped within the volume of the building or if the units will have balconies.

In addition, this prototype is developed to be used in the Autodesk Revit BIM environment. Among the advantages of this decision is the software's ability to include information about the project's environment and location. For example, it is possible to import a plan view of the project location – terrain and cadastre. In the BIM software it is possible to incorporate information about the latitude and longitude of the location, and to configure the north of the project. This allows for environmental simulations to be performed and the impact of the sun on the volume to be studied. Based on this, the algorithm's functions can include capabilities to reduce the solar impact on the final volume, generate designs for different types of architectural modules for solar protection, optimize the performance of technologies such as solar panels by placing them in areas that allow better performance, among other benefits.

5.4.1.2.2 System configuration algorithms

A configuration system can be considered an artificial intelligence system (Haug et al., 2012; Yang & Dong, 2012), which allows the configuration of a product using as elements the different modules that make it up and their configuration rules. Crafting a BIM-based configuration algorithm can use any or several of the computational design techniques mentioned in the previous section. However, due to the limited time of the study and its proven effectiveness in the literature (Pirozzfar, Popovic 2021), it is proposed to use a parametric design approach that allows the configuration process to be traversed from a linear approach, performing one configuration process at a time and guided by the user's ability to create and evaluate the building design options.

Applying the concept of modularity, this section proposes to break down the building configuration problem into smaller problems, which will help explain the development of the configuration algorithms for the processes mentioned in Figure 2. This decomposition facilitates the management of the configuration process, allowing each sub-problem to be addressed individually and efficiently, using parametric design techniques to create and evaluate design options.

5.4.1.2.2.1 Creation and definition of the building volumetric proposal

This section will explain the two steps of the configuration algorithm that helps creating the building volume according to the requirements of the project. The resulting volume is a parallelepiped, obtained by placing the volumetric units of the horizontal circulation in the center and the rest of the units on the sides of the building (see image 5.4). The following sections will detail how the prototype addresses the sub-issues that make it possible to generate the volumetry within the configuration process.

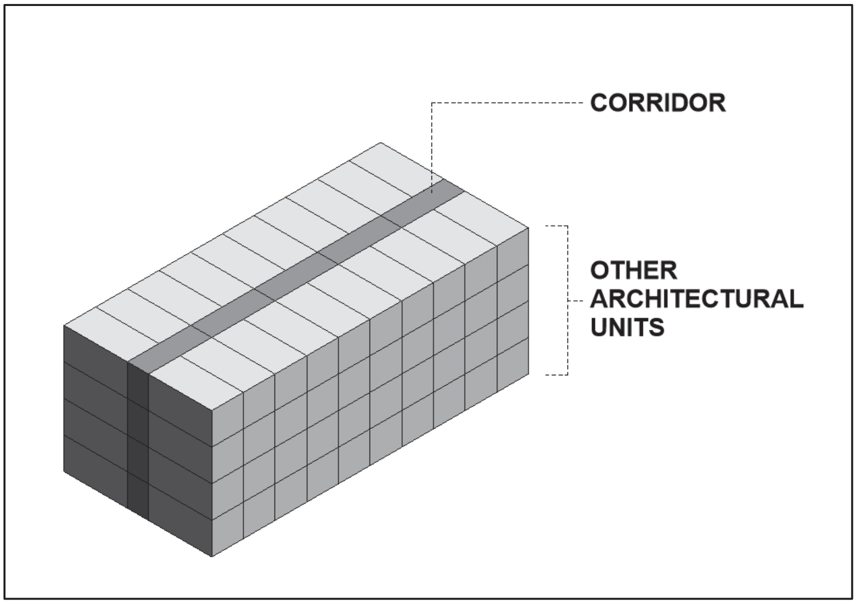

Figure 5.4 Distribution of module types within the building volume

5.4.1.2.2.1.1 Define the dimensions of the final volume of the building

For this prototype, the dimensions of the architectural modules that will be used were defined with careful consideration of both functional and logistical factors. The modules were considered as architectural products to meet the following functions: housing units, balconies, main entrance of the building, upper covering of the building, and vertical and horizontal circulation of the building. In pre-defining the module’s dimensions, special attention should be taken to the method of transporting the modules, as transportation constraints set the limits on their size. These constraints, including the need for special permits and appropriate handling and erection equipment, were considered from the earliest stages of design (Rochat, 2024). This ensures that the modules can be efficiently manufactured, transported, and assembled on-site, while fully meeting the functional requirements of the building.

5.4.1.2.2.1.2 Locate the volume in the space

To locate the volume in space, it is proposed that the user draws a line that represents the central axis of the building. Next, the algorithm would propose a first model of the building volume with the maximum possible dimensions, according to the dimensions of the modules defined above and centered with reference to the line (image 5.5).

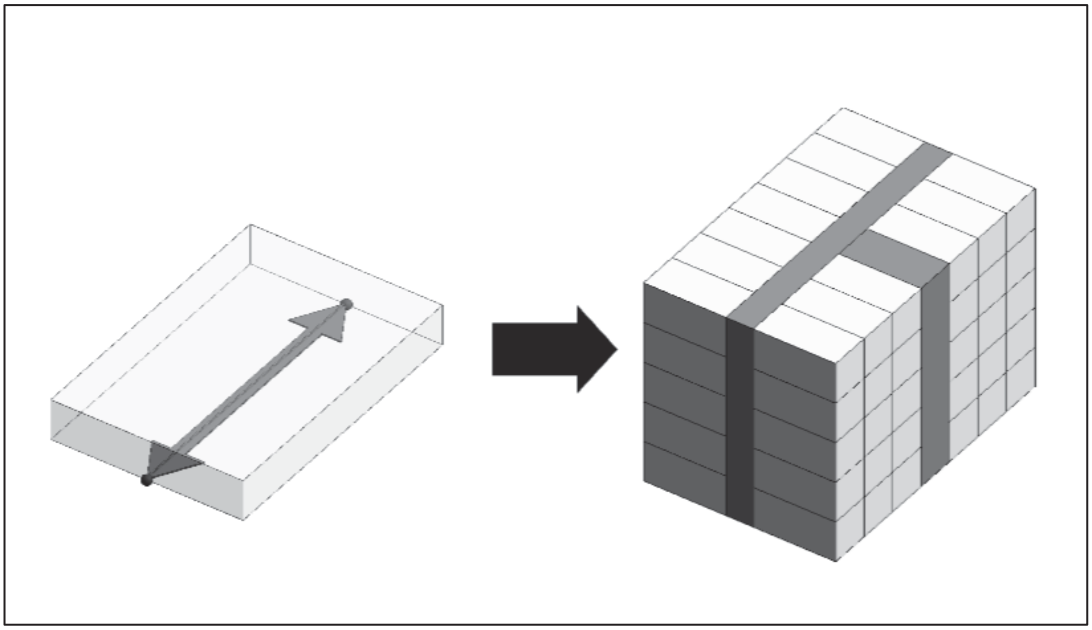

Figure 5.5 Positioning of the volume in space

5.4.1.2.2.2 Creation and definition of the modules assortment options

Once the volume of the building has been defined, it is necessary to determine how the architectural units will occupy the building to meet the requirements of the project. The following section describes the various steps of the configuration algorithm to generate and define the different design options possible with the prototype of the proposed configuration platform.

5.4.1.2.2.2.1 Locate the modules in the designated volume

The entire process for locating each module considers two main criteria: the size of the module to be used and the function of the module. To this end, the different modules and their variations were grouped as follows, considering that in each group the modules have the same dimensions but may have different functions:

- Group 1: Housing units, main building entrance, vertical circulation.
- Group 2: Balconies.
- Group 3: Horizontal circulation. and
- Group 4: Superior Building Coverage.

The spatial distribution of the different modules was carried out by creating virtual containers around the central axis of the building. This spatial design strategy can be expressed mathematically as a three-dimensional matrix, following a Unified Matrix Approach (Sharafi et al., 2017). In this way, an array is created that can be mathematically declared as 5xMxL. The figure 5.6 graphically shows the five rows of virtual containers and the following paragraph will detail the different modules that each container houses. In this matrix expression, M is the number of columns in the matrix; To calculate this value, the length of the central axis is divided by the width of the modules in group 1. The unknown L represents the number of levels of the building, determined by the user.

After defining the number of rows, columns, and layers in the three-dimensional array, the algorithm defines the dimensions of each virtual container. The virtual containers that will house the modules of group 1 belong to rows 2 and 4, rows 1 and 5 contain the modules of the balconies of group 2, while row 3 is intended for the horizontal circulation of group 3 (image 5.6).

