Two-stage BIM-enabled Decision Support System for the Selection of a Suitable Industrialized Building System in Off-site Construction

by

Amirhossein MEHDIPOOR

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Amirhossein Mehdipoor, 2024

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THIS THESIS HAS BEEN EVALUATED

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Dr. Ivanka Iordanova, Thesis Supervisor
Department of Construction Engineering, École de Technologie supérieure

Dr. Mohamed Al-Hussein, Thesis Co-supervisor
Department of Civil and Environmental Engineering at University of Alberta

Dr. Louis Rivest, President of the Board of Examiners
Département de génie des systèmes at École de technologie supérieure

Dr. Erik Andrew Poirier, Member of the jury
Département de génie de la construction at École de technologie supérieure

Dr. Zoubeir Lafhaj, External Evaluator
Département MSO (Mécanismes, Structures et Ouvrages), École Centrale de Lille

THIS THESIS WAS PRESENTED AND DEFENDED

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Système d'aide à la décision en deux étapes basé sur le BIM pour la sélection d'un système de construction industrialisé adapté à la construction hors site

Amirhossein MEHDIPOOR

RÉSUMÉ

L'industrie de la construction connaît des changements transformateurs, stimulés par l'intégration de technologies innovantes et de cadres décisionnels stratégiques. L'objectif de ce projet est d'améliorer l'efficacité de la construction en promouvant et en développant les techniques de construction hors site et leur intégration avec la modélisation des informations du bâtiment. Cette thèse présente une approche holistique visant à améliorer la productivité et l'efficacité dans la construction hors-site grâce au système d'aide à la décision à deux étapes pour la sélection d'un système de construction industrialisé adapté. La première étape du système d'aide à la décision consiste à évaluer la faisabilité de l'intégration de la construction hors-site dans les projets de construction, en tenant compte de dimensions telles que les caractéristiques du projet, la chaîne d'approvisionnement, le temps, le coût, la qualité, les approvisionnements et les aspects socioculturels. Cette évaluation, améliorée par la numérisation et la modélisation des informations du bâtiment (BIM), permet aux parties prenantes de prendre des décisions éclairées concernant l'adoption de la construction hors-site, en tenant compte des avantages tels que l'accélération des délais de construction et l'amélioration du contrôle de la qualité. En s'appuyant sur l'évaluation de la faisabilité de la construction hors-site, la deuxième étape du système d'aide à la décision se concentre sur la sélection d'un système de construction industrialisé adapté aux besoins du projet. Cette étape exploite un flux de travail numérisé spécialement conçu pour les projets de construction hors-site, dans le but de mettre en œuvre avec succès le système de construction industrialisé dans un projet particulier grâce à une approche systématique et numérisée. En adoptant une approche de recherche en sciences de la conception (*Design Science Research*), le système d'aide à la décision proposé en tant qu'artefact de ce projet, intègre la logique floue (*fuzzy logic*) avec le processus hiérarchique analytique (*Analytic Hierarchy Process - AHP*) dans une méthodologie de décision multicritère renforcée par la connexion avec la modélisation des informations du bâtiment. Cette intégration vise à rationaliser les processus de prise de décision et à garantir des décisions fiables et éclairées couvrant tous les aspects, contribuant ainsi à la réussite du projet. En plus de la validation par des experts, une étude de cas réelle et une analyse de données empiriques valident les facteurs clés de soutien à la décision identifiés et l'efficacité du système d'aide à la décision dans l'optimisation du processus de prise de décision. Par exemple, la mise en œuvre d'un système d'automatisation dans le processus de fabrication d'un système de construction industrialisé et son impact sur le temps et le coût de fabrication et d'assemblage, en tant que partie des facteurs clés de soutien à la décision appliqués dans la solution proposée, sont examinés en profondeur. Les résultats apportent des informations précieuses dans le domaine de la construction hors-site, des systèmes de construction industrialisés et des systèmes d'aide à la décision, offrant des orientations pratiques aux professionnels de l'industrie, aux chercheurs et aux décideurs qui naviguent dans le paysage dynamique de la productivité et de l'efficacité de la construction.

Mots-clés : construction hors site, système d'aide à la décisionision, Système de construction industrialiséisé.

Two-stage BIM-enabled Decision Support System for the Selection of a Suitable Industrialized Building System in Off-site Construction

Amirhossein MEHDIPOOR

ABSTRACT

The construction industry is undergoing transformative changes driven by the integration of innovative technologies and strategic decision-making frameworks. The aim of the research described herein is to enhance construction efficiency by advancing Off-site Construction (OSC) techniques and their integration with Building Information Modelling (BIM) through informed decision-making. This thesis presents a holistic approach to enhancing productivity and efficiency in OSC through a Two-Stage BIM-Enabled Decision Support System (BeDSS) for selecting a suitable Industrialized Building System (IBS). The first stage of the BeDSS involves assessing the pertinence of using OSC for a building project, considering dimensions such as project characteristics, supply chain, time, cost, quality, procurement, and socio-cultural. This assessment, augmented by digitalization and BIM, enables stakeholders to make informed decisions regarding the adoption of OSC for a given project, taking into account benefits such as accelerated construction schedules and improved quality control. Building upon the OSC pertinence assessment, the second stage of the BeDSS focuses on the selection of a suitable IBS tailored to the project's requirements. This stage leverages a digitalized workflow specifically designed for off-site construction building projects, where the aim is to successfully implement IBS in a particular project through a systematic and digitalized approach. By adopting a Design Science Research approach, the proposed BeDSS, as the artifact of this project, integrates fuzzy logic with the Analytic Hierarchy Process (AHP) in a multi-criterion decision method incorporating BIM. This integration streamlines the decision-making process and ensures reliable and informed decisions that take into consideration all aspects of the project, thereby contributing to the success of the project. In addition to expert validation, a case study and empirical data analysis validate the identified Key Decision Support Factors (KDSFs) and the effectiveness of the BeDSS in optimizing decision-making. For instance, the implementation of automation in the manufacturing process in IBS, and its impact on the time and cost of manufacturing and assembly as KDMFs applied in the proposed solution, are investigated and discussed in depth. The findings contribute valuable insights to the field of OSC, IBS, and decision support systems, offering practical guidance for industry professionals, researchers, and policymakers navigating the evolving landscape of construction productivity and efficiency.

Keywords: off-site construction (OSC), decision support system, Industrialized Building System.

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LIST OF ABREVIATIONS AND ACRONYMS

AHP	Analytic Hierarchy Process
AM	Additive Manufacturing
BCPI	Building Construction Price Index
BeDSS	BIM-enabled Decision Support System
BIM	Building Information Modeling
BIMAC	BIM-based Automated Construction
CAD	Computer-Aided Design
CAM	Computer-Aided Manufacturing
CBA	Cost Benefit Analysis
CMHC	Canada Mortgage and Housing Corporation
CNC	Computerized Numerical Control
COVID-19	Coronavirus disease 2019
CPI	Consumer Price Index
CR	Consistency Ratio
DfMA	Design for Manufacture and Assembly
DMF	Decision-Making Factors
DSR	Design Science Research
DSS	Decision Support System
ECA	Elemental Cost Analysis
FAHP	Fuzzy Analytic Hierarchy Process
GIRDD	Groupe de recherche en integration et développement durable

IBS	Industrialized building system
KDSF	Key Decision Support Factor
MiC	Modular Integrated Construction
MMC	Modern Method of Construction
MS	Mean Score
NC	Numerical Control
NHPI	New Housing Price Index
NMS	National Master Specification
OSC	Off-site Construction
OSCM	Off-site Construction Manufacturing
OSM	Off-site Manufacturing
PCA	Point of Construction Assembly
PMBOK	Project Management Body of Knowledge
SLR	Systematic Literature Review

LIST OF SYMBOLS

α	internal consistency
K	number of groups or categories
Σ	sum over a set of values
∑s^2 y	sum of each variable variance
s^2 x	variance of a sum of variable value
s	sample standard deviation
N	number of observations
x_i	observed values of a sample item
$\bar{x}$	mean value of the observations
Rs	Spearman correlation coefficient

INTRODUCTION

The construction sector is lagging behind other industries in terms of productivity, often resulting in cost overruns and delays in building projects (Van Vuuren, 2020; Jin *et al.*, 2018a). This shortfall arises from multiple factors, with a notable emphasis on low productivity (Bertram *et al.*, 2019; Changali, Mohammad et van Nieuwland, 2015; de Laubier *et al.*, 2019). Specifically in Canada, the housing shortage has become critical (Conference Board of Canada, 2024), underscoring the need to address low productivity in construction.

According to a report by the Canada Mortgage and Housing Corporation (CMHC, 2024), there is projected to be a 3 million housing unit supply gap in Canada by 2030. Considering current economic and immigration trends, this gap could widen from 3 million to 4 million housing units (CMHC, 2023). The shortage in Canada's housing supply is identified as the primary cause of the country's housing affordability challenges (CMHC, 2022).

In this context, transitioning from traditional on-site construction methods to modular construction in Europe and North America could result in annual savings of up to $22 billion (Bertram *et al.*, 2019). The adoption of off-site construction (OSC) methodology has demonstrated its effectiveness in improving efficiency in construction projects (Abdul Nabi et El-adaway, 2020).

Despite various factors causing low productivity and inefficiency, adopting the OSC methodology has proven effective in enhancing efficiency in construction projects. OSC, it should be noted, is a construction approach in which construction tasks traditionally carried out on-site are instead carried out in an industrial manufacturing environment (Liu *et al.*, 2017). There has been a significant increase in the adoption of Industrialized Building Systems (IBSs) in OSC, leading to improved productivity and successful project outcomes.

Although the adoption of digital technology such as Building Information Modelling (BIM) can enhance productivity in construction, research on construction automation has primarily centred on the design phase, with little attention given to technological advancements in other aspects such as decision-making in various stages including design phase (Bowmaster et Rankin, 2019a; Tang, Chong et Zhang, 2019).

Moreover, according to Marcher et al. (2020), while OSC and IBS are well established within the construction industry, the growing interest in OSC underscores the critical importance of carefully selecting the appropriate construction method and accompanying techniques to ensure project success (Marcher, Giusti et Matt, 2020). Due to the complexity of the construction process and the variety of different techniques and methods involved in planning, manufacturing, and constructing a building project, effective decision-making in the selection of suitable construction methodology is critical (Daget et Zhang, 2019).

The aim of the research presented in this thesis is to enhance construction efficiency by advancing OSC techniques and their integration with BIM through informed decision-making.

The specific objectives are to:

- Identify, introduce, validate, and evaluate Key Decision Support Factors (KDSFs) for OSC projects in Canada;
- Assess, analyze, and rank the most relevant KDSFs for OSC projects in Canada; and
- Propose a method for evaluating and selecting suitable IBS using BIM-enabled Decision Support System (BeDSS) for a particular OSC project.

A two-stage decision-making method is proposed in which Stage 1 determines whether OSC should be used in a given building project; and Stage 2 involves evaluating and selecting a suitable IBS solution based on relevant decision-making factors for the given OSC project.

This research draws upon the Design Science Research (DSR) method. A real project is selected to which to apply the proposed decision support system, demonstrating successful implementation and evaluation of the solution. Expert validation, including semi-structured interviews and questionnaires, is used to validate the research findings.

Four standalone papers appear as the core chapters of this thesis, each of these having been either published (Proceedings of Canadian Society of Civil Engineering Annual Conference, Journal of Digital Manufacturing and Technology), accepted (Journal of Construction Engineering and Management), or submitted (Automation in Construction) to a peer-reviewed journal to fulfill the requirements of an article-based thesis. Two additional papers are included as annexes to provide further discussion on different aspects of the thesis. The core articles are organized in the following order:

The first article presents a Systematic Literature Review (SLR) on digital fabrication, BIM, and OSC. The purpose of the review is to identify existing research gaps at the interface of these fields. Then, to address the gaps identified, a two-stage BIM-enabled decision support system is proposed as a potential solution to the identified gaps and challenges.

The second article has an objective to identify, introduce, validate, and assess the key decision support factors for choosing OSC for a particular building project. This study uses a mixed-methods design, including an SLR and expert reviews through semi-structured interviews and surveys, to achieve the research objectives and ensure the validity and reliability of the findings. The identified and ranked factors are used in the development of the proposed decision support system (presented in the third article).

The third article presents the development of the proposed two-stage BIM-enabled decision support system for the selection of a suitable IBS in OSC. Multi-criterion decision-making (MCDM) methods and Fuzzy Analytic Hierarchy Process (FAHP) are applied and programmed as a Revit plugin to integrate the BeDSS with the BIM model and automate some parts of the decision-making process. The evaluation and validation are conducted through the implementation of a real case study, expert interviews, and a questionnaire, followed by a post-validation method using an alternative approach for the same case study. The process is discussed in detail in Chapter 5.

The fourth paper emphasizes the importance of the research findings by presenting a digitalized workflow for light-gauge steel OSC projects. This paper discusses the identified KDSFs and their application in the development of the BeDSS. It focuses on bridging the gap between knowledge and practice by introducing a comprehensive workflow specifically tailored to light-gauge OSC projects. The paper explores the role of KDSFs in shaping the proposed workflow. Additionally, a Cost-Benefit Analysis (CBA) is conducted, which aids decision-makers in evaluating the integration of BIM and automation technology within Industrialized Building Systems (IBS). The findings confirm several KDSFs, such as time, cost, and quality, which are vital in selecting appropriate IBS solutions and reinforce the importance of the Decision Support System. The CBA demonstrates the financial feasibility of embracing digitalization and semi-automation, aligning with the financial KDSF and reinforcing the thesis's focus on informed, economically sound decision-making in the selection of OSC and IBS methods.

In terms of thesis organization, Chapter 1 establishes the theoretical foundation in the form of a comprehensive literature review, presenting the problem statement and outlining the research objectives. The second chapter introduces the chosen research methodology. Subsequently, Chapters 3 to 6 present the aforementioned four articles (one conference paper and three journal papers) that form the core of this thesis.

Finally, a general discussion and conclusion chapter complete the thesis, providing a comprehensive overview of the research findings and their implications.

CHAPTER 1

LITERATURE REVIEW

1.1 Literature Review Approach

This research employed a systematic literature review approach, which is discussed in greater detail in Chapter 3 in the form of a conference paper. This chapter outlines the objectives of the literature review and provides a comprehensive research background on the key trends relevant to the objectives of this study, including Off-site Construction, BIM, Industrial Building Systems, and Decision Making in OSC.

A systematic literature review is an integral part of the research methodology employed in this study. A mixed-method approach, combining both quantitative and qualitative methods, was used to achieve the following objectives:

- Evaluate the existing literature on OSC, BIM, Decision Making in construction management and digital fabrication, and analyze various bibliometric parameters within these domains.
- Identify current research themes and emerging trends in the aforementioned domains.
- Determine the key decision-making factors contributing to the successful implementation of OSC and its integration with BIM and digital fabrication within the construction industry, with a focus on enhancing construction efficiency.
- Conduct an in-depth evaluation of significant trends in OSC, BIM, and digital fabrication, identifying research gaps and providing recommendations for future research in these domains.

The mixed-method approach refers to the integration of quantitative and qualitative methods in order to leverage the strengths and mitigate the weaknesses of each method within a single research study (Zou, 2014). Greene, Caracelli, and Graham (1989) defined five foundations for the mixed-method approach: triangulation, complementarity, development, initiation, and expansion.

- Triangulation: The mixed-method approach facilitates a robust substantiation between quantitative and qualitative methods.
- Complementarity: The results obtained from one method can be used to interpret, support, and enhance the findings of the other.
- Development design: The concurrent application of both methods allows each method to improve upon the advantages of the other.
- Initiation: The mixed-method approach helps to enhance the research design by identifying any potential inconsistencies or phenomena in the results.
- Expansion: Through the use of a mixed-method approach, the depth of knowledge and scope of the research can be expanded.

The aforementioned rationale is referenced by Yin et al. (2019) in their review of current literature on BIM for OSC. The mixed method combines both quantitative and qualitative review methods in the review process (Greene, Caracelli, and Graham 1989.; Yin et al. 2019).

To facilitate an in-depth evaluation of the main trends in OSC, identify research gaps, and determine potential key success factors for OSC, BIM, and digital fabrication, an initial search was conducted on BIM, Off-site Manufacturing (OSM), OSC, and prefabrication. This initial search was then filtered by searching for a set of BIM-related keywords within the initial results. The filtered results were subsequently considered during the qualitative review.

By searching for “BIM” within the initial search results, and for “Prefabrication”, “OSM”, and “OSC” within the subset of initial results for “BIM”, a total of 219 and 230 related articles, respectively, were found. The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), which is an evidence-based approach designed to implement transparent and complete systematic review, (Sarkis-Onofre *et al.*, 2021), was employed in this regard.

The systematic approach resulted in a total of 46 journal papers being identified as key articles. The following steps were undertaken:

(a) Pre-Selection: Importing data generated from VOSviewer in .csv format to Excel in order to detect any duplications and screening article titles to exclude conference proceedings, book chapters, and editorial letters.

(b) Selection: Reading abstracts to exclude articles that do not focus on digital fabrication, BIM, and OSC.

(c) Conclusion: Skim reading the main body of articles to determine the final list of key papers.

To analyze and enhance the results, the following strategy was implemented:

1.2 Bibliometric Analysis

Bibliometric analysis, as defined by Van Eck and Waltman (2010), is an important technique in the field of bibliometric approaches that uses map generation to visualize the structural and dynamic aspects of scientific research (van Eck et Waltman, 2010). VOSviewer, a computer program introduced by the aforementioned Van Eck and Waltman (2010), was used in the present study for constructing and viewing bibliometric maps. This program can display maps in various ways, such as highlighting key journals, scholars, publications, countries within a specific search area, authors, and the co-occurrence of research keywords. The results of the bibliometric analysis are discussed in Chapter 3.

1.3 Qualitative Review

Following the bibliometric analysis, a qualitative approach was employed to analyze the current research trends in OSC and OSM in construction and evaluate the extent to which digital fabrication, BIM, and OSC are addressed in the existing body of knowledge. The definitions of the main concepts studied in this thesis, including OSC, BIM, digital fabrication, and similar terms, are provided in the following subsections.

1.4 Off-site Construction

In the literature, there are various terms used to refer to off-site construction, including off-site manufacturing in construction, modern method of construction (MMC), off-site production (OSP), and off-site prefabrication (Taylor, 2010). The following definitions provide further clarity:

OSC is a widely used term that refers to the preparation, design, fabrication, and assembly of building elements at a location separate from their final installation site. The aim of OSC is to expedite and improve efficiency in the construction process by shifting it to an industrial manufacturing environment (Iordanova, 2020). Another definition states that OSC “brings on-site construction works into a climate-controlled facility where advanced machinery and manufacturing technologies can be utilized to prefabricate buildings in a standardized and efficient manner” (Liu et al. 2017).

OSM, meanwhile, refers to the process of manufacturing construction components at a location different from the final point of construction assembly (PCA). These components are then delivered to the PCA for installation at various stages of the project lifecycle (Goulding and Rahimian, 2019). The Construction Industry Council defines OSM as a delivery method that adds significant value to a product and process through factory manufacturing and assembly intervention (Abenda et al., 2017). The main types of OSM identified by these authors include panellized, volumetric, hybrid, modular system, and components & sub-assembly systems (Abenda et al., 2017; Earlie et al., 2011).

Kamar et al. (2009) define the industrialization of the construction industry using the following terms: The term "off-site" is used to describe a wide range of applications where buildings or structures, or components thereof, are manufactured and assembled digitally before their final installation on site (Gibb and Pendlebury, 2006). "Pre-assembly" refers to the manufacture and assembly of buildings or building components primarily taking place off-site and earlier in the process compared to traditional on-site construction, with the final installation occurring later (Gibb and Isack, 2003).

Prefabrication is a manufacturing process that typically occurs at a specialized facility, where various materials are joined to form components of the final installation.

Modern Method of Construction (MMC) is a term used by the UK government to describe several innovations in house building, including those involving off-site technologies that shift work from the construction site to the factory (Gibb, 1999; Pan et al., 2007; BURA, 2005; Ross et al., 2006).

OSC and OSM are interchangeable terms that refer to a part of the construction process carried out in a location other than the actual building site, such as a factory or production facility that may be near the construction site (Gibb and Pendlebury, 2006).

Off-site fabrication (OSF) combines prefabrication and pre-assembly, involving the design and manufacture of units and modules, usually digitally, with the final installation taking place on-site (Gibb, 1999).

In this research, a combination of definitions provided by Iordanova (2020), Liu et al. (2017), and Gibb and Pendlebury (2006) is used. Iordanova's definition covers all stages of off-site construction, including preparation, design, fabrication, and assembly of building elements. The definition of Liu et al. complements this by emphasizing the use of advanced machinery and technologies. Gibb and Pendlebury's definition covers other terms commonly used in the construction industry. As a combination of these, the following definition is introduced in this thesis: off-site construction, also known as off-site manufacturing or off-site production, involves the preparation, design, fabrication, and assembly of building elements at a separate location from their final installation site. The purpose of this approach is to expedite and improve construction efficiency by shifting the construction process to an industrial manufacturing environment and utilizing advanced machinery and manufacturing technologies.

1.5 Building Information Modelling

BIM is defined as the construction of a model that contains information about a building across all phases of its lifecycle including operation and maintenance (ISO 16757-1: 2015). According to the American Institute of Architects (2008), BIM is a model-based technology that encompasses project information data. It provides a digital and data-rich representation of the building, serving as a useful platform for the storage and conveyance of information. Furthermore, it allows project team members to provide feedback on process performance and equipment, driving improvements in future projects (Morton, 2011). BIM also offers novel opportunities to support the computerized design and fabrication of industrialized buildings, resulting in increased productivity and cost-effectiveness (He et al., 2021).