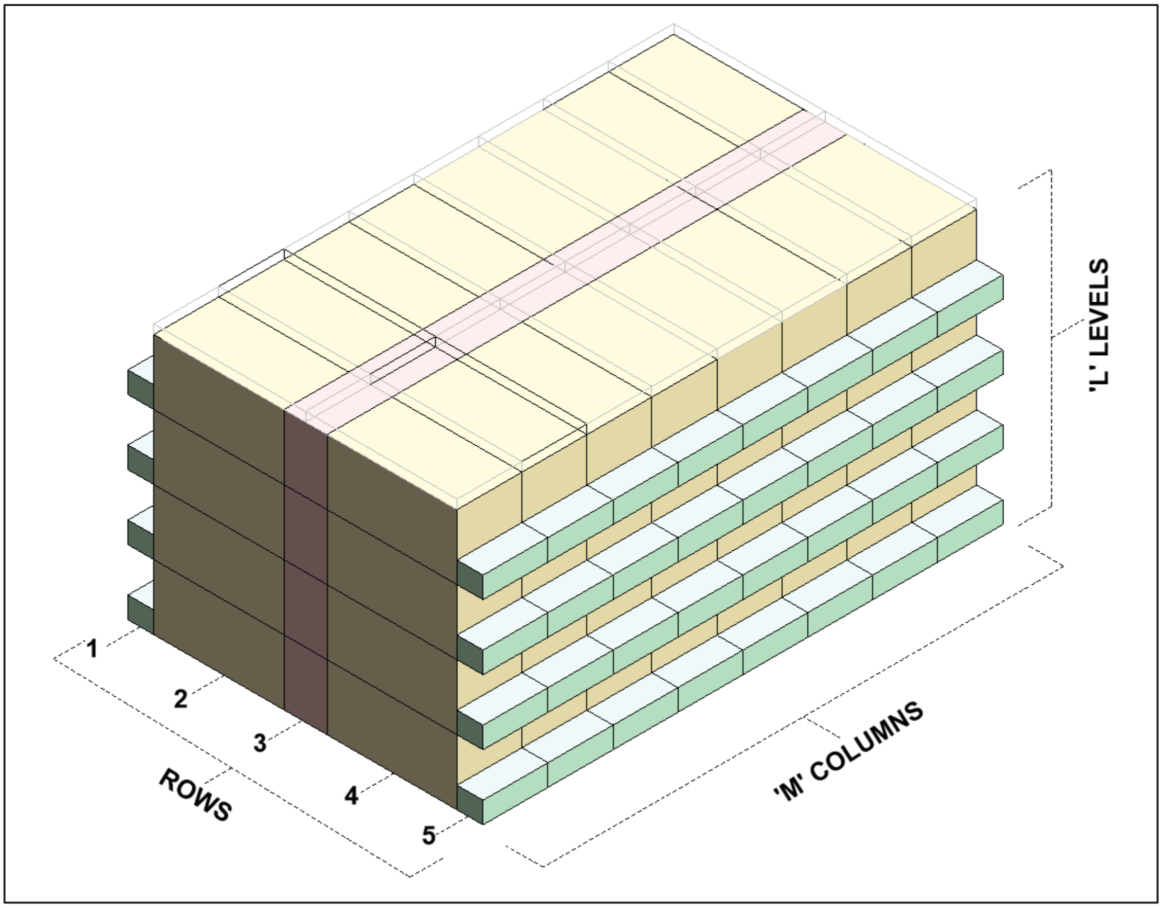

Figure 5.6 Three-dimensional matrix for the distribution of architectural units

Finally, for the containers of group 4, a second two-dimensional matrix of 2xM is created, which allows the modules to be distributed more efficiently, since the dimensions of these modules are designed to efficiently cover the area occupied by the modules of groups 1 and 3 that make up the building (image 5.7).

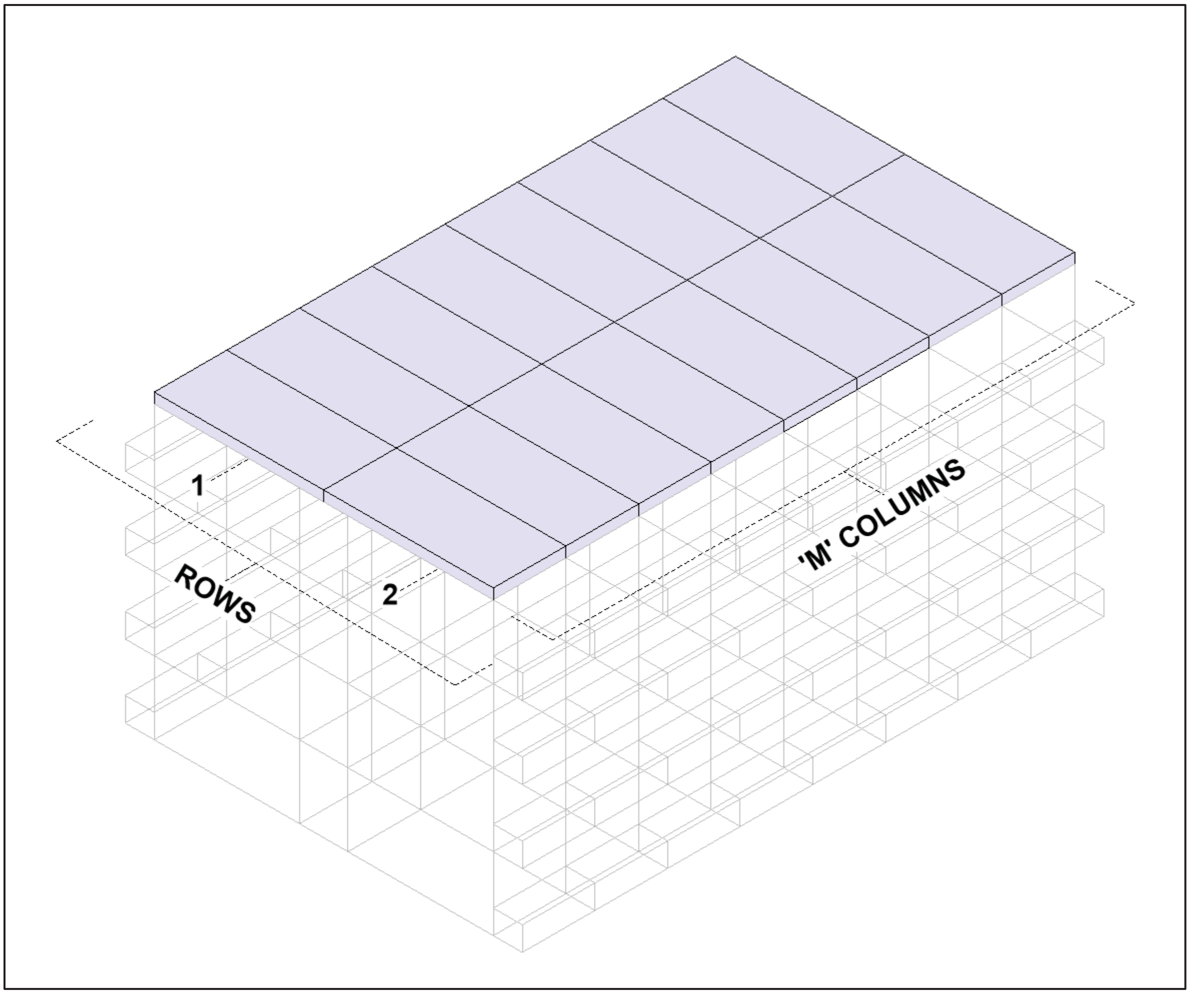

Figure 5.7 Two-dimensional matrix for the distribution of upper covering modules

5.4.1.2.2.2.2 Configuration system of the modules assortment

The configuration of a building predefines the location of certain modules such as the entrance and those of horizontal and vertical circulation. However, the number of different housing units could vary depending on the requirements of the project, as well as the way in which these units will be placed in the space as they could be stacked vertically or horizontally. In addition, the prototype provides the possibility of customizing the façade of the building including balconies with different designs according to the different housing units to which they will be attached. Finally, for each design option it offers different indicators with the aim of allowing the user to make the most informed design decisions. The following section will elaborate in greater detail on this topic.

5.4.1.3 Evaluation of options and generation of outputs

During the configuration process, the software prototype displays the value of different indicators in real time in two dashboards (image 5.10). One of these is the carbon footprint of the design option, which is calculated based on the structure's BIM parametric model. This is possible because the parametric family adapts the number and dimensions of its elements according to the dimensions of the module. With a database that provides different coefficients to calculate the impact of the carbon footprint of products according to the volume of their material, it is possible to estimate this indicator. In addition, a database with price ranges is used to calculate approximate values of the design options. In this way, the evaluation process is integrated into the configuration process and allows the process to be streamlined. Image 4 shows the interface of the prototype, where in the different control panels you can see the values of each mix of architectural units represented by different colors.

In addition to the evaluation during the configuration stage with the use of control panels, the prototype proposes the possibility of transferring more detailed information about these indicators to tables of quantities that are part of the BIM model of the building and that also allow different material options to be compared. The following sections explain the prototype's ability to generate valuable information for the project, such as BIM models, quantity tables, manufacturing drawings, and architectural drawings in an automated way.

5.4.1.3.1 Architectural modeling

After selecting the desired configuration within the configuration algorithm user interface, it is possible to create a detailed BIM model of the building. To do this, as part of the prototype, a template was created in the Autodesk Revit software. The template features pre-built quantification tables that allow information to be transferred to the manufacturing stages and more detailed information about the indicators used in the setup stage. Additionally, as proof of concept that it is possible to compare the carbon footprint indicator between construction systems, a function is included that allows different materials to be selected to estimate their value in the parametric structure model. In this way, it is intended to estimate the values of the carbon footprint at the time of creating the BIM model and offer a second option to make a comparison. In addition, the template has summary tables of the total cost of the project and each group of modules. Finally, new quantification tables can also be created respecting the data structure required by the project, in order to provide the appropriate information.

5.4.1.3.2 Final architectural model customization

The final architecture model will be composed of all the BIM model links of the modules inserted in the project template. After finishing the configuration process and generating the BIM model of the building, it is possible to edit the different modules or customize different architectural units by creating singularities within the configuration. These changes will also be reflected in the information tables provided by the template.

5.4.1.3.3 Prepare information for production and manufacturing

Manufacturing information was previously considered in the parametric design of the BIM model of structures. In order to transfer this information to the manufacturing stage, the template has pre-configured drawings and tables to read and represent by 2D drawings the parameters of the elements in the final BIM model. In this way, the manufacturing drawings and the pre-existing tables in the template are updated with the information from the structure models that make up the final result of the process, demonstrating that this information can be transferred to the manufacturing stage.