The integration of BIM and OSC can maximize the benefits of both to the construction industry, helping to improve construction efficiency (Yin et al., 2019). Additionally, translating parametric BIM fabrication data into computerized numerical control (CNC) machine language as part of the member production process enables automatic member shape recognition and fabrication (Lee et al., 2019).

Numerous studies have explored the benefits of enhancing construction efficiency by integrating BIM with digital fabrication and automation. Recent research underscores several significant advantages of this approach in OSC. Automated systems guarantee greater precision and uniformity in construction activities, resulting in a higher quality final product with fewer defects and less rework. The implementation of computer-aided design and manufacturing technologies ensures that components are manufactured to precise specifications, thereby improving the overall structural integrity and aesthetic appeal of buildings (Chea et al., 2020).

These improvements can be facilitated by automation in construction and the deployment of advanced machinery for specific manufacturing and assembly tasks. Concurrently, BIM aids designers in comprehending design requirements for digital fabrication and automated manufacturing and assembly systems, a concept often known as DfMA (Abd Razak et al., 2022).

Furthermore, one of the least utilized features of BIM is its capability to generate an energy model of a building through the BIM 6D methodology. This digital information model allows for the simulation of the building's actual energy performance and the optimization of both natural and artificial lighting systems. BIM 6D supports design and operational decisions that boost energy efficiency, especially in Nearly Zero-Energy Buildings (NZEB) and the renovation of existing structures. For example, in public buildings like hospitals, BIM 6D can result in substantial energy savings and improved lighting efficiency, aiding in the decarbonization of high-energy-use buildings and enhancing their energy certification (Montiel-Santiago et al., 2020). Moreover, the use of BIM for the automated fabrication of components enables more efficient material handling and waste recovery (Hamid et al., 2018).

As summarized above, the integration of BIM, automation, and digital fabrication represents a critical pathway toward improving the efficiency of manufacturing and assembly in OSC.

1.6 Industrialized Building System: An Innovative Approach in Digital Fabrication

Digital fabrication is a methodology that encompasses various processes in a construction project, including generation, planning, design, material processing, assembly, and erection, all of which are carried out using digital tools (Agkathidis, 2010). It involves computer-based design methods and robotics-based production processes (Agustí-Juan et al., 2017). Ding et al. (2014) introduced a novel procedure for large-scale projects within the domain of automated construction systems and digital fabrication called BIM-based Automated Construction (BIMAC). BIMAC integrates modern Computer-Aided Design (CAD), Computer-Aided

Manufacturing (CAM), CNC technology, new material technology, and BIM to enhance efficiency for large-scale projects (Ding, Wei et Che, 2014).

According to Ilhan et al. (2019) and Petersen et al. (2019), in order to utilize graphical data, such as 2D drawings and BIM models, from the design stage to the construction stage with machines, it is necessary to translate this information for CNC machines, 3D printers, and robots (Petersen *et al.*, 2019). Moreover, Design for Manufacture and Assembly (DfMA), which is a method that simplifies and minimizes the use of material, labour and manufacturing/production activities, can be integrated with these tools (i.e., BIM, CNC machines, 3D printers, and robots) to improve productivity (Lu *et al.*, 2021a). Although there are machine-specific software tools available for this purpose, the process is still evolving (Ilhan *et al.*, 2019).

The term Industrialized Building System (IBS) is commonly used in the context of digital fabrication, representing the concept of prefabrication within the construction industry. The IBS concept is used by different stakeholders, including practitioners, researchers, and governmental bodies, to industrialize the construction process (Agkathidis, 2010).

According to Richard (2003), industrialization refers to simplifying the production of complex goods by dividing them into smaller components using technology to reduce costs. Richard identifies five degrees of industrialization: prefabrication, mechanization, automation, robotics, and reproduction. In this context, IBS can be defined as an innovative technology that offers greater automation, higher productivity, increased cost efficiency, and improved site safety by shifting building activities from traditional construction sites to off-site factory-based manufacturing environments (He et al., 2021).

Shukor, Mohammad, and Mahbub (2011) define IBS as a construction process and approach that involves manufacturing different components off-site or on-site. IBS is a prefabricated construction method where activities such as concrete forming, placing, finishing, and curing are carried out away from the final project location, and the prefabricated components are then assembled and erected at the project site to form a completed structure (Abdallah, 2007).

As a key step toward industrialization, efforts have been made to increase automation in construction, although achieving full autonomy for most construction tasks remains a distant goal. Nevertheless, significant steps have been taken towards automation in construction through the development of advanced machines designed for autonomous operation, as well as material–robot systems for specific assembly tasks (Petersen et al., 2019).

Anane et al. (2023) developed a framework for modular robotic prefabrication of discrete aggregation based on a computational approach that uses computation to generate algorithmically combinable aggregation. Their framework is driven by BIM, computational design, and a robotic approach to the prefabrication process (Anane, Iordanova et Ouellet-Plamondon, 2023). Moreover, Ham & Lee (2019) investigated the advantages of digital fabrication in construction management, considering project management factors based on the Project Management Body of Knowledge (PMBOK). Their study demonstrated that the use of digital fabrication brings positive benefits to projects. They argued that, although certain factors, such as cost reduction and control, may present challenges, this does not imply that the use of digital fabrication is not beneficial overall (Ham & Lee, 2019).

In order to maximize the benefits of Industrialized Building Systems (IBS) in enhancing productivity in construction, it is essential to consider the concept of Design for Manufacturing and Assembly (DfMA). The application of DfMA in IBS projects can improve sustainability by reducing waste and ensuring timely project delivery with enhanced construction quality (Abd Razak *et al.*, 2022).

DfMA is a method that takes into account manufacturing and assembly procedures from the early stages of planning and design, with the aim of eliminating potential production issues. This approach optimizes quality, time, and overall cost by addressing these concerns proactively (Roxas *et al.*, 2023). The advantages of DfMA are extensive, and the literature highlights several key benefits: enhanced quality, reduced fabrication and construction costs, shorter construction times, decreased labour requirements with improved health and safety, and strengthened sustainability and circular economy principles (Langston et Zhang, 2021).

Research demonstrates that DfMA can elevate the quality of construction projects from the design stage through to manufacturing and construction (Bao *et al.*, 2022a; Favi, Germani & Mandolini, 2017). Optimizing DfMA contributes to lower project costs, as supported by numerous studies (Lu *et al.*, 2021b; Tan *et al.*, 2020; Wasim *et al.*, 2020). The most significant advantage, as reported by Montazeri (2024), is the reduction in program time, a benefit echoed in several other studies. According to the literature (Bakhshi *et al.*, 2022; Machado, Underwood & Fleming, 2016), implementing DfMA increases labour productivity by minimizing or eliminating labour-intensive activities on-site, thereby improving health and safety during assembly. Lastly, a few studies have explored the sustainability and environmental impacts of DfMA in construction projects (Favi, Germani & Mandolini, 2017; Gao, Low & Nair, 2018).

Despite the significance of DfMA in the construction industry, researchers have identified several challenges (Langston et Zhang, 2021). There is a lack of guidelines, standards, and affordable technologies globally to facilitate better adoption of DfMA (Lu *et al.*, 2021b). Knowledge limitations (Gao, Jin et Lu, 2020; Gerth *et al.*, 2013), a resistant community mindset, social attitudes, and user acceptance issues (Lu *et al.*, 2021b; Montali *et al.*, 2018) also pose significant hurdles. Additionally, there is insufficient supply chain management (Langston et Zhang, 2021; Tan *et al.*, 2020). In the early stages, adopting DfMA can be costly due to the need for new technologies and ecosystem investment (Langston et Zhang, 2021; Lu *et al.*, 2021b; O'Rourke, 2013), along with a lack of suitable technical requirements (Bakhshi et al., 2022).

According to Montazeri et al. (2024), as part of a SLR conducted for this research and reported in Annex II, DfMA challenges are categorized into nine categories: economic and financial, technological, legal contractual, technical cognitive, procedural, cultural, geographical, policy, and commercial. The research concluded that economic and financial challenges, such as initial capital costs, cost overruns and contingencies, insurance and liability considerations, and financing options and funding, are the most important and relevant for implementing DfMA in building projects. In contrast, commercial-related factors, such as available market options, competitive market pressure, and market acceptance, have the least influence on the implementation of DfMA in off-site construction (OSC) projects.

In summary, this chapter provided an overview of OSC, BIM, and IBS in the context of digital fabrication. Now, we will discuss the success factors for decision-making in OSC and the selection of a suitable IBS in OSC projects. Several factors contribute to successful decision-making in OSC. The selection of OSC as a suitable construction methodology and IBS plays a crucial role. Different types of IBS, such as panellised, volumetric, hybrid, modular system, and components & sub-assembly system, offer various advantages and considerations. Additionally, the integration of BIM with OSC can enhance decision-making. BIM provides a digital and data-rich representation of the building, allowing project stakeholders to collaborate and share information throughout the project's life cycle. Furthermore, the concept of Design for Manufacturing and Assembly (DfMA) is essential in decision-making for OSC projects. The decision on which IBS to use should be based on different factors, which are discussed in the following section

1.7 Success factors for decision making in OSC

Studying the success factors for OSC provides an overall understanding of the need for a shift from commonly used project delivery systems, such as engineering, procurement, and construction (EPC), towards OSC systems to support the optimal use of modularization. The success of off-site systems depends on various factors related to project characteristics, such as the size of prefabricated components, targeted cost, schedule, and the scope of OSC (Salama et al., 2017).

O'Connor et al. (2014) identified 72 potential success factors for the application of OSM in construction, further narrowing these down to 21 critical success factors (CSFs) related to modularization. The top CSFs highlighted the importance of considering design limitations, aligning the project team on project drivers, allocating adequate owner-planning resources, achieving on-time design freeze, and having a clear scope of work (O'Connor, O'Brien, & Choi, 2014). Daget and Zhang (2019) developed a multi-criterion decision-making support system based on 30 success factors for assessing industrialized building construction. The three main decision factors identified were customer needs, supply chain, and the construction industry. Their study found the potential and practicality of the model in evaluating different alternatives across multiple decision-making factors (Daget & Zhang, 2019).

Antwi-Afari et al. (2018) identified several CSFs for BIM implementation, the most notable being collaboration among design, engineering, and construction stakeholders; early and accurate 3D visualization of design; coordination and planning of construction works; enhanced exchange of information and knowledge management; and improved site layout planning and site safety (Antwi-Afari et al., 2018).