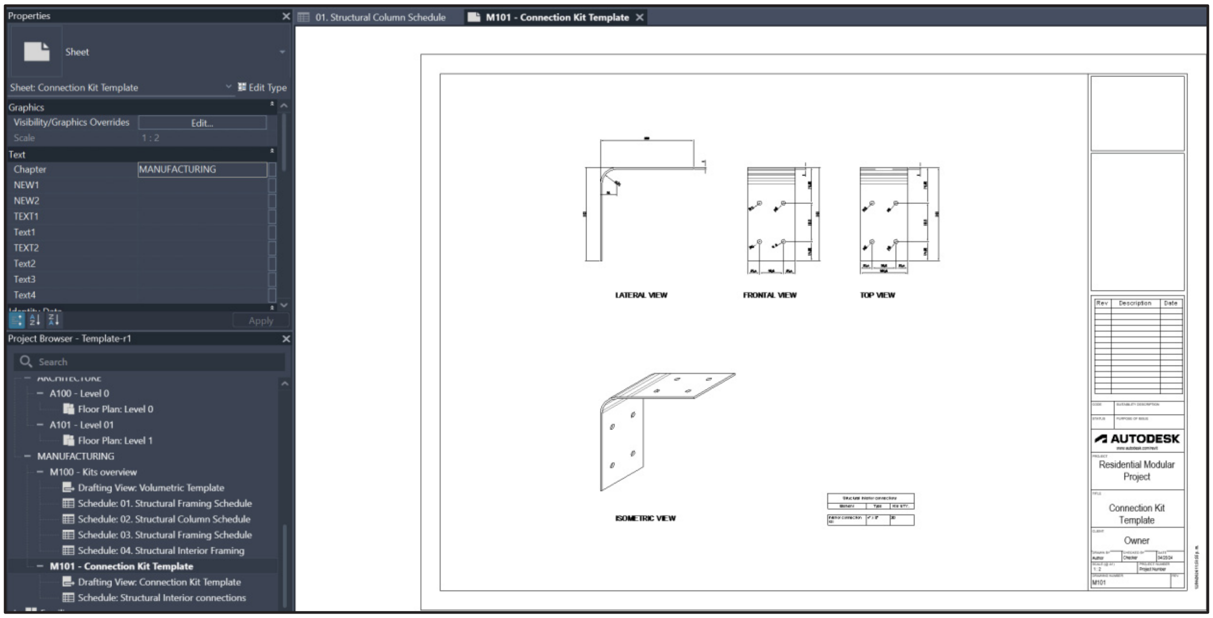

Figure 5.8 Template with pre-configured manufacturing drawings

5.4.2 Evaluation by implementation in a real-world project

The subsection 5.4.2.1, "Description of the Pilot Project," outlines the key characteristics of the project employed as an implementation case. Subsection 5.4.2.2, "Implementation of the Framework", provides a detailed account of how project information is organized and integrated within a Revit document. This part discusses the prototype implementation process by highlighting the features mentioned in the previous section.

5.4.2.1 Description of the Pilot Project

The project is at 2295, Rue Saint-Dominique, Jonquière, is a leading initiative that combines advanced technologies and sustainable practices to address social and environmental challenges. Its goal is to improve residents’ quality of life and urban aesthetics. Central to the project is the increase in affordable housing, with fifty-one units designed to be affordable for low- and moderate-income families. This effort responds to the critical need for shelter in the region. In terms of sustainability, it aligns with Novoclimat’s standards to optimize energy use and reduce costs, benefiting both the environment and residents by reducing energy consumption. In addition, modular construction central to the project promotes faster construction and less waste, with quality control that ensures durable and reliable structures.

5.4.2.2 Implementation of the proposed framework

To prepare the study, a BIM model of the project context was created. Several assumptions were made in order to fill the gaps that could limit the execution of the process, such as the number of existing or new structures that can be part of the final proposal or other considerations that are not subject to the building's volume because the artifact does not consider structural elements of foundations or basements. In addition, a template was prepared that would allow ordering information about the quantification of materials to meet the requirements of the project and some views that would allow to show the potential of the tool to generate information for different purposes in distinct stages of an off-site construction project.

Upon completion of the tasks associated with the Revit template, the configuration process is initiated using Dynamo software. As it is a graphical interface for visual programming, the tasks of coding the algorithm, manipulation of the database and graphical user interface are conducted within the same software (Figure 5.10).

The developed algorithm can create a three-dimensional matrix of virtual containers from the trace of the central axis of the building's corridor. Figure 5.9 shows a graphic description of the operation of the algorithm that always respects a single configuration in terms of the typology of the building, i.e. all the configurations obtained by this system will have a central corridor and the modules of the different architectural units next to it.

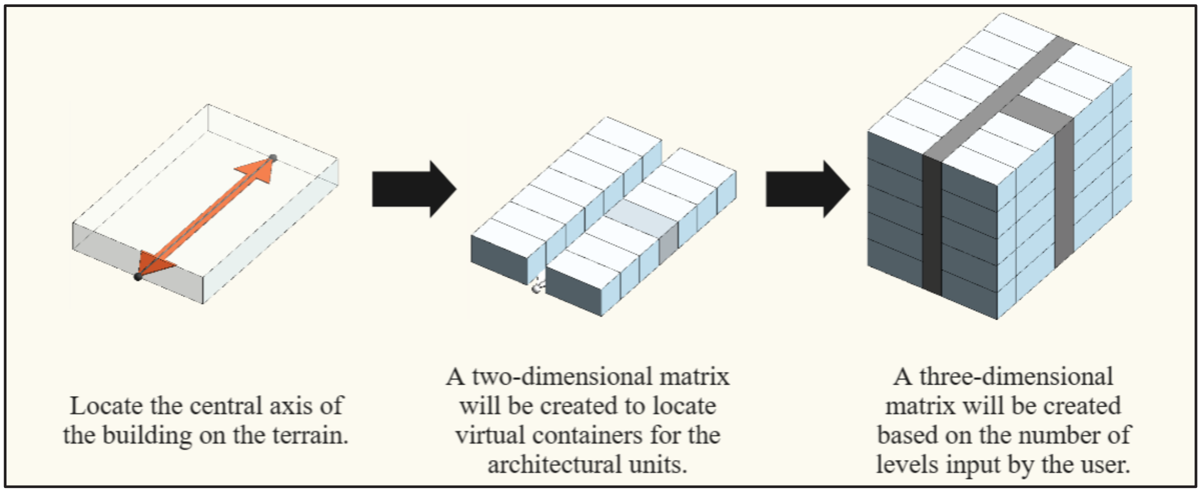

Figure 5.9 Sequence to create the building's geometry.
Taken from Llave & Iordanova, (2024)

The figure 5.10 represents the user interface proposed on Dynamo: at the left is the conceptual volume of the building, while at the right are the inputs and outputs described in the next paragraphs.

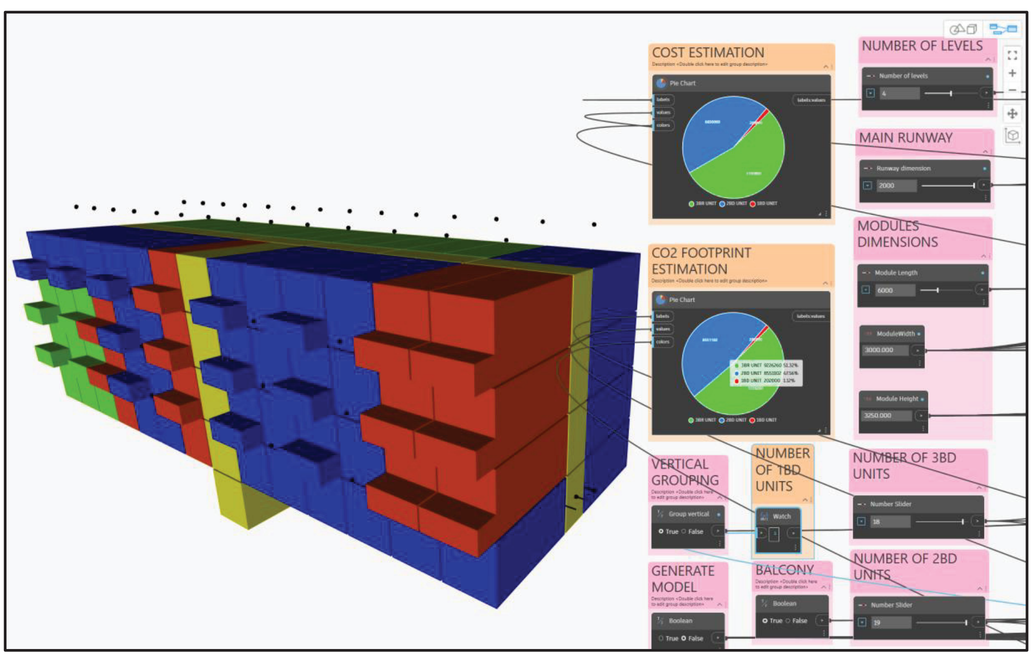

Figure 5.10 Dynamo graphic user interface of the artifact

The process begins by selecting the dimensions of the modules to be used, which requires having these modules prepared in a database. Each module is self-supporting, to reduce its environmental impact and support the trends of the local industry of the adoption of wood-based construction systems. All modules within the proposed database use a light timber-based structural system. In addition, they comply with the transport dimension limitations imposed by the regulations.

Once the dimensions of modules to be used have been selected from the database, the central axis of the building should be drawn, and the number of levels of your building selected (Figure 5.11). This will result in the initial geometry of the building. After this step, it is possible to modify some design criteria, such as the number of different units required in the final configuration or alter the design of the façade by including balconies for the apartment units. It is also possible to modify the logic with which these modules are grouped, for example, whether all modules of a single type are stacked on top of each other or grouped horizontally (image 5.12).