Project Management Institute (2000) introduced and categorized potential success factors under specific areas, including but not limited to the Project Management Body of Knowledge (PMBOK): Integration Management, Scope Management, Time Management, Cost Management, Quality Management, Human Resource Management, Communication Management, Risk Management, Procurement Management, and Stakeholder Management (Project Management Institute, 2000).

In addition to the PMBOK areas, Duncheva and Hairstans (2019) discussed success factors in decision-making using a classification that is more closely related to sustainability, regulations, digitization, productivity, culture, and human capital. These factors can be considered similar to the human resource management aspect in PMBOK (Duncheva & Hairstans, 2019).

Salama et al. (2017), finally, identified critical factors for the selection of modular construction in on-site manufacturing, including limitations in on-site connections, transportation and weight, crane costs, and required concrete quantities for project foundations.

In conclusion, successful decision-making in OSC projects requires careful consideration of KDSFs, the integration of BIM, and the application of IBS including DfMA. Overcoming challenges related to guidelines, standards, knowledge, resistance, user acceptance, supply chain management, and initial investment is crucial for achieving success in OSC projects. an examination of recent research in the fields of OSC, BIM, digital fabrication and decision-making in construction management, reveals a dearth of studies on the integration of these practices. While research has been conducted within each of these domains individually, there is a lack of literature assessing the factors that contribute to the successful integration of OSC, BIM, and digital fabrication.

Despite the recognition and discussion of the relationship between BIM and OSC by pioneering researchers, gaps remain concerning the integration of BIM and digital fabrication and the incorporation of IBSs into OSC. In addition to the aforementioned gaps in research, there is also a lack of studies on the integration of these practices into decision-making in construction management, particularly with respect to OSC. These gaps highlight the need for further research and development on decision-support systems that can effectively integrate OSC, BIM, digital fabrication (including IBS), and KDSFs. By taking into account KDSFs in the selection of a suitable construction method (i.e., traditional on-site versus OSC) and IBS, stakeholders can make informed choices and optimize the implementation of these practices in construction projects.

CHAPTER 2

METHODOLOGY

2.1 Introduction

This research began with an exploratory approach the purpose of which was to investigate the current trends in OSC, BIM, digitalization, and decision-making in construction management. The objective was to gain a comprehensive understanding of these areas and identify potential areas for integration. As the research progressed, it evolved into the development of a framework for integrating the decision-making process with OSC in a computerized format, leveraging the capabilities of the BIM platform. This evolution was guided by the principles of the DSR method. DSR is a research approach in which the researcher develops novel artifacts to provide solutions to real-world problems, thereby making a valuable contribution to the existing scientific knowledge (Hevner et Chatterjee, 2010).

In this chapter, the research methodology employed in this research is defined and explained in detail. The chapter follows a structure that aligns with the stages of the DSR method. It begins with the identification of the research problem, followed by the design and evaluation cycle of the proposed framework. Each stage is described, outlining the specific activities and approaches undertaken to address the research objectives.

This chapter concludes with a discussion of the thesis structure, emphasizing the significance of the research findings and their implications for the field of OSC. This includes a discussion of the advancements made in developing the two-stage BIM-enabled decision support system for OSC. These advancements have the potential to have a significant impact on industry practice and to contribute substantively to the body of academic knowledge in the field.

2.2 Problem statement, aim, objectives and research questions

The problem statement underlying this research was identified based on the literature review. As presented in Chapter 3 in the form of a conference paper, a review of recent research in the domains of OSC, BIM, and digital fabrication revealed a lack of studies on the integration of these practices. While individual research projects have been conducted in each domain, there is a dearth of literature assessing the success factors for the integration of OSC, BIM, and digital fabrication.

Although success factors for modularization and BIM applications have been discussed, there is a need for the development of a decision-support system to facilitate the decision-making process for OSC. Furthermore, gaps exist with respect to the integration of BIM and digital fabrication into OSC, despite the potential of this integration to enhance various activities, such as planning, simulation, design evaluation, material processing and manufacturing, transportation, and site assembly.

Additionally, while various types of Industrialized Building Systems (IBSs) are available in the market, there is no comprehensive DSS based on locally validated factors that can advance the application of IBS and improve the decision-making process in the construction industry.

Research Questions:

- What are the Key Decision-Support Factors (KDSFs) at play in the decision whether to select the OSC approach and how do they affect the decision?
- How can a DSS be developed to facilitate the decision-making process for OSC?
- How to select a suitable IBS for a particular OSC project?

Research assumptions:

- KDSFs significantly influence the decision of whether to select traditional construction methods or OSC for a given project and its impact on the decision-making process.
- The development of a DSS for OSC will enhance the efficiency and effectiveness of the decision-making process.
- The identification and evaluation of KDSFs will enable the selection of the most suitable IBS for a given OSC project.

Research Objectives:

1. To identify and analyze the Key Decision-Support Factors that play a crucial role in the feasibility of the OSC approach toward the success of the project and examine their impact on the decision-making process.
2. To develop a computerized BIM-enabled decision-supporting system that facilitates and improves the decision-making process for OSC building projects.
3. To devise a method for determining the most suitable IBS for a given OSC project based on the specific project requirements and constraints.

2.3 Design Science Research Methodology

As per Rocha et al. (2012), the primary objective of design science methodology, also known as the constructive method, is to systematically create a solution grounded in scientific principles for real-world problems. This is achieved by establishing meaningful connections between theoretical frameworks and practical applications (Rocha *et al.*, 2012). The DSR process has been extensively discussed in the field of Information System research, including by Vaishanavi and Kuechler (2007), Hevner and Chatterjee (2010), and Holmstrom et al. (2009). The application of design science methodology in addressing diverse managerial challenges within the field of construction management was demonstrated by AlSehaimi et al. (2012). Furthermore, Rocha et al. (2012) conducted a study examining the process and outcomes of employing design science methodology in the context of lean construction. Rocha (2011) specifically introduced a set of steps for implementing the design science approach in the construction domain that was employed in the present study. For the purpose of this research, the proposed steps were synthesized from the work of Rocha's (2011) work. An overview of the DSR methodology employed in this study is presented in Figure 2.1.

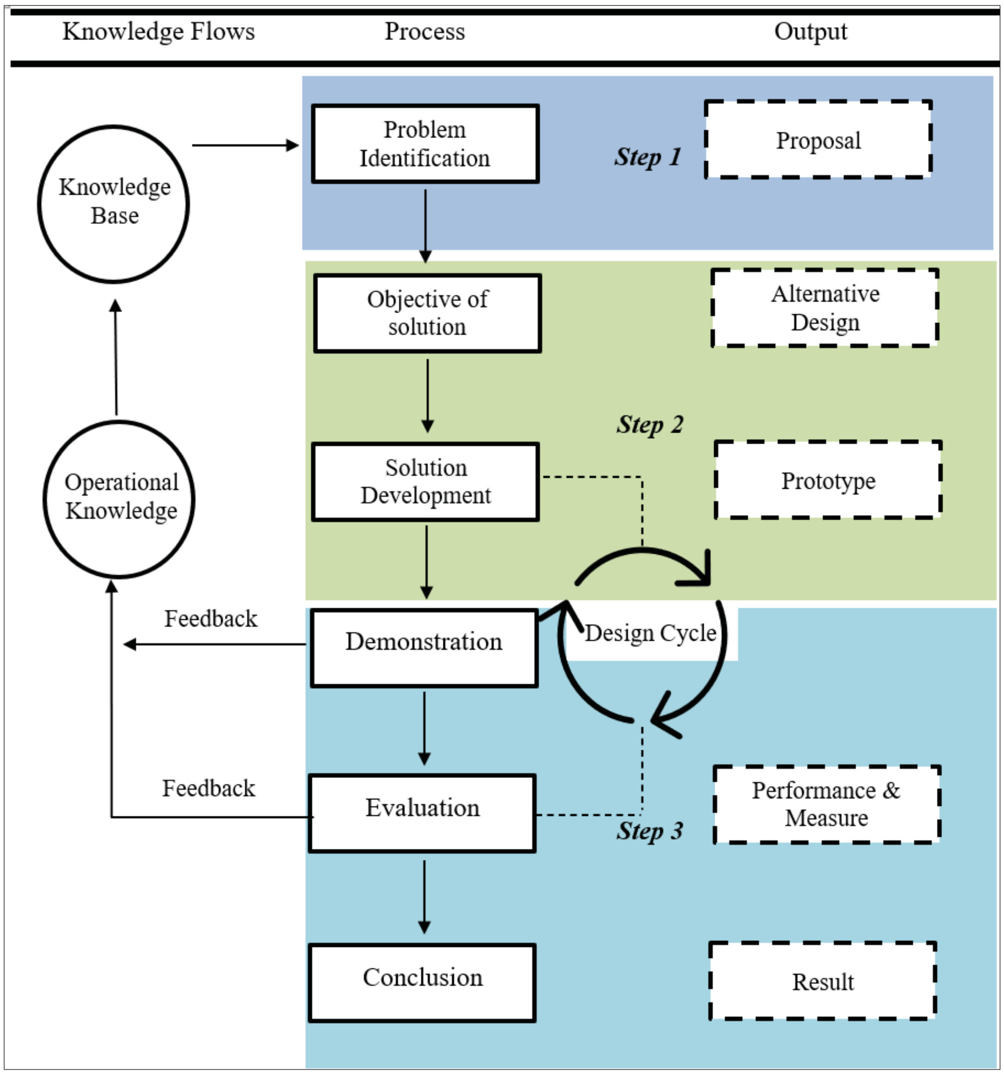

Figure 2.1 Overview of the DSR methodology

The steps involved in the DSR method employed in this research are outlined as follows:

Step 1 of DSR method: The initial step involves acquiring a comprehensive understanding of the subject matter and identifying the practical problems that are relevant. This entails examining the literature, consulting domain experts, and conducting empirical investigations to gain insights into the specific challenges that need to be addressed. As mentioned in Chapter 1, SLR was used to identify the potential success factors. Table 2.1 presents the 77 factors initially identified as potentially affecting decision-making in OSC, that were subject to validation through expert interviews.

To identify the potential success factors for the application of BIM, OSC, and digital fabrication, the following procedure is employed: (a) compile a list of all success factors identified by previous researchers as presented in the decision-making-related papers represented in the list of key articles (Table 2.1); (b) Differentiate the factors in each domain of BIM, digital fabrication, and OSC; (c) exclude duplicate/similar factors; and (d) exclude factors not related to the other clusters. This process resulted in 35 factors categorized into 7 dimensions. After the validation process, which involved conducting semi-structured expert interviews, the final list of validated factors consists of 32 factors introduced as KDSFs.