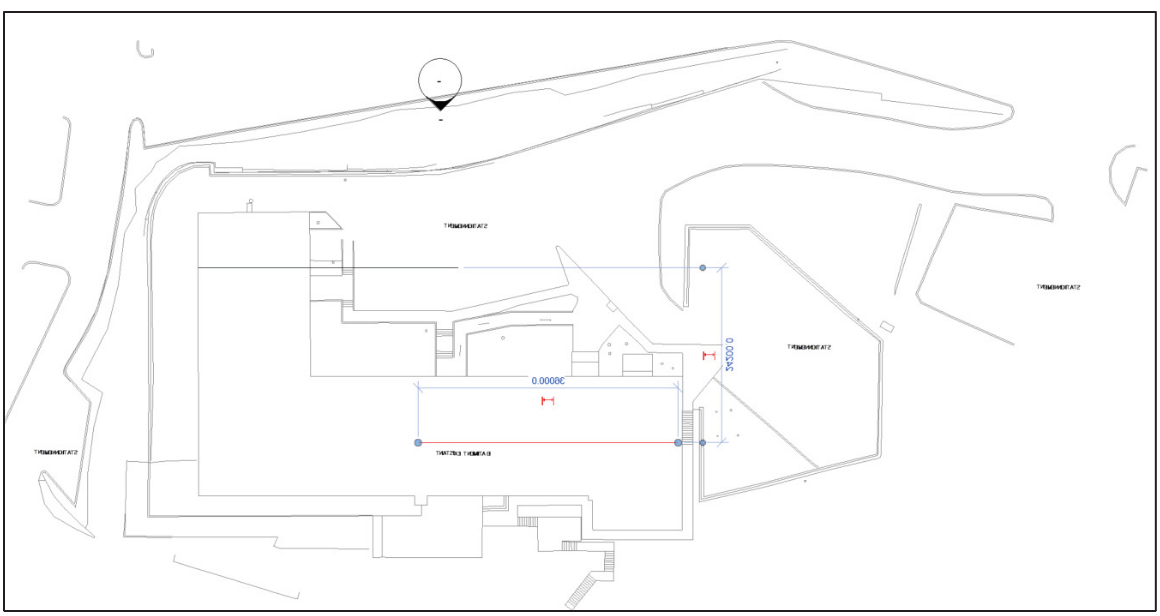

Figure 5.11 Creating the central axis of the building

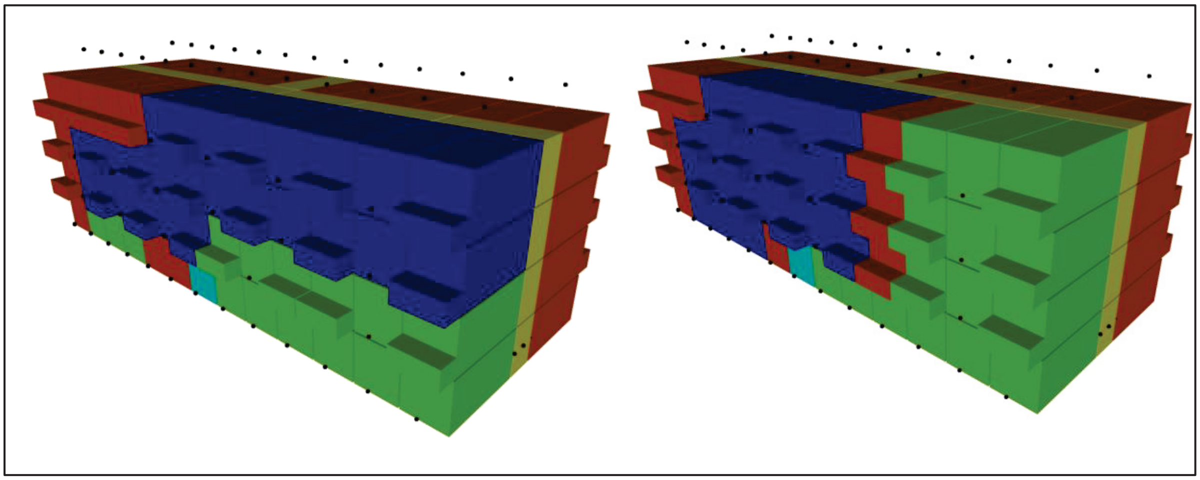

Figure 5.12 At the left a vertical stacking and at right an horizontal grouping

During the creation of design options, different algorithms can be used to measure the carbon footprint of the model by utilizing various materials for the structural system. For this task the database used is - The Inventory of Carbon and Energy database - developed at the University of Bath's Sustainable Energy Research Team. It allows for the calculation of the carbon footprint impact of different materials based on their volume. This enables the quantification and comparison of the materials' impact on the total structure of the building. Additionally, it is possible to estimate and compare the cost of each design option. All this information is available on the dashboards within the Dynamo user interface, which updates dynamically with any changes in the input parameters (Figure 5.10).

After creating, comparing, and selecting the desired option, the BIM model of the building can be created automatically. The algorithm inserts the database modules into the predefined locations in the configuration. This process automatically provides information about material quantities, design, and manufacturing drawings in the Revit template. Additionally, it is possible to customize any component of the BIM model to meet client requirements.

As mentioned in previous paragraphs, the BIM model has tables of quantities according to the requirements of the Project, this would allow to calculate the cost of the materials to be used.

However, as it is a predefined database it is possible to calculate the price range of each module and store it in another external database. By using another custom algorithm, it is possible to quantify the number of units used in the proposal and calculate the price range of the final proposal. Additionally, Annexe 3 provides more details on the operation of the artifact.

5.5 Results and Discussion

The implementation of this configuration system has implications for project efficiency, customization, inter-team communication, functional aesthetics, and sustainability. The referenced studies in this document have documented these changes, which will be thoroughly examined in this section. Each aspect mentioned at the outset of this paragraph will be deliberated upon considering the findings from the bibliography and the information gleaned from the implementation case.

The development efficiency of the pilot project has been potentially improved through the adoption of modular design and construction technologies. The proposed artifact provides an opportunity to reduce development time in the predesign phase, which has a direct impact on the cost of this stage of the project (Ghannad & Lee, 2022). In the same way, the proposed System provides the possibility of generating information that can be used in various stages of the Project. According to Cao et al., (2021) product configurators that operate through several phases of the project can improve the coordination and execution of the project.

The configuration system proposal provides functions for the generation of different design configurations and for the final customization of the building, while retaining its flexibility to adapt to the specific needs of the client. The level of customization of the artifact is directly proportional to the level of granularity of the design of the architectural modules used, from the literature modularization allows great flexibility without compromising economies of scale (Jensen et al., 2015). This adaptability is reinforced by product platforms that must be closely aligned with market demands to ensure effective customization and operational efficiency (Popovic, Schauerte, et al., 2021).

The proposed platform could be integrated to a digital DfMA support environment for all those involved in the Project, this would allow effective communication that contributes to the success of any construction project. BIM-based interactive environments have improved collaboration, facilitating platforms that allow real-time discussion of issues (Potseluyko et al., 2022). In addition, Ezzeddine & García de Soto, (2021) emphasized that better connectivity between teams facilitates efficient management and reduces errors.

Configuration systems allow designers and builders to tailor projects to clients' aesthetic and functional needs. According to Piroozfar et al., (2019), configuration platforms that allow for detailed customization have been crucial in increasing customer satisfaction, by allowing adjustments that reflect personal preferences without compromising design standards.

Additionally, off-site construction systems facilitate the use of sustainable materials and construction techniques that are less harmful to the environment. Approaches like those of Cao et al., (2022), which use configurators to optimize material usage and promote module reuse, contribute to reducing waste and the carbon footprint. The proposed configuration platform allows for the calculation of the carbon footprint of structural elements from the conception stage, demonstrating how the carbon impact of different design options can be optimized.

In summary, implementing a BIM-based configuration system can transform efficiency, customization, inter-team communication, aesthetics, and sustainability in modular construction projects. Adopting this design strategy can significantly improve project efficiency by reducing time and costs in the pre-design phase. The proposed system's detailed and flexible customization meets specific client needs without compromising economies of scale, allowing further modifications to tailor the final proposal to project requirements. Focusing on sustainability through material optimization helps reduce the carbon footprint and environmental impact. Together, these innovations have the potential to increase client satisfaction and operational efficiency and establish a framework for adopting modular construction practices that address current and future environmental demands.

5.6 Conclusion

This last chapter of the master's thesis illustrates the applications of the proposed configuration system for modular residential buildings in a pilot project provided by SHQ. The configurator automates the generation of initial design proposals, thus reducing time and costs at this stage. Additionally, these BIM-based design proposals allow for the evaluation of cost and environmental impact indicators using external databases. This enables users to compare design options based on these criteria and make more informed decisions.

Beyond these benefits, configurators are a key tool for promoting the adoption of off-site construction methods. The set of rules that defines the configuration system bridges the gap between the lack of technical knowledge of those involved in the initial stage of a modular construction project and the specific manufacturing and assembly requirements. This approach facilitates better integration of design and construction processes, ensuring greater efficiency and coherence in the development of modular projects. It is noteworthy that SHQ showed significant interest and approval regarding this implementation.

On the other hand, beyond the limitations of the software set out in detail in Annexe 3, it is crucial to develop systems that are not only technically advanced but also highly adaptable to varied design contexts and customer needs, which will require continuous investment in a multidisciplinary task aimed at finding customizable and scalable solutions.

Methods for assessing environmental and economic impacts need to be refined and based on more accurate and comprehensive data to ensure that construction decisions are sustainable and economically viable in the long term. The use of databases developed for incorporation into configuration processes could improve the quality of the information provided for decision-making.

Continuing professional training and education in the latest technologies and methods are critical to facilitating the adoption and effective leveraging of these advanced technologies in the construction industry.

In summary, this document provides a foundation for understanding the applications and limitations of configuration platforms for modular construction. However, it also highlights the urgent need for technological advancements.

CONCLUSION

This section summarizes the key findings and contributions of the research on the development of a BIM-based configuration platform for modular residential buildings. It provides an overview of the entire research process and revisits the main research objective along with the research questions, highlighting how they were addressed, as well as the resulting findings and contributions.

A systematic examination of scholarly literature was conducted to uncover materials pertaining to the utilization of configuration platforms in construction projects. By employing the PRISMA framework, the current functions were identified and categorized, resulting in a comprehensive inventory of features and capabilities. This process also shed light on the pertinent application domains and methodology. This facilitated the establishment of criteria for assessing various technologies. Subsequently, the primary aim was established as the development of a digital platform for the design phase of modular residential construction projects, utilizing the DSR methodology. Subsequently, a thorough examination was conducted to compare different digital configuration platforms. This analysis involved gathering information on the requirements of companies involved in modular projects and testing various configurators available in the market. Then, utilizing the data collected from this testing phase about the capabilities of these platforms and the functions of configurations in construction projects identified in the initial literature review, the comparison criteria were generated. By evaluating specific criteria, the comparison facilitated the identification of strengths, shortcomings, and areas that require improvement. This information was then used to design a tailored platform.

After gathering, analyzing, and producing the required data, a configuration methodology based on BIM was suggested. The purpose of this process was to enhance decision making and promote cooperation throughout the initial design phases of modular residential projects. Additionally, it aimed to provide tools to solve any gaps in knowledge regarding assembly, transportation, and installation criteria. The completed artifact was subsequently evaluated to observe its functionality and determine its adherence to the research objectives. An implementation case potentially demonstrated the practical use of the BIM-based configuration system, showcasing substantial enhancements in decision-making, decreased execution times, and improved project efficiency.

The main objective of this research was to create a digital platform to be used during the design phase of a modular home building project. The purpose was to address the lack of knowledge in transportation, manufacturing, and installation that currently hampers the widespread use of OSC methods. The research has effectively created a configuration platform based on BIM that seamlessly combines data throughout all phases of a project, from the initial design to the final assembly. This platform functions as a consolidated repository for all project information, enabling easy access for all stakeholders and guaranteeing that everyone operates with the most current data.