Table 2.1 List of potential factor affecting decision making in OSC

No.	Potential factor	No.	Potential factor	No.	Potential factor
1	Suitability of design for modularization (DMF1)	27	High standard quality of both internal and external finishes of a building (DMF27)	53	Alignment on Drivers (DMF53)
2	Presence of repetitive layout in design (DMF2)	28	Reduction in defects of product/facility (DMF28)	54	Owner's Planning Resources & Processes (DMF54)
3	Number of stories (DMF3)	29	Improved construction safety (DMF29)	55	Timely Design Freeze (DMF55)
4	Building exterior type (DMF4)	30	Reducing environmental impact through the reduction of site activities (DMF30)	56	Early Completion Recognition (DMF56)
5	Structural stability of individual and assembled modules (DMF5)	31	Reducing neighborhood disruption and noise (DMF31)	57	Preliminary Module Definition (DMF57)
6	Need for inspection/supervision of manufacturing units (DMF6)	32	Reducing traffic movement to/from site which cause less neighborhood pollution and congestion (DMF32)	58	Owner-Furnished/Long Lead Equipment Specification (DMF58)
7	Lead time for fabricated modules (DMF7)	33	Reduce time on site (DMF33)	59	Cost Savings Recognition (DMF59)
8	Module's size (DMF8)	34	logistics optimization (DMF34)	60	Contractor Leadership (DMF60)
9	Site accessibility (DMF9)	35	Whole life-cycle approach (DMF35)	61	Contractor Experience (DMF61)
10	Transportation equipment (DMF10)availability	36	Design for Manufacture and Assembly + Disassembly (DMF36)	62	Module Fabricator Capability (DMF62)
11	Construction equipment availability (DMF11)	37	International protocols. Increased export opportunities (DMF37)	63	Investment in Studies (DMF63)
12	On-site labour availability (DMF12)	38	Local frameworks and policies. Third party accreditation (DMF38)	64	Heavy Lift/Site Transport Capabilities (DMF64)
13	Labour cost at site location (DMF13)	39	Industry standards and quality assurance. Quality management system (DMF39)	65	Vendor Involvement (DMF65)
14	Availability of production information, skilled workforce and experienced team (DMF14)	40	Internet of things. Integrated multi-disciplinary design (DMF40)	66	Operations and Maintenance (O&M) Provisions (DMF66)
15	Availability of experienced labour force in a factory environment (DMF15)	41	Fourth industrial revolution. Automated production lines (DMF41)	67	Transport Infrastructure (DMF67)
16	Site location (DMF16)	42	Building Information Management. Design and production components with attached information (DMF42)	68	Owner Delay Avoidance (DMF68)

Table 2.1 List of potential factors affecting decision-making in OSC (continued)

No.	Potential factor	No.	Potential factor	No.	Potential factor
17	Availability of manufacturing plants/facilities within economical transport distance (DMF17)	43	Learn theory and automation. Labour and materials resources optimization (DMF43)	69	Data for Optimization (DMF69)
18	Organization's familiarity with Prefab (DMF18)	44	Construction industry performance. Inherent efficiency theory (DMF43)	70	Continuity through Project Phases (DMF70)
19	Early involvement of top management (DMF19)	45	Economic impact. Increased housing delivery capacity (DMF45)	71	Management of Execution Risks (DMF71)
20	Use of information and communication technology (e.g., BIM) (DMF20)	46	Collaboration. Local multi-skilled labour force (DMF46)	72	Transport Delay Avoidance (DMF72)
21	Size and type of project (DMF21)	47	Leadership. Talent attraction and retention (DMF47)	73	Onsite connections (DMF73)
22	Need for expediting the schedule (DMF22)	48	Skills gaps. Reduced need for labour onsite (DMF48)	74	Transportation limitations (DMF74)
23	Overall project timescale (DMF23)	49	Business models. Supply chain integration (DMF49)	75	Weight's limitations (DMF75)
24	Certainty of project completion date (DMF24)	50	Health & Safety. Reduced manual handling and work at height (DMF50)	76	Crane cost limitation (DMF76)
25	Certainty of project cost (DMF25)	51	Contractual basis. Collaborative contracts with reduced adversity (DMF51)	77	Required concrete quantities for project foundation (DMF77)
26	Minimizing labour and plant cost on site (DMF26)	52	Module Envelope Limitations (DMF52)		

To develop the Key Decision Support Factors for the proposed two-stage BIM-enabled Decision Support System, the potential factors were classified into seven dimensions and 35 factors, as illustrated in Figure 2.2.

The process of validation of the KDSFs by the industry started with 12 semi-structured pilot interviews with local experts, each possessing between 5 and 35 years of experience in the construction industry. Following these pilot interviews, certain factors were excluded, such as data for optimization and the whole life cycle approach, due to not being significantly focused on and dependent on OSC. Meanwhile, other factors were added, including financing and local authority regulations (workers' union syndicate). The final list of validated KDSFs consists of 32 factors. The validation and assessment of these KDSFs are discussed in Chapter 4.

Chapter 5 elaborates on the consolidation of the factors, resulting in a total of 21 factors for the development of the BeDSS. For instance, the factors of design flexibility and design complexity were merged into the single factor of project design in the BeDSS development. This merge was justified because both design flexibility and design complexity are inherently interrelated aspects of project design. Design flexibility often necessitates managing design complexity, and vice versa. Combining them provides a more holistic and integrated approach to evaluating project design, ensuring that the interplay between flexibility and complexity is adequately addressed without redundancy.

The factors used in the BeDSS development during the decision-making process were further validated through questionnaires and interviews with 15 experts, including both local and international professionals, as part of the overall BeDSS evaluation and validation process. To assess the generalizability of the research findings, experts from Germany and Malaysia also participated in this exercise.

All experts had more than five years of professional experience in the construction industry and came from diverse backgrounds, including architecture, mechanical and electrical engineering, project management, construction management, cost management, BIM management, environmental and sustainability expertise, manufacturers, and contractors.

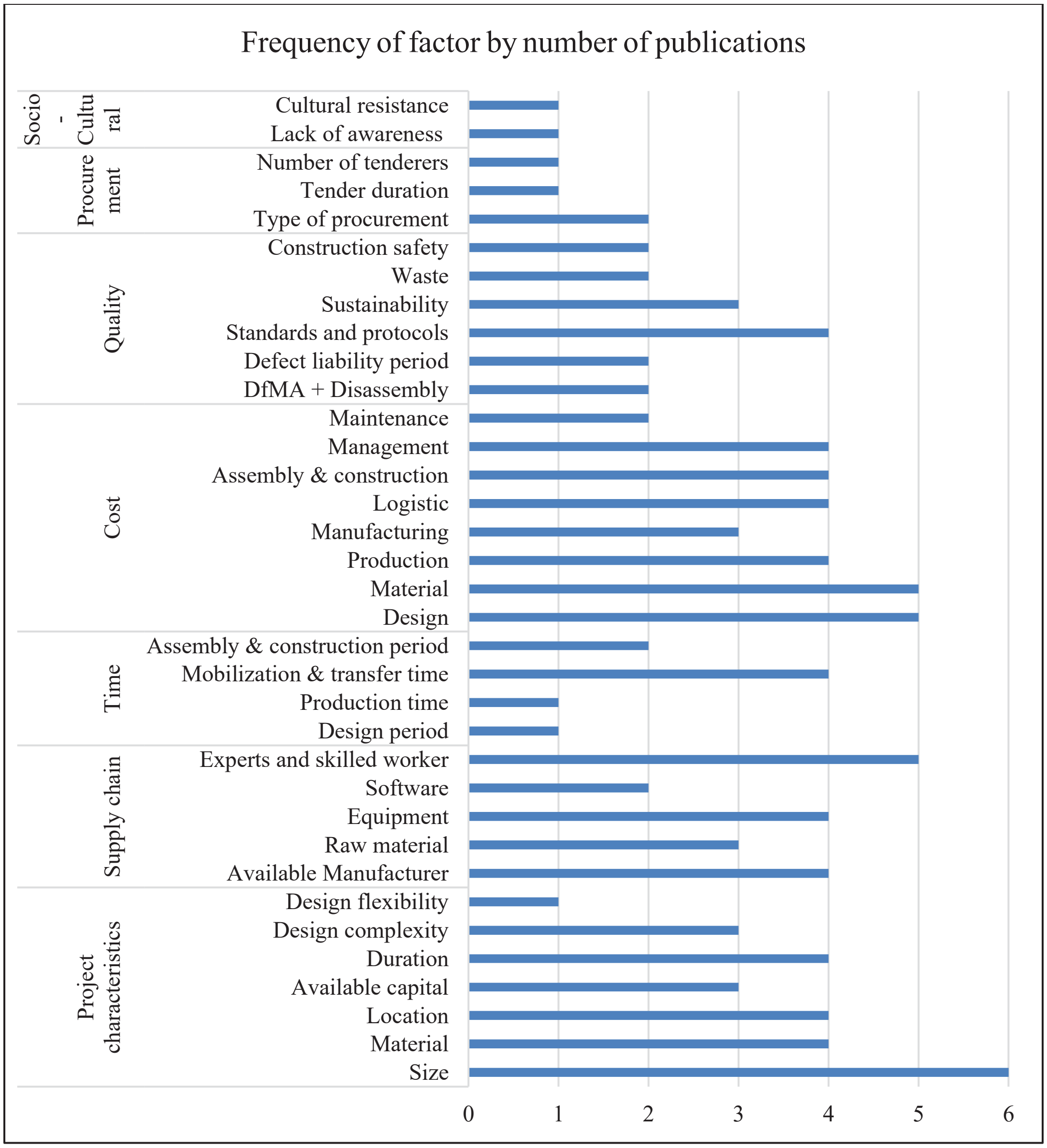

Figure 2.2 Frequency of factor by number of publications
where they were identified

<u>Step 2 of DSR method</u>: Following the identification of the problem, the next step entails proposing a potential design solution and subsequently developing an artifact or prototype that has the capability to effectively resolve the identified problem. This involves employing a combination of theoretical frameworks, established principles, and innovative approaches to devise a solution that aligns with the objectives of the research. In this step, the development of the proposed artifact of this research, namely the BeDSS, is undertaken.

Step 3 of DSR method: Once the artifact or prototype has been developed, it is necessary to assess and evaluate its performance in real-world scenarios. This is achieved through the application of the proposed solution in case studies. By subjecting the solution to practical implementation and rigorous evaluation, its effectiveness, efficiency, and suitability can be measured and analyzed.

The case studies, representing different phases of a real project, are provided by the industry partner of this research. The industry partner is a design and build company with the capacity to manufacture prefabricated volumetric modules as well as various types of industrial building systems, such as prefabricated wall and service modules. The company is categorized as a small to medium-sized enterprise, employing approximately 58 individuals, including 3 directors, 5 managers, 10 architects and engineers, 25 skilled workers, 10 general workers, and 5 finance and administration staff. The company's headquarters are located in Montreal, Quebec, Canada. The company operates as a joint venture among the board of directors, who collectively possess over 40 years of experience in the construction industry, providing design, engineering, manufacturing, and delivery of various types of building projects, including housing, commercial, and educational buildings, utilizing both onsite and offsite construction methodologies.