The BIM-based configuration platforms have the potential to address knowledge gaps by offering design options that incorporate key aspects of logistics, manufacturing, and installation. These platforms guide users in making informed decisions early in the design process, helping to prevent future complications. They recommend only those solutions that align with transportation, production, and assembly requirements specific to the selected construction method.

From a logistics perspective, the platform accounts for transportation constraints by limiting module sizes to allowable dimensions and alerting users if non-compliant options are selected. In manufacturing, parametrized kits of parts provide the necessary information for each component, while automated manufacturing drawings ensure that the design is feasible for production.

Regarding installation, the platform integrates predefined assembly rules aligned with the chosen building system, helping ensure smooth module integration. Additionally, the ability to simulate scenarios and evaluate their outcomes allows users to explore optimal design solutions. Throughout the process, precise and current specifications enable well-informed decision-making, enhancing project outcomes from the earliest stages.

Finally, the platform facilitates information sharing through collaborative tools like Autodesk Construction Cloud, ensuring all stakeholders can access up-to-date data and contribute effectively to the project. While these features show promise in bridging knowledge gaps, further evaluation is needed to confirm their full impact.

Overall, this research successfully accomplished its primary objective of developing a BIM-based platform that addresses the lack of information in modular home building. The platform has the potential to improve decision-making, foster collaboration, and promote the adoption of sustainable and efficient building practices to boost the construction industry. This research presents a systematic method for utilizing BIM configuration platforms in the construction of modular housing. It provides a comprehensive overview of the essential stages, starting from the original design phase and concluding with the final assembly process.

This research also addresses the core research questions posed at the outset, providing critical insights into the development and application of configuration platforms for modular residential construction. The first research question - What are the functions provided by commercially available configuration platforms for construction projects? - was explored through a combination of academic literature review, software testing, and consultations with industry stakeholders. The study identified a comprehensive set of functions, including automated design generation, modular product selection, parameter customization, and simulation tools. However, it also highlighted limitations, particularly the difficulty of integrating data seamlessly across the design, manufacturing, and assembly stages, which constrains the full potential of these platforms.

The second research question - What would be the best design approach for a configuration platform in modular residential projects that would help minimize the impact of knowledge gaps in shipping, manufacturing, and assembly? - was addressed through the proposal of a framework that covers the entire project lifecycle, from design to manufacturing drawings. This framework embeds logistical, production, and assembly constraints into the platform, ensuring that the design options generated align with real-world conditions. By addressing these knowledge gaps within the platform, the framework enables more informed decision-making and reduces the risk of complications during project execution. Moreover, the platform is designed to perform the tasks of the three types of configurators identified in the literature: planning configurators, design configurators, and production configurators, providing a comprehensive solution for modular construction projects.

The third research question - How can medium-density residential buildings apply a BIM-based configuration system at the initial stage to enable stakeholders to make decisions when adopting modular construction for housing? - was answered by demonstrating how BIM-based configuration systems link design models with sustainability and cost indicators. This integration allows stakeholders to visualize design alternatives in real-time, run scenario analyses, and make data-driven decisions early in the project. The platform also fosters collaboration through shared data environments, ensuring that all stakeholders remain aligned with logistical, manufacturing, and financial requirements. This approach not only enhances efficiency in modular construction but also supports the wider adoption of modular methods as a practical solution to the global housing crisis.

This study elucidated the synergistic potential of integrating BIM with modular building methodologies to enhance project outcomes. This examines technological convergence and systems engineering from multiple viewpoints and establishes a solid foundation for future investigations in this field.

LIMITATIONS

This section outlines the key limitations encountered throughout the research and offers recommendations for future investigations. While the study successfully developed a BIM-based configuration platform for modular residential construction, certain challenges affected the scope and depth of the outcomes. Identifying these constraints is essential to better understand the research findings and guide future efforts in refining the proposed solutions for broader industry adoption.

Despite the advancements made in developing a BIM-based digital platform for modular residential construction, the research encountered certain constraints that impacted its outcomes and scope. Acknowledging these limitations is essential to fully understand the findings and provide direction for future research aimed at refining the proposed solutions. The following sections outline the key limitations identified and offer recommendations for future investigations.

One significant limitation is the limited consideration of the perspectives of creators, designers, and architects on the potential of configuration platforms. Although the study explores the technical and functional capabilities of these tools, it only briefly addresses how these stakeholders perceive and experience the use of configuration systems. As part of the proposed platform, customization tools were developed to tailor individual elements of the configuration system, but further insights from industry professionals could enhance its alignment with real-world needs. Future research could benefit from qualitative feedback from these stakeholders to ensure the platform meets their expectations and integrates seamlessly into design practices.

Additionally, the absence of quantitative results from real-world projects using configuration platforms represents a critical gap in the study. While the theoretical benefits and proposed framework are discussed, the research lacks empirical validation to confirm the platform's effectiveness in practice. Future studies should aim to test the platform in real modular construction projects, measuring metrics such as time savings, cost reductions, and design quality improvements. Gathering feedback from participants through qualitative assessments would further strengthen the evidence for the platform's practical value.

The author's limited experience in scientific research presented another challenge during the project. Although the advisor provided essential support, the time constraints negatively impacted the depth of the information analysis. Additionally, the multidisciplinary nature of the project required gaining expertise in fields such as programming, systems engineering, and product design, which demanded extra time. Enhancing future research through a more extended timeline could allow for deeper analysis and more comprehensive exploration of the platform's potential.

Addressing these limitations in future studies will contribute to refining the proposed platform and ensure that it better meets the needs of stakeholders involved in modular construction.

FUTURE RESEARCH DIRECTIONS

While this research has provided valuable insights and practical applications for developing and utilizing configuration platforms in modular projects, the study offers significant value for the construction industry but leaves certain aspects for further exploration. The complexity of the subject and time constraints limited the scope, making it necessary to outline future research directions that can build on these findings.

To better understand the impact of BIM-based configuration platforms across the entire project life cycle, future research should avoid relying exclusively on central corridor layouts and develop a broader range of building configurations. These configurations should allow the integration of AI systems capable of generating building shapes based on initial parameters and terrain conditions. Exploring different computational design approaches, with a focus on generative design techniques, would further enhance this process by automating the generation of design solutions tailored to site-specific constraints and project requirements.

In addition, it is essential to investigate the role of customization tools in addressing architects' biases toward off-site construction. Future research could focus on identifying which tools most effectively provide the architectural freedom needed to shift perceptions and increase acceptance of modular methodologies among architects and designers. This exploration would help ensure that configuration platforms support creative flexibility while promoting the practical benefits of modular construction.

Further case studies across various modular project types and environments would also be critical to validating the proposed platform. Testing the platform’s performance in diverse settings would demonstrate its adaptability and reveal areas for improvement. Additionally, these studies should incorporate environmental impact assessments to ensure that the platform facilitates not only efficient building practices but also sustainable development.

Moreover, future studies should explore the standardization of construction systems for modular methodologies and the development of standardized information formats for manufacturing stages to improve communication and coordination between design and production teams. The integration of configuration platforms with Enterprise resource planning systems offers another promising avenue, aligning business management processes with modular construction workflows to enhance operational efficiency.

By addressing these research directions, the field can advance the efficiency, sustainability, and overall impact of modular construction projects, fostering broader industry adoption.

ANNEX I

RECOMMENDED READING CONTROL CHART

	TITLE	Authors	Pub. Year.	Digitization	DfMA + BIM	OFF SITE CONSTRUCTION	CONFIGURATORS FOR BUILDING PROJECTS	MODULAR CONSTRUCTION	TIMBER CONSTRUCTION	COMPUTATIONAL DESIGN	PRODUCT DESIGN
1	Design for manufacturing and assembly (DfMA): a preliminary study of factors influencing its adoption in Singapore. Architectural Engineering and Design	Gao, Shang	2018		x						
2	A holistic review of off-site construction literature published between 2008 and 2018. Journal of Cleaner Production	Jin, Ruoyu	2018	x							
3	Decoding digital transformation in construction	Koeleman, Jan	2019	x							
4	Development of a Design Driven Parametric Mass Timber Construction System for Modular High-Rise Urban Housing.	Lang, Oliver	2019		x	x		x	x		
5	BIM Standardization and Wood Structures	Nawari, N	2022		x				X		
6	Industrialized Construction: Emerging Methods and Technologies	Razkenari, Mohamed	2019	x	x						
7	Perceptions of offsite construction in the United States: An investigation of current practices	Razkenari, Mohamed	2020			x					
8	The role of modularity in sustainable design: A systematic review.	Sonego, Monique	2018		x			x			
9	BuildingInformationModeling(BIM)andDesignfor Manufacturing and Assembly(DfMA) for MassTimber Construction	Staub-French, Sheryl	2018	x	x	x			x		
10	Computational design in architecture: Defining parametric, generative, and algorithmic design	Caetano, Ines	2020				x			x	
11	Integrated BIM and DfMA parametric and algorithmic design based collaboration for supporting client engagement within offsite construction	Bakhshi, Sajjad	2022		x		x			x	
12	BIM as a generic configurator for facilitation of customisation in the AEC industry	Farr, Eric R.P.	2014				x			x	
13	BIM-enabled computerized design and digital fabrication of industrialized buildings: A case study	He, Rui	2021	x	x		x				
14	Framework for Digital Development in Industrialized Housebuilding	Säfsten, Kristina	2020	x							x
15	Computational design in architecture: Defining parametric, generative, and algorithmic design	Caetano, Inês	2020	x						x	
16	Industry 4.0 for the Built Environment: Methodologies, Technologies and Skills	Bolpagni, Marzia	2022		x	x		x		x	
17	Parametric and Generative Design techniques in mass-production environments as effective enablers of Industry 4.0 approaches in the Building Industry	Pasetti Monizza, Gabriele	2018	x		x	x			x	
	USED IN SLR										
18	Mirror-breaking strategies to enable digital manufacturing in Silicon Valley construction firms: a comparative case study	Hall, Daniel M.	2020	x	x		x				x
19	Breakdown Structure in the Digitalization of Design Work for Industrialized House-Building: A Case Study of Systems Building Using Predefinition Levels of Product Platforms	Jansson, Gustav	2019	x							x
20	Cross-phase product configurator for modular buildings using kit-of-parts	Cao, Jianpeng	2021		x		x	x			x
21	Design for Manufacture and Assembly-oriented parametric design of prefabricated buildings	Yuan, Zhenmin	2018		x		x				
22	Configuration platform for customisation of design, manufacturing and assembly processes of building façade systems: A building information modelling perspective	Piroozfar, Roorang	2019				x			x	