The project involved in this research is an administrative complex with an approximate gross floor area of 2,500 square meters, located in the Canadian Arctic. The project was awarded to the company in August 2021, with a completion date set for December 2023. Different phases of this project are used as real case studies as part of the Design Science Research methodology in this research. The insights gained from these case studies contribute to the refinement and validation of the proposed solution, thereby enhancing its practical applicability and scientific rigour.

2.4 Artifact Development: BIM-enabled Decision Support System

The proposed artifact consists of two stages: Stage 1 involves the decision whether or not to use OSC in a given building project, while Stage 2 focuses on evaluating and selecting the most appropriate IBS for the project. For the evaluation of alternatives in each step, a multi-criterion DSS is employed. The multi-criterion decision (MCD) methodology is widely recognized as an effective approach for DSSs in various phases of construction projects (Jato-Espino *et al.*, 2014). Indeed, Marcher et al. (2020) found it to be the most commonly utilized methodology in decision support for building construction (Marcher, Giusti et Matt, 2020). Moreover, MCD is considered a suitable method for decision-making with diverse applications in the construction sector (Antucheviciene *et al.*, 2015), (Navarro, Yepes et Martí, 2019).

To address the prioritization of alternatives based on quantitative techniques and the judgment of decision-makers, Fuzzy logic is combined with the Analytic Hierarchy Process (AHP), a method introduced by Saaty (1987) (Saaty, 1987). Aboelmagd (2018) successfully applied AHP to develop a DSS for selecting optimal bid prices for construction projects, highlighting its efficacy as a powerful management technique (Aboelmagd, 2018). However, fuzzy logic is needed to account for the level of decomposition in the hierarchical model and the inconsistencies and subjectivity in the decision-maker's judgment, which AHP alone cannot account for (Ishizaka, 2014; Ayhan, 2013).

To overcome these limitations and leverage the advantages of both fuzzy logic and AHP, the fuzzy analytic hierarchy process (FAHP) method is employed. FAHP combines Fuzzy logic and AHP to address uncertainty and incorporate vagueness in personal judgment (Ayhan, 2013). Ayhan (2013) applied the FAHP approach to develop a decision-making model for selecting a proper supplier, demonstrating its effectiveness in overcoming such challenges. The development of the FAHP-based method proposed in this research, i.e., BeDSS, is discussed in detail in Chapter 5.

2.5 Structure of the article-based thesis

In this section, the structure of the articles comprising this thesis is presented. Each article is self-contained, but they combine to collectively fulfill the primary research objective of *developing a two-stage BIM-enabled decision support system for the selection of a suitable industrialized building system (IBS) in off-site construction"*.

Table 2.2 Structure of this article-based thesis

Articles	Presented as	Objectives met	Journals/Proceedings	Year
Article No.1- Conference Paper: Systematic Literature Review on The Integration of Digital Fabrication, BIM and Off-Site Manufacturing in Construction - A Research Road Map	Chapter 3	1	Proceedings of the Canadian Society of Civil Engineering Annual Conference 2021(Springer)	Published in 2022
Article No.2 – Journal Paper: Identification and Evaluation of The Key Decision Support Factors for Selecting Off-Site Construction in Canada: A Building Information Modeling (BIM)-enabled Approach	Chapter 4	1 and 2	Journal of Digital Manufacturing Technology (Universal Wiser)	Published in 2023
Article No.3 – Journal Paper: Enhancing Decision-Making in Off-site Construction: A Two Stage BIM-enabled Decision Support System for The Selection of a Suitable Industrialized Building System	Chapter 5	2 and 3	Journal of Automation in Construction (Elsevier)	Submitted in 2024
Article No.4 – Journal Paper: Enhancing the Manufacturing Process in Light-Gauge Steel Off-Site Construction Using Semi-Automation	Chapter 6	2 and 3	Journal of Construction Engineering and Management (ASCE)	Accepted for publication (with revisions) in 2024

2.5.1 Article 01 - Systematic Literature Review on The Integration of Digital Fabrication, BIM and Off-Site Manufacturing in Construction - A Research Roadmap

The first article provides a comprehensive review of the scientific literature on the integration of digital fabrication, BIM, OSC, and decision-making in construction. The main objective of this review is to identify any areas where knowledge gaps exist and further research is needed. A bibliometric analysis is conducted to study the relationship between the studied topics. The review identifies the main trends and research gaps in OSC and points to potential avenues for future research in this area. The findings indicate that there has been insufficient research on the integration of off-site manufacturing, BIM, and digital fabrication. Although the benefits of BIM and digital fabrication in off-site manufacturing have been separately discussed by pioneer scholars, little research has been found linking BIM and digital fabrication in OSC. Overall, the article contributes to the existing body of knowledge by identifying research gaps and proposing a practical potential solution in the form of a two-stage BIM-enabled DSS, which has the potential to improve the efficiency and effectiveness of construction processes involving digital fabrication, BIM, and OSC.

2.5.2 Article 02 - Identification and Evaluation of The Key Decision Support Factors for Selecting Off-Site Construction in Canada: A Building Information Modeling-Enabled Approach

The second article focuses on identifying, validating, and assessing the KDSFs involved in selecting the appropriate construction method for building construction. The study uses a mixed-methods approach, including a systematic literature review as well as expert reviews (interviews and surveys) to ensure the validity and reliability of the findings. The research methodology includes an SLR and expert reviews through interviews and surveys which was presented in the first article. Thirty-two KDSFs are validated and grouped into seven dimensions. The most important dimension identified is project time, which includes the design period, production time, mobilization and transfer time, assembly, and construction period. The least important dimension identified is the cost dimension consisting of the Cost of Design, Material, Production and Manufacturing, Logistics, Assembly and Construction, Management, and Maintenance. This research highlights the importance of time-related factors in the decision-making process for OSC projects. It also emphasizes the need to consider a comprehensive set of KDSFs beyond merely cost savings. The findings provide a guideline by which for OSC practitioners to select an appropriate construction method. This guideline is subsequently used in the development of the proposed BeDSS. The BeDSS development as the core artifact of this thesis is discussed in the next article.

2.5.3 Article 03 - Enhancing Decision-Making in Off-site Construction: A Two-stage BIM-enabled Decision Support System for The Selection of a Suitable Industrialized Building System

The use of IBSs in OSC has gained popularity as a means of increasing productivity and ensuring project success. However, as OSC becomes more prevalent in building projects, it becomes crucial to decide if to use OSC or not in the early design phase, when comprehensive data may be limited. This third article introduces the development of a two-stage BIM-enabled DSS for selecting an appropriate IBS in OSC, based on the KDSFs defined in the second article. The system incorporates multi-criterion decision-making (MCDM) methods and FAHP, and is integrated as a Revit plugin to automate parts of the decision-making process using BIM.

Once the decision about using OSC is taken, decision-makers in the construction industry, including designers and developers, face challenges in choosing the right IBS for implementation in a given OSC project. While there are numerous types of IBSs available in the market, a comprehensive DSS based on validated factors from the local construction industry is needed to facilitate the application of IBS in OSC. The validated factors, introduced as the dimensions (main factors) and KDSFs in the second paper, form the basis for the methodology presented in the third paper, which consists of two stages. Stage 1 involves determining whether OSC should be utilized in a given building project, while Stage 2 focuses on evaluating and selecting the most suitable IBS options, such as a volumetric modular or panelized system, based on the decision-making factors relevant to the given OSC project in the case study used in this research.

The next paper (Article 04) builds upon the research findings and goes beyond theoretical exploration. It presents an implementation of the proposed BeDSS solution in a real-world project, thereby providing practical insights and further emphasizing the importance of the research outcomes.

2.5.4 Article 04 - Enhancing the Manufacturing Process in Light-Gauge Steel Off-Site Construction Using Semi-Automation

The fourth paper presents a digitalized workflow specifically designed for light-gauge steel (LGS) OSC projects. The paper discusses the identified KDSFs and their application in the development of the proposed workflow. Moreover, the Cost–Benefit Analysis (CBA) in this research assists decision-makers in making reliable decisions regarding the integration of BIM and automation technology in implementing IBS.

The motivation for this research stems from the persistent productivity challenges faced by the construction industry. Building on the findings from Chapter 4 (Paper-2), where time and quality-related factors were identified as the most critical, and cost-related factors as the least significant, a more in-depth investigation and discussion of these factors is deemed necessary. Furthermore, the inclusion of the additional Key Decision Support Factor of finance, following the validation process, has led to a deeper analysis of the financial feasibility of initial investments, with the aim of facilitating more informed decision-making in OSC. This is one of the primary objectives of this Ph.D. thesis.

The study emphasizes reducing task duration, improving data flow, and enhancing project cost assessment in the implementation of IBS within OSC projects.

This article is intrinsically linked to the overarching Ph.D. thesis, contributing significantly across multiple dimensions:

Informed Decision-Making for Integration of Digitalization and Automation in OSC: The article demonstrates the practical application of digitalization and semi-automation in OSC, which aligns with the thesis' objective of enhancing construction efficiency through informed decision-making in the selection of OSC and IBS.

Validation of Key Decision Support Factors (Mainly on Time, Quality, and Cost-related KDSFs): The findings from the article validate several KDSFs identified in the thesis, such as time, cost, and quality-related KDSFs. Time and quality-related factors were identified as the most important, while cost-related factors were considered less important compared to the rest, although still critical. Therefore, this paper investigated these factors further to complement the previous results. These factors are critical in the decision-making process for selecting suitable IBS solutions, thereby reinforcing the relevance of the Decision Support System.

Empirical Evidence: The article provides empirical evidence of the effectiveness of digitalized workflows and semi-automation in improving productivity and accuracy in OSC projects.

Financial Feasibility: The cost-benefit analysis conducted in the article highlights the financial viability of adopting digitalization and semi-automation. This aligns with the KDSF of finance and the thesis's goal of providing robust and informed decision-making that considers economic factors in the selection of OSC and IBS solutions.

Relevance to Research Questions: The article's focus on reducing task durations, enhancing data flow, and improving cost assessments directly relates to the research questions of the Ph.D. project. It provides practical insights and validation for the proposed DSS, ensuring that the system addresses real-world challenges and delivers tangible benefits.

The proposed workflow is developed using the DSR approach. The following two hypotheses are tested: (1) the implementation of a digitalized workflow significantly reduces task duration and improves project cost assessment, and (2) the application of semi-automation is a financially feasible investment with a payback period shorter than the total project duration. A real OSC project is selected to which to apply the workflow and evaluate the hypotheses.

The findings demonstrate that the proposed workflow leads to a significant reduction in task duration and improved accuracy of the bill of quantities. On average, the application of the workflow in the case study is found to result in a 38% reduction in production and assembly duration and an 11% improvement in measurement accuracy. Moreover, the CBA shows that the initial investment has a payback period of 10 months and 26 days.