Figure A I- 1 Recommended reading control chart

ANNEX II

SYSTEMATIC LITERATURE REVIEW CONTROL CHART

	Title	Authors	Pub. Year.	ARCHITECTURAL DESIGN	STRUCTURAL DESIGN	MANUFACTURING	PRODUCT DESIGN	CONFIGURATOR	BIM	MODULAR
1	Configuration through the parameterization of building components	Jensen P., Olofsson T., Johnsson H.	2012	X	X	X	X	X	X	X
2	Design configuration with architectural objects: Linking customer requirements with system capabilities in industrialized house-building platforms	Wikberg F., Olofsson T., Ekholm A.	2014	X			X			X
3	Platform use in systems building	Jansson G., Johnsson H., Engström D.	2014	X						
4	A framework for generating and evaluating façade designs using a multi-agent system approach	Pantazis E., Gerber D.	2018	X	X					X
5	Design for Manufacture and Assembly-oriented parametric design of prefabricated buildings	Yuan Z., Sun C., Wang Y.	2018			X			X	
6	Design for manufacture and assembly in offsite construction and relationship with concurrent engineering	Arashpour M.	2019			X			X	
7	Configuration platform for customisation of design, manufacturing and assembly processes of building façade systems: A building information modelling perspective	Piroozfar P., Farr E.R.P., Hvam L., Robinson D., Shafiee S.	2019	X				X		
8	Breakdown Structure in the Digitalization of Design Work for Industrialized House-Building: A Case Study of Systems Building Using Predefinition Levels of Product Platforms	Jansson G., Mukkavaara J., Elgh F., Lennartsson M.	2019	X		X	X	X	X	X
9	Design of prefabricated wall-floor building systems using meta-heuristic optimization algorithms	Baghdadi A., Heristchian M., Kloft H.	2020		X					
10	A model for implementing product modularity in buildings design	Gravina da Rocha C., El Ghoz H.B.C., Jr Guadanhim S.	2020				X			X
11	Architecture at Scale: Reimagining One-Off Projects as Building Platforms	Curtis C.	2020			X	X			
12	Mirror-breaking strategies to enable digital manufacturing in Silicon Valley construction firms: a comparative case study	Hall D.M., Whyte J.K., Lessing J.	2020	X				X		X
13	A model for implementing product modularity in buildings design	Gravina da Rocha C., El Ghoz H.B.C., Jr Guadanhim S.	2020	X					X	X
14	Architecture at Scale: Reimagining One-Off Projects as Building Platforms	Curtis C.	2020	X					X	X
15	Connecting teams in modular construction projects using game engine technology	Ezzeddine A., García de Soto B.	2021							X
16	Mass-customisation of cross-laminated timber wall systems at early design stages	Jalali Yazdi A., Ahmadian Fard Fini A., Forsythe P.	2021	X	X	X	X			
17	BIM based decision-support tool for automating design to fabrication process of freeform lattice space structure	Haghir S., Haghnazar R., Saghafi Moghaddam S., Keramat D., Matini M.R., Taghizade K.	2021		X	X			X	
18	Sustainable modular product architecture design by Bi-level leader-follower joint optimization with switching-based meta-heuristic algorithm	Hossain M.S., Chakrabortty R.K., El Sawah S., Ryan M.J.	2021	X	X	X	X	X	X	X
19	Configuration of flexible volumetric elements using product platforms: Information modeling method and a case study	Popovic D., Elgh F., Heikkinen T.	2021		X	X	X	X	X	X
20	Green Design Studio: A modular-based approach for high-performance building design	Shen J., Krietemeyer B., Bartosh A., Gao Z., Zhang J.	2021	X					X	X
21	Computational design and fabrication of highly customizable architectural space frames: Making a flat-cut Weaire-Phelan structure	Liu J., Lee Y.-C., Cardoso Llach D.	2021		X					
22	A framework to automate the design of digitally-fabricated timber plate structures	Rezaei Rad A., Burton H., Rogeau N., Vestartas P., Weinand Y.	2021					X	X	
23	Product platform alignment in industrialised house building	Popovic D., Schauerte T., Elgh F.	2021				X	X		
24	Connecting teams in modular construction projects using game engine technology	Ezzeddine A., García de Soto B.	2021					X	X	
25	Mass-customisation of cross-laminated timber wall systems at early design stages	Jalali Yazdi A., Ahmadian Fard Fini A., Forsythe P.	2021		X			X	X	
26	BIM based decision-support tool for automating design to fabrication process of freeform lattice space structure	Haghir S., Haghnazar R., Saghafi Moghaddam S., Keramat D., Matini M.R., Taghizade K.	2021				X	X	X	
27	Sustainable modular product architecture design by Bi-level leader-follower joint optimization with switching-based meta-heuristic algorithm	Hossain M.S., Chakrabortty R.K., El Sawah S., Ryan M.J.	2021	X			X		X	X
28	Configuration of flexible volumetric elements using product platforms: Information modeling method and a case study	Popovic D., Elgh F., Heikkinen T.	2021	X				X	X	X
29	Green Design Studio: A modular-based approach for high-performance building design	Shen J., Krietemeyer B., Bartosh A., Gao Z., Zhang J.	2021	X				X	X	X
30	Cross-phase product configurator for modular buildings using kit-of-parts	Cao J., Bucher D.F., Hall D.M., Lessing J.	2021	X	X	X		X	X	
31	Computational design and fabrication of highly customizable architectural space frames: Making a flat-cut Weaire-Phelan structure	Liu J., Lee Y.-C., Cardoso Llach D.	2021			X		X		X
32	A framework to automate the design of digitally-fabricated timber plate structures	Rezaei Rad A., Burton H., Rogeau N., Vestartas P., Weinand Y.	2021		X	X		X	X	
33	Product platform alignment in industrialised house building	Popovic D., Schauerte T., Elgh F.	2022	X			X	X	X	
34	Framework of an algorithm-aided BIM approach for modular residential building information models	Pibal S.S., Khoss K., Kovacic I.	2022	X				X	X	
35	Integration of manufacturers' product data in BIM platforms using semantic web technologies	Kebede R., Moscati A., Tan H., Johansson P.	2022			X		X	X	
36	Game-like interactive environment using BIM-based virtual reality for the timber frame self-build housing sector	Potseluyko L., Pour Rahimian F., Dawood N., Elghaish F., Hajirasouli A.	2022	X	X	X		X	X	
37	Developing a Framework for Dynamic Organizational Resilience Analysis in Prefabricated Construction Projects: A Project Life Cycle Perspective	Wang B., Geng L., Dang P., Zhang L.	2022	X				X	X	
38	Automated modular housing design using a module configuration algorithm and a coupled generative adversarial network (CoGAN)	Ghannad P., Lee Y.-C.	2022	X				X	X	X
39	A BIM-Based Approach to Automated Prefabricated Building Construction Site Layout Planning	Yang B., Fang T., Luo X., Liu B., Dong M.	2022					X	X	
40	Integrated multi-objective evolutionary optimization of production layout scenarios for parametric structural design of flexible industrial buildings	Reisinger J., Zahlbruckner M.A., Kovacic I., Kán P., Wang-Sukalia X., Kaufmann H.	2022		X			X	X	
41	Adaptable modular construction systems and multi-objective optimisation strategies for mass-customised housing: A new user-driven paradigm for high-rise living in Hong Kong	Ma C.Y., van Ameijde J.	2022	X				X	X	X
42	Design and optimization of prefabricated building system based on BIM technology	Xiao Y., Bhola J.	2022					X	X	X
43	Integrated BIM and DfMA parametric and algorithmic design based collaboration for supporting client engagement within offsite construction	Bakhshi S., Chenaghlou M.R., Pour Rahimian F., Edwards D.J., Dawood N.	2022					X	X	X
44	Client-engaged collaborative pre-design framework for modular housing	Hwang K.-E., Kim I., Kim J.I., Cha S.H.	2023	X				X	X	X
45	Optimizing Modularization of Residential Housing Designs for Rapid Postdisaster Mass Production of Housing	Ghannad P., Lee Y.-C.	2023	X				X	X	X

Figure A II- 1 Systematic literature review control chart

ANNEX III

USER MANUAL FOR THE USE OF THE ARTIFACT

A III.1 Configuration System Usage

This section of the document is intended to be a user guide for the artifact made, for this purpose various stages of the process will be mentioned, as well as the use of the files of the database shared with this document. The first section is oriented to the preliminary steps to the use of the configuration algorithm in the project and the next to its direct application in the case of studies. Each section is intended to show written and graphical support of the procedures, as well as mentioned the limitations of the artifact at each step due to its limited development time. These will enable the implementation of the proposed framework and will present the way in which the results were obtained that will later be evaluated.

A III.1.1 Configuration of the files prior to use

Each Project must have its own requirements that must be implemented within the template, such as Project information, data structure for cost analysis, among others. However, information about other aspects of the project can also be included from the post-design stages or data to support decisions within the design stage. To this end, this artifact proposes to incorporate within the Revit template sheets that allow the transfer of manufacturing and assembly information in later stages of the Project according to the specifications of the selected modules.

The following paragraphs describe all the considerations that were used to develop the implementation case using the proposed artifact.

A III.1.2 Configure Base Template

This step consists of entering specific information of the Project within the template that will allow the automation of the process of quantifying materials and publishing technical drawings. To do this, in the template provided with the name “Template-r1”, the quantity tables were created according to the project documentation. These new templates were placed within chapter “03. Project Schedules”, as shown in Figure A III- 1. The other groups of schedules belong to tables that are used in manufacturing drawings or to tables used to collect information that can be used in the setup process. As a last step, a .dwg file was added containing the geometric information of the boundaries of the terrain and existing conditions.

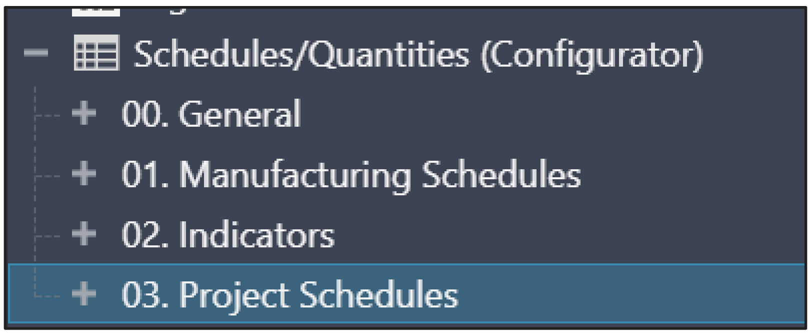

Figure A III- 1 Schedules hierarchy in Revit template

A III .1.3 Configure main algorithm

The main algorithm within the proposal is named “Building arrangement- Modules location - 240504”. Figure A III- 2 shows the header of a group of nodes that must be configured to connect the database to the process. These nodes have as their name the file to which they should be assigned, to access the library of modules within the files shared with this document the following path must be used: ... 02 Revit\01 Modules.

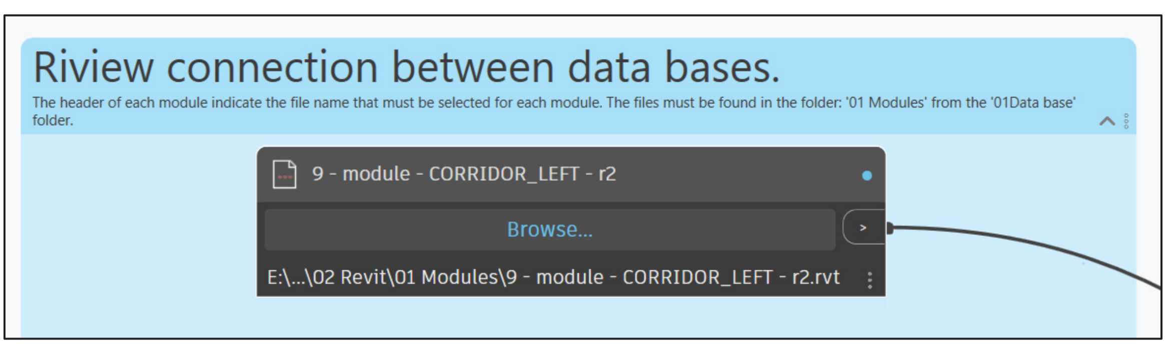

Figure A III- 2 Node that must be configured to connect the database to the process

Currently the algorithm is preconfigured to work with a module library of 3000x6000 mm for architectural units and 2000x3000 mm for horizontal circulation units (corridors). To be able to work with varied sizes, it is necessary to incorporate the edited modules into the library according to the desired characteristics.

AIII.2 Using the Configuration System

After you have made all the previous settings described in the previous section, it is possible to run the configuration algorithm. To do this, the instructions below must be followed.

Draw the central axis of the building. **-** The central line of the building should be drawn according to the desired location of the proposal (fig. A III- 3). Due to the limited time for algorithm development, you can currently only work with lines in 180 degrees.

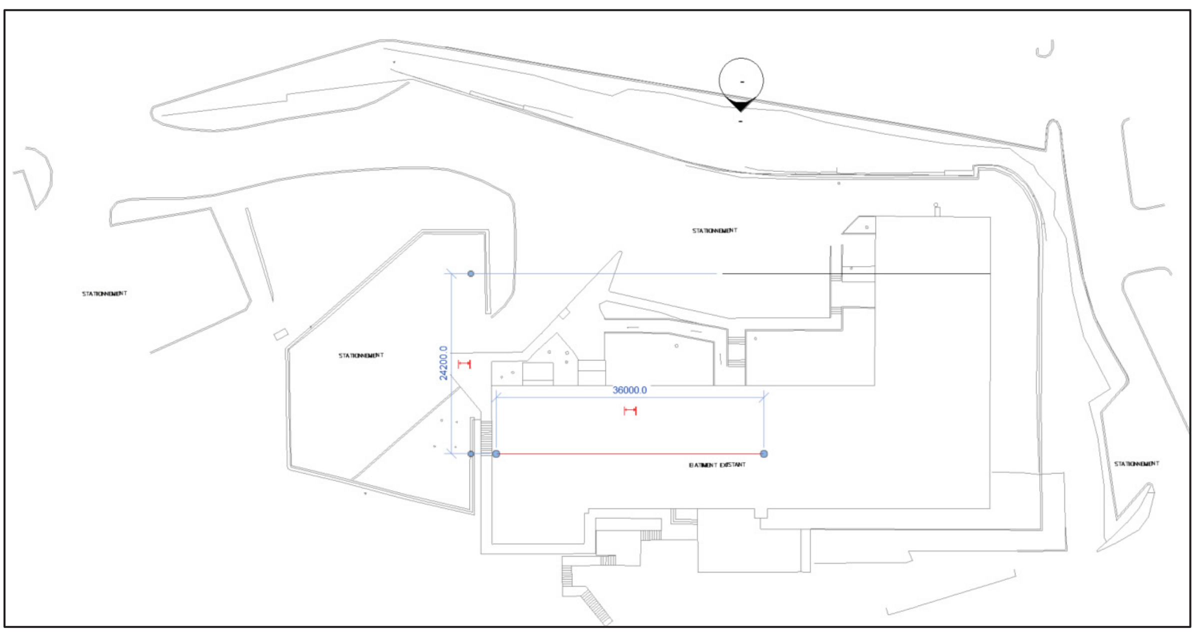

Figure A III- 3 Central axis of the building at its final location

AIII.2.1 Select the central axis of the building

To do this, it is necessary to open the previously configured Dynamo file “Building arrangement- Modules location -240529”. This file contains an area with red groups that gather all the nodes requiring user input. Figure 4 illustrates the node responsible for selecting the baseline. Next, the algorithm must be executed from the Dynamo interface to obtain a volumetric proposal.

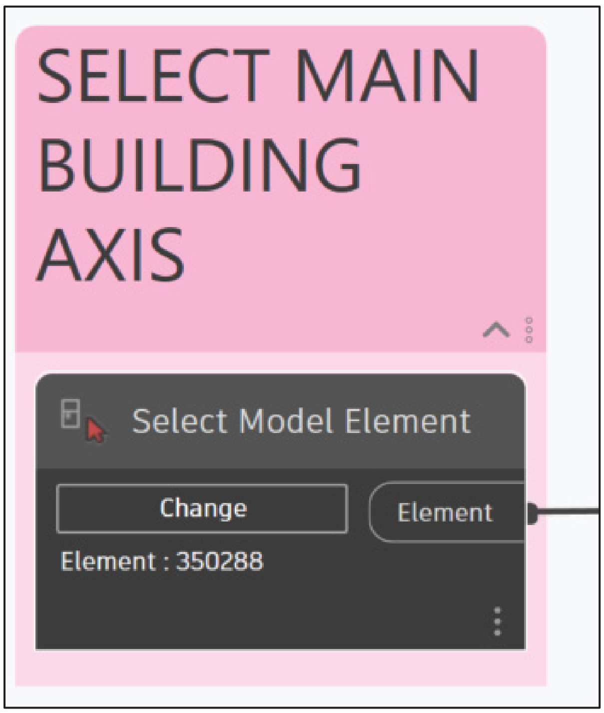

Figure A III- 4 Node that allows the selection of the central axis of the building

AIII.2.2 Using the proposed configuration system

The Dynamo interface is used to visualize the final geometry of the building, giving an assorted color to each type of architectural unit used in the proposal. Figure A III - 5 shows how the Dynamo interface can be used as a Graphic User Interface (GUI), as well as an interface that allows you to create and configure the application’s backend processes.

It can be seen that on the right side of image A III - 5 there is a group of options that allow: assign dimensions to the different types of modules, assign the number of architectural units used, define if the façade of the building will use a balcony, define the logic of grouping the units used and finally place the modules to the template to generate the BIM model of the building. The number of units used for the studio case is 18 2-bedroom units, 19 1-bedroom units, and 15 studio units.

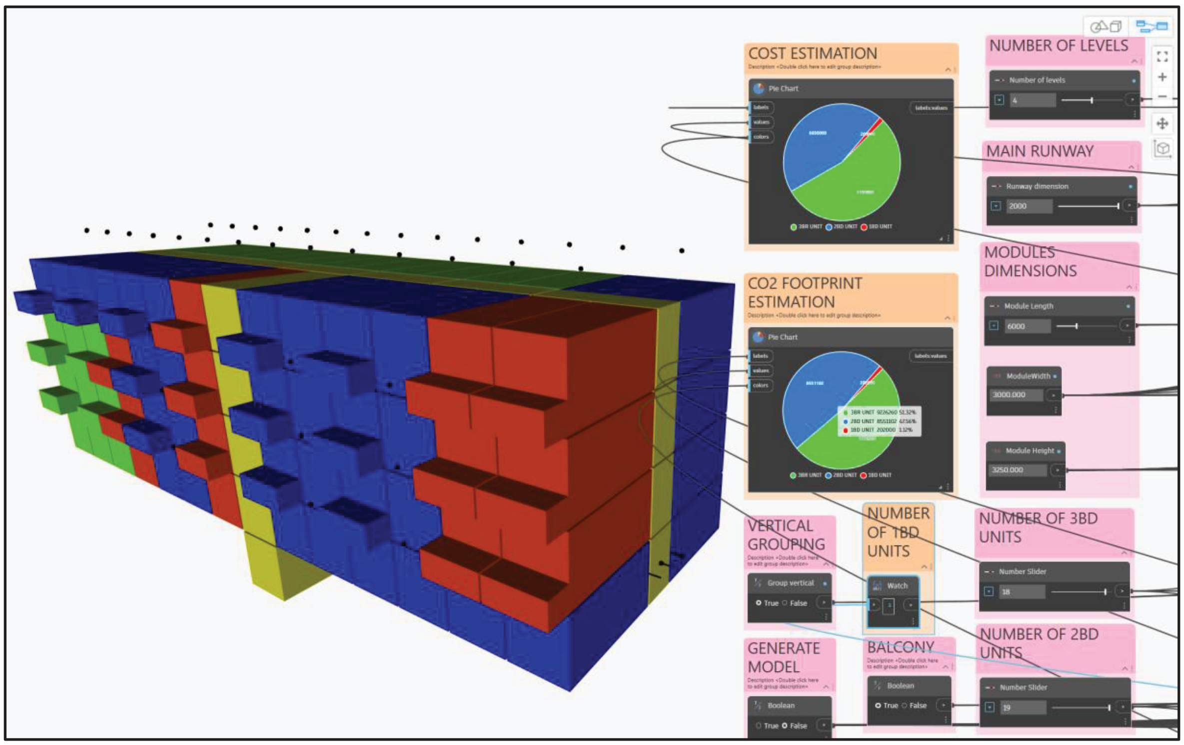

Figure A III- 5 Graphic User Interface of the proposed artefact

AIII.2.3 Create BIM model of the building

It should be considered that the nodes used to insert the architectural units in the BIM model have a bug that must be solved manually before executing this function. To do this, all Revit Links entered by the algorithm during the option creation process in the previous step must be removed from the Revit interface. After removing the links and selecting the desired configuration, the final BIM model of the building can be created with the specified level of detail configured in the database. To do this, the value "True" must be selected in the last node of the input collection, the name of this node is “Generate BIM model” and can be seen in image A III- 6.