The findings highlight the importance of tailoring workflows for specific construction contexts and emphasize the potential of digitalization and automation technologies in revolutionizing traditional construction practices. The research presented in this article underscores the need for a systematic approach to mitigate uncertainties and enhance productivity in OSC. Moreover, the article outlines a flexible and implementable strategy for improving manufacturing processes in LGS-OSC projects.

CHAPTER 3

SYSTEMATIC LITERATURE REVIEW ON THE INTEGRATION OF DIGITAL FABRICATION, BIM AND OFF-SITE MANUFACTURING IN CONSTRUCTION - A RESEARCH ROAD MAP

A. Mehdipoor[1], I. Iordanova[1]

[1]Department of Construction Engineering, École de Technologie Supérieure, 1100 Notre-Dame Ouest, Montréal, Québec, Canada H3C 1K3

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3.1 Abstract

According to the scientific literature, 98% of megaprojects in the construction sector suffer from cost overruns of more than 30%. This is due to several reasons, the most important of which is issues with productivity (Changali, Mohammad et van Nieuwland, 2015). Off-site manufacturing in construction is one solution to increase productivity, but there is a current lack of studies linking it to the concept of design for manufacturing and assembly (Jin *et al.*, 2018a). Building information modelling (BIM) also offers new opportunities to underpin the computerized design and fabrication of industrialized buildings, providing greater productivity and cost-effectiveness (He *et al.*, 2021). The integration of BIM and off-site construction (OSC) could maximize their benefits to the construction industry and their applications are highly recommended to improve construction efficiency (Yin *et al.*, 2019). However, even if the relationship between BIM and off-site construction has been identified and discussed among pioneer researchers, gaps were found in the literature concerning the integration of BIM and digital fabrication with off-site manufacturing in construction. There has been insufficient research on integrating these practices. The aim of this literature review is to assess the current state of the combined use of digital fabrication, BIM, and OSM in the context of Construction 4.0. A bibliometric analysis was conducted to study the relationship between these practices. The contribution to the body of knowledge will be the outcome of this literature review

including an in-depth discussion of main trends in off-site construction, research gaps, and recommendations for near-future perspectives in off-site construction.

3.2 Introduction

According to the scientific literature, 98% of megaprojects in the construction sector suffer cost overruns of more than 30%. This is due to many reasons, the most important of which is issues with productivity (Changali, Mohammad et van Nieuwland, 2015). According to their report, construction productivity has been flat for decades while over the same period, it has doubled in manufacturing. This finding is also supported by the Mackinsey Global Institute, which reported that the construction industry has very low average profit margins compared to other sectors such as manufacturing (Mackinsey Global Institute, 2017).

Digital fabrication and off-site manufacturing in construction have recently become a prominent domain as they are seen as a potential response to the problems experienced by the industry. However, there have been very limited studies in this domain that link off-site manufacturing in construction to the concept of design for manufacturing and assembly (Jin *et al.*, 2018a).

The adoption of digital technology would be a way to increase productivity in construction. However, it is reported that the majority of construction automation research is related to the actual fabrication phase, and very little research has been done to develop technology in construction (Bowmaster & Rankin, 2019). According to the same authors, in Canada, hardly any research has been conducted on the application of automation and robotics in construction. The development and implementation of automation technology in construction has been slow due to the unavailability of suitable automation technology as well as effective and economical engineering technology for large and mega-scale projects (Ding, Wei et Che, 2014).

These technologies should be considered early, from the planning and design phases. Their integration within a BIM environment, connected to the IoT for real-time information, would make it possible to monitor the progress and performance of a project. This in turn could potentially improve overall productivity. BIM facilitates a wide range of building activities, such as the digital fabrication of different building components as well as building construction. It has been observed that BIM is helping to improve the performance of off-site manufacturing projects through its integrated management and cooperative behaviour (Tang, Chong et Zhang, 2019). The application of BIM in an OSC project can improve its efficiency. For example, the quality of the design in an OSC project can be improved by BIM-based generative design. In addition, efficiency in data sharing can be improved by cloud BIM-based data exchange (Yin *et al.*, 2019).

The aim of this literature review is to study the most up-to-date practices combining digital fabrication, building information modelling, and off-site manufacturing in construction. In the most recent studies, the application of BIM for OSC has been studied mainly in relation to design, data sharing, robotics and 3D printing for OSC. However, since this research is the initial phase of a project to develop a decision support system for BIM and OSM, key articles that discuss the process of decision-making in BIM and OSM have been included.

The objective of this work will be met by answering two research questions: a) What are the current research topics and trends regarding digital fabrication, BIM, and OSM in construction? b) What are the research gaps, needs, current activities, and opportunities for future research (research road map)? This literature review will contribute to the body of knowledge by providing in-depth discussions on the main trends in off-site construction and current research gaps and providing recommendations for near-future directions in off-site manufacturing. It is part of a larger research project to identify the key success factors to help improve construction efficiency through OSM.

3.3 Methodology

This study is the initial stage of a comprehensive research project related to the development of a BeDSS for digital fabrication in off-site manufacturing. In order to define the research focus, current studies related to BIM and OSM were investigated. The methodological approach of this study is based on a systematic literature review (SLR), which combines qualitative and quantitative methods, namely, a quantitative review by bibliometric approach and a qualitative review.

Bibliometric mapping is an important technique that visualizes the structural and dynamic aspects of scientific research (van Eck et Waltman, 2010). Eck and Waltman (2010) developed VOSviewer, a program that displays large bibliometric maps in an efficient way. This program is able to display a bibliometric map of authors or journals based on co-citation data or a map of keywords based on co-occurrence data (van Eck et Waltman, 2010). VOSviewer was utilized by Oraee et al. (2017) to conduct a bibliometric analysis to research the collaboration of BIM-based construction networks (Oraee *et al.*, 2017).

A bibliometric search of digital fabrication, BIM, and OSC was performed in Scopus, which was chosen as the search engine for this research. By reviewing previous studies such as (Bowmaster et Rankin, 2019b; Jin *et al.*, 2018a; Mengist, Soromessa et Legese, 2020; Oraee *et al.*, 2017; Yin *et al.*, 2019), the initial keywords were selected and all associated journal papers published in English between 2010 and 2020 were chosen.

Scopus provides downloadable data that can be imported into VOSviewer to generate bibliometric maps, such as a map of the network among publications (Jin *et al.*, 2018a).
Figure 3.1 shows the literature review analysis diagram on the application of BIM and digital fabrication in off-site manufacturing.

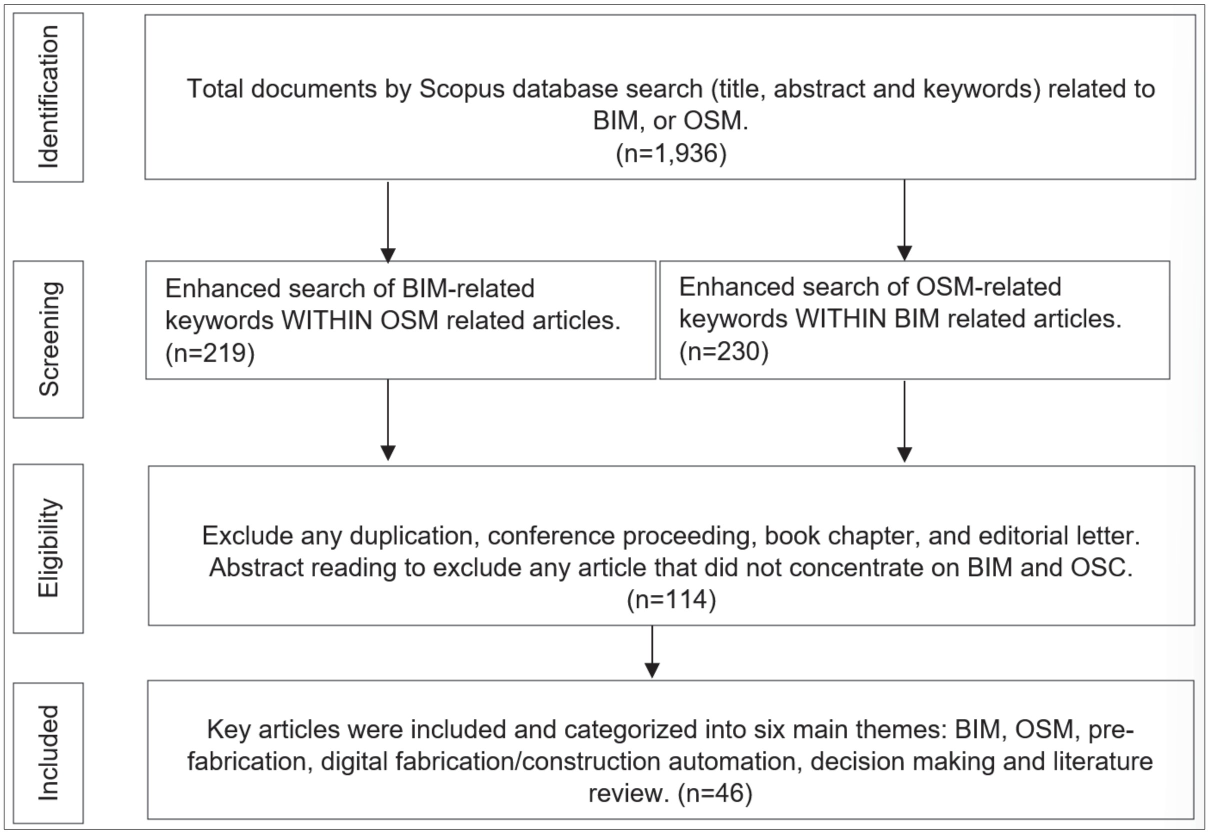

Figure 3.1 Literature review analysis diagram

The diagram in Figure 3.1, shows the initial OSM search, which was filtered by searching a BIM-related set of keywords within the initial search. The dataset will be used further, during the discussion of the qualitative method. By searching BIM within the initial search results, OSM within BIM's initial result and excluding any duplication, conference proceeding, book chapter, and editorial letter, the total number of related enhanced articles filtered to 219.

These articles have been used for a qualitative analysis to achieve the objective of this research. The systematic approach, including abstract reading and main body skim-reading to exclude non-related articles, limited the total number of key articles to 46 journal papers.