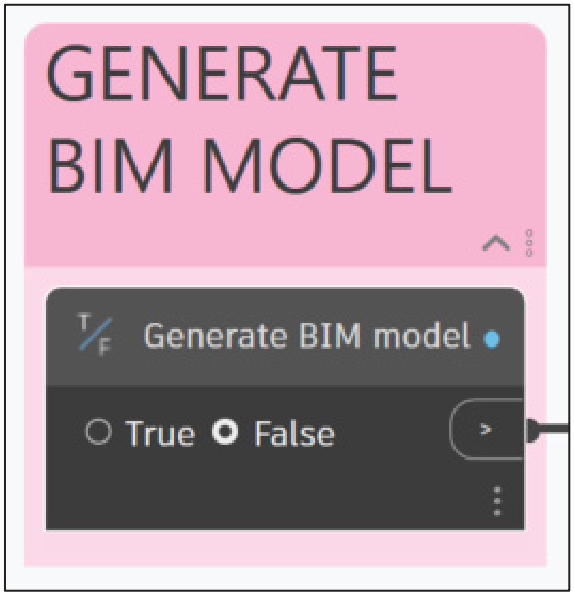

Figure A III- 6 Generate BIM model node

AIII.2.4 Evaluation of indicators

To execute this function, the algorithm will be used in the “CO2 FP-Calculation - r0” file, where the location of the database in the node shown in Figure A III- 7 must be checked. The file that the mentioned node should reference is “ICE DB Machine Readable V3.0a Beta - 10 Nov 2019” and the database path is “... 02 Revit\02 Carbon calculation”.

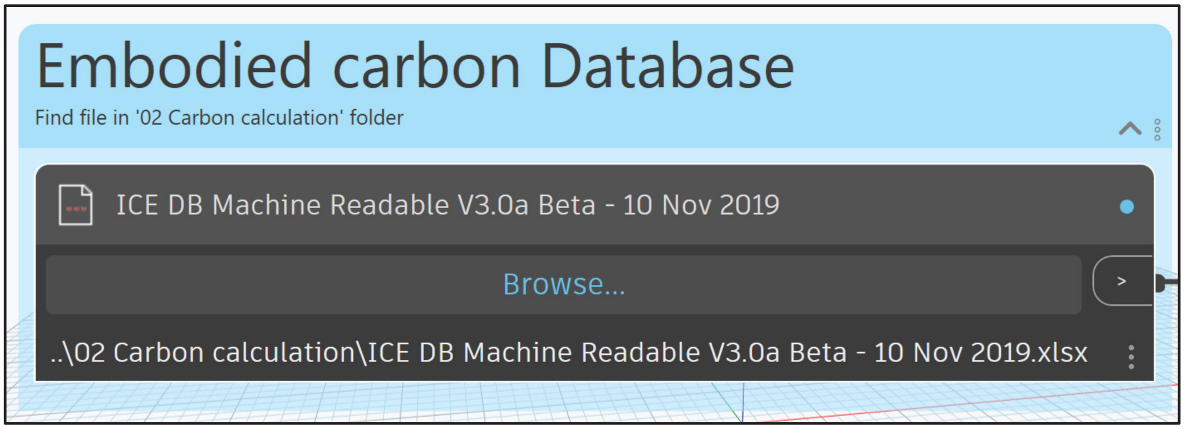

Figure A III- 7 Node to reference the data base with information on the impact of carbon footprint by material

After configuring the database, the algorithm must be executed to preview the list of material options that can be assigned to the evaluation. Figure A III- 8 shows the list and how to select two options for comparison via the slider bar that allows you to choose the index of the material in the list for comparison.

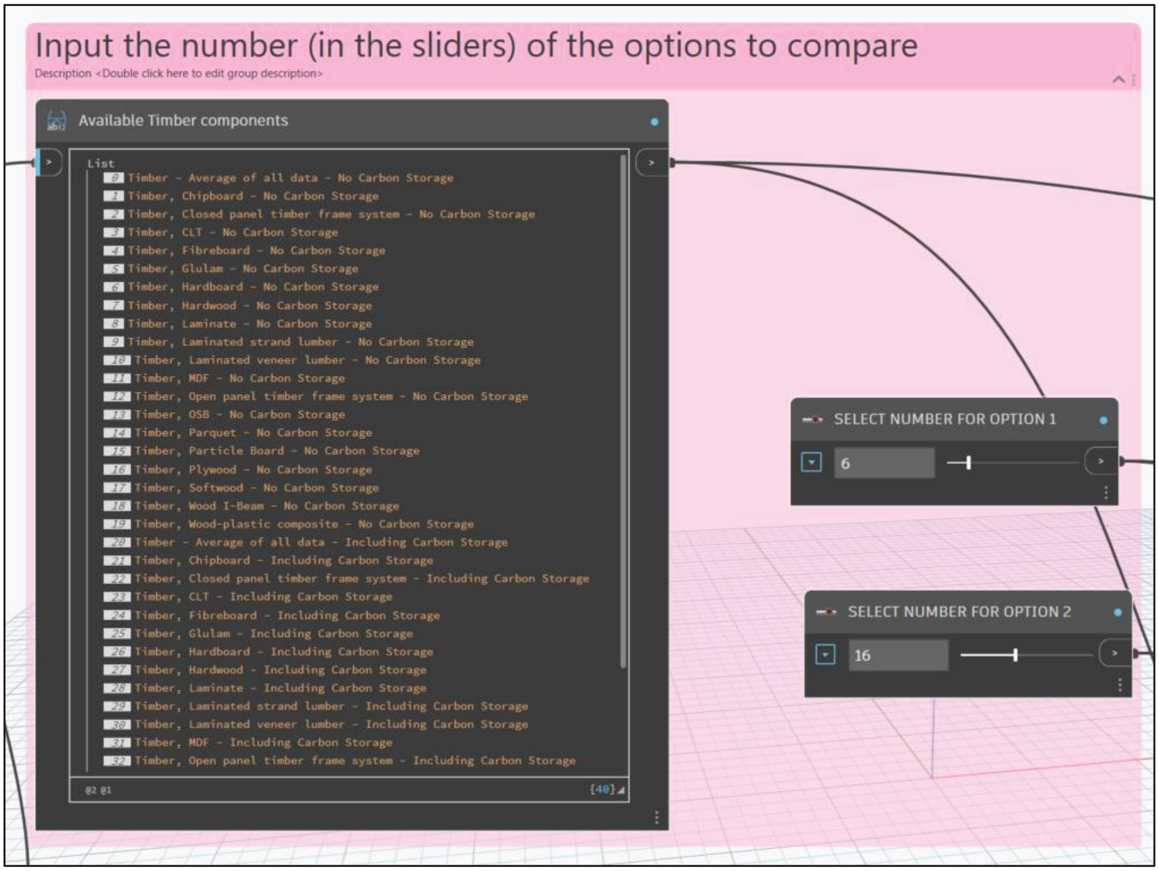

Figure A III- 8 List of materials available for CO2 impact comparison

Finally, the last node of the algorithm must be unfrozen and run again to see the results in the table of the template with the name “CO2 Sample” within the group “02. Indicators”.

AIII.2.5 Generate a table of global costs according to the types of modules used

To perform this calculation, the algorithm uses the database created for this purpose, named “Cost_database” which must be linked to the algorithm through the module shown in Figure A III- 9. This database gathers minimum and maximum values of the predefined modules for this implementation case with the intention of calculating the range of the cost of the building, for which reference values were used.

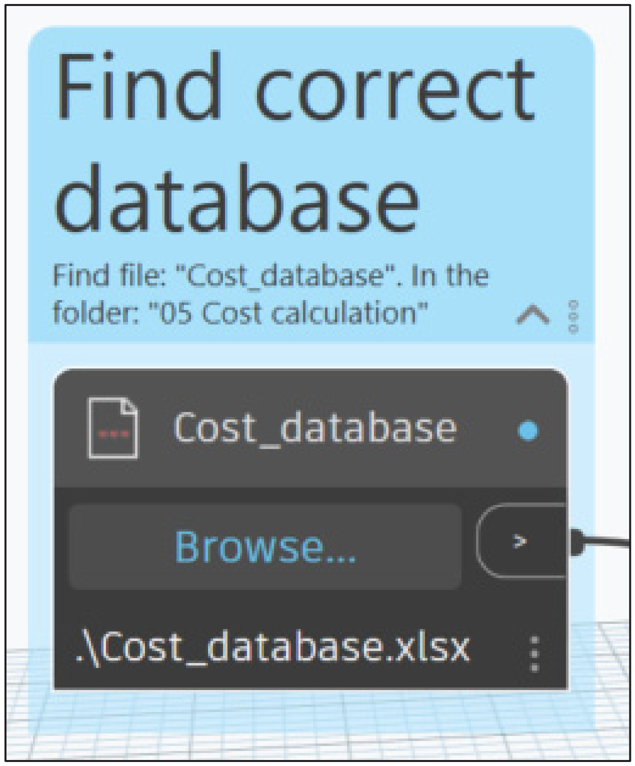

Figure A III- 9 Cost database of the modules used in the case of study

The file to use for this process is “CreateCostSchedule-240504” within the following path: “...\ 02 Revit\03 Dynamo”. After running the algorithm, you will be able to find the table with the results named "Cost estimation" within the group “02. Indicators”.

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