Table 3.1 Summary of key articles based on these research themes

Author	Year	Research Theme					
		BIM	OSM/OSC	Pre-Fabrication	Digital Fabrication /Construction Automation	Decision Making	Literature Review
He et al.	2021	√			√		
Wondimagegn Mengist	2020						√
Ala Nekouvaght Tak	2020	√	√	√		√	
Rui He	2020	√		√	√		
Shi An	2020	√	√	√	√	√	
M.F. Antwi-Afari	2020	√			√	√	
Sherif Abdelmageed	2020		√				√
Pablo Martinez	2019	√	√				
Xi Tang	2019	√	√				
Tsvetomila Duncheva	2019		√			√	
Xianfei Yin	2019	√	√				√
Xiao Li	2019	√		√			
A.Q. Gbadamosi	2019	√	√	√	√		
A.Q. Gbadamosi	2019	√				√	
Yingbo Ji	2019	√	√	√			
Jeremy Bowmaster	2019		√		√		√
Ibrahim Y. Wuni	2019		√	√		√	√
Yidnekachew T. Daget	2019			√		√	√
J. S. Goulding et al.	2019		√	√			
Lee et al.	2019	√			√		
Daget et al.	2019		√	√		√	
Liu et al.	2019	√	√	√	√		
Alwisy et al.	2019	√	√	√			
Liu et al.	2018	√	√	√		√	
Ruoyu Jin	2018		√				√
Bon-Gang Hwanga	2018			√		√	
M. Reza Hosseinia	2018		√				√
Hamid et al.	2018	√			√		

Table 3.1 Summary of key articles based on these research themes (continued)

Author	Year	Research Theme					
		BIM	OSM/OSC	Pre-Fabrication	Digital Fabrication /Construction Automation	Decision Making	Literature Review
Hwang et al.	2018		√	√		√	
Antwi-Afari et al.	2018	√				√	
Yuan et al.	2018	√	√	√			
Liu et al.	2017	√	√	√	√		
F.H. Abanda	2017	√	√				
Salama et al.	2017		√			√	
Singh et al.	2017	√	√	√			
Azadeh Fallahi	2016			√			
Liu et al.	2015	√					
Lieyun Ding	2014	√	√		√		
James T. O'Connor	2014		√	√		√	
Caneparo et al	2014		√	√	√		
Nawari O. Nawari,	2012	√	√	√			
Yingbo Ji	2010						√
Agkathidis et al.	2010		√	√	√		
Iwamoto	2009		√	√	√		
Jeoing et al.	2009	√	√				
Karner	2008	√	√	√			

The articles were categorized into six themes, namely: BIM, OSM/OSC, Prefabrication, Digital Fabrication/Construction Automation, Decision Making, and Literature Review. Table 3.1 shows the summary of 46 key articles categorized based on these research themes.

3.4 Quantitative Analysis

To identify publications related to BIM, a search in Scopus for articles from the year 2010 to 2021 (until December 13, 2020), was conducted. The set of keywords used in this search was: TITLE-ABS-KEY "BIM" OR ("Building Information Model") OR ("Building Information Modelling") OR ("VDC") OR ("Virtual design and construction").

The results of the above-mentioned initial search were then filtered to search OSM/OSC and Manufacturing within the BIM cluster. A total of 230 articles were selected as being the most related publications for further qualitative analysis. Figure 3.2 shows key journals related to OSC within BIM and the number of publications combined with these two topics during the years 2010-2020.

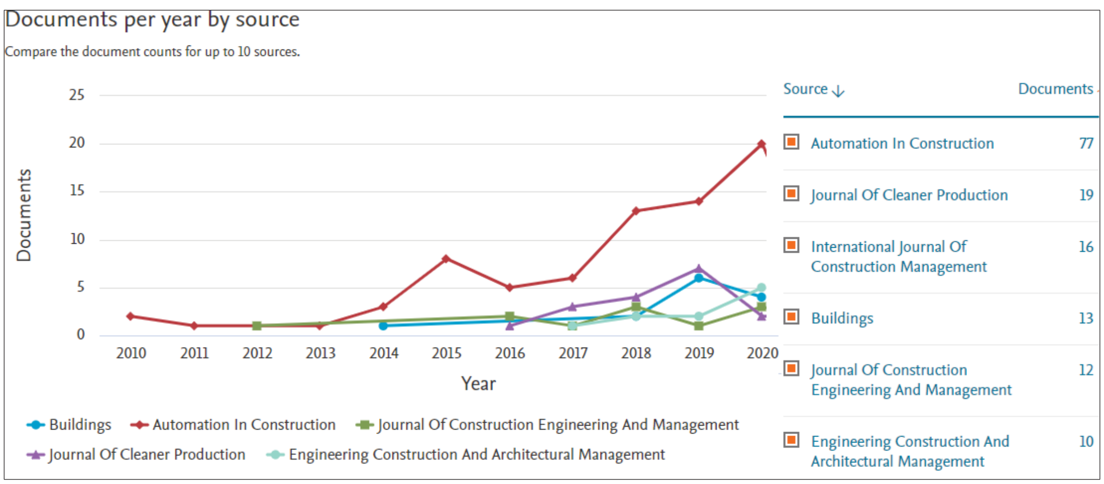

Figure 3.2 Key journals related to OSC within BIM

To identify pioneer researchers in OSM within BIM, a bibliometric analysis was conducted and the key authors in OSM/OSC related to BIM were identified. The following figure illustrates the result for authors with more than 5 publications in this domain.

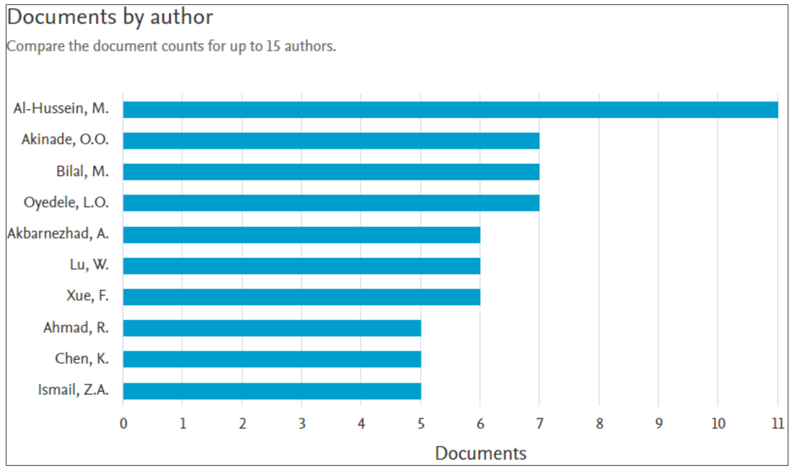

Figure 3.3 Authors with more than 5 publications

The following keywords were used in a bibliometric search in Scopus, to identify the related articles published from 2009 to 2020 (up to December 8, 2020). All non-related subject areas were excluded, and the search was limited to English articles only. The set of keywords used for the initial search is as follows:

TITLE-ABS-KEY("Off-Site Construction") OR ("Off site Construction") OR ("Offsite Construction") OR ("Off-site manufacture") OR ("Off-site manufacturing") OR ("Offsite manufactu*") OR ("Off site manufactu*") OR ("Off-site manufactu*")

Data was exported from Scopus to VOSViewer software for bibliometric analysis to identify related keywords in this domain. Figures 3.4 and 3.5 were generated by the software. Figure 3.4 shows the country mapping for OSC-related articles and Figure 3.5 shows the results for the keywords that occur more than 3 times. Country mapping for OSM/OSC determines the pioneering countries as well as direct and indirect relationships in terms of the information flow in this domain. As shown in Figure 3.4, the United Kingdom, Australia, China, Canada, and the United States are productive with direct and indirect relationships with each other.

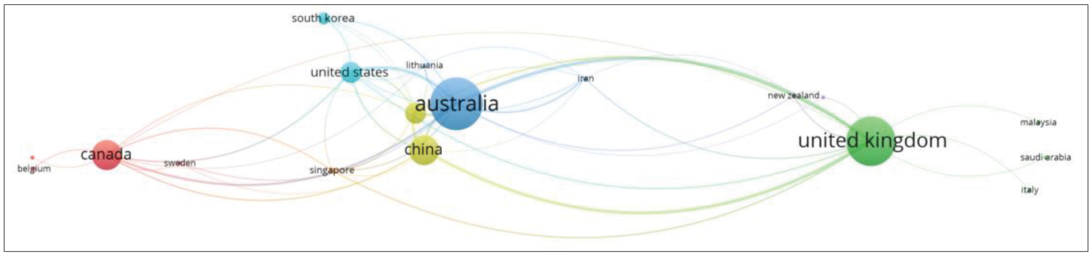

Figure 3.4 Country mapping

Table 3.2 Pioneer countries in publishing papers related to OSC

Country	Numbers of Article	Citations	Total link strength
Australia	29	476	131
United Kingdom	27	385	90
Canada	16	252	38
China	16	384	82
Hong Kong	11	241	69
United States	11	132	57
South Korea	6	55	9
Singapore	3	71	19

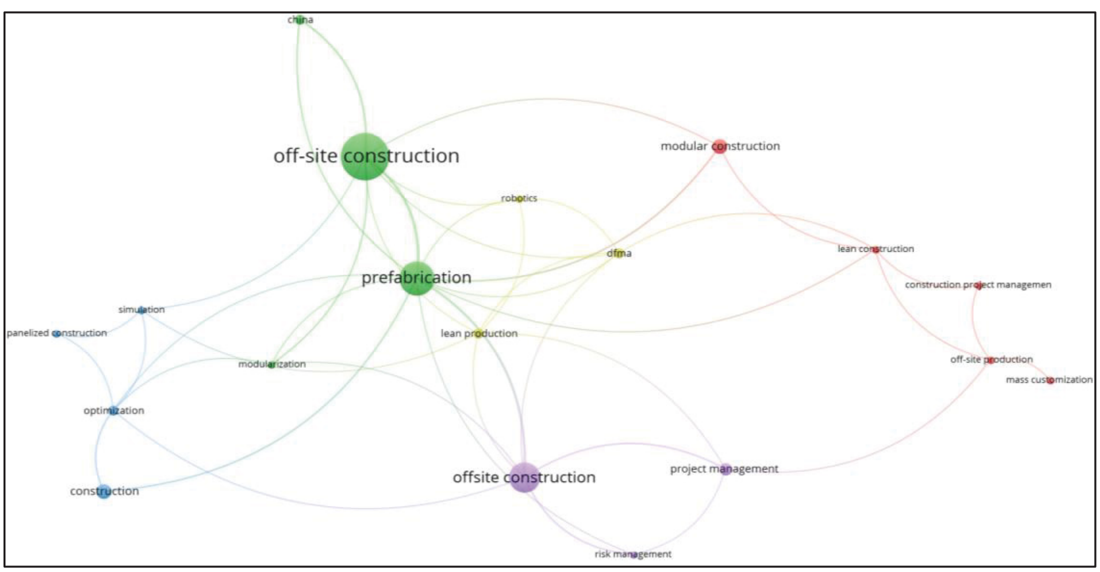

Figure 3.5 - Keywords map

Figure 3.5 maps the OSC keywords and shows that none of the BIM-related keywords such as Building Information Model, Building Information Modelling, or VDC appears in the keyword mapping. This is supported by Table 3.3, which shows OSC keywords that occur more than three times. Therefore, it can be concluded that there is a lack of integration between BIM, digital fabrication, and OSC. Each cluster is represented by a different colour. However, one specific keyword could appear in two different clusters due to a different spelling, for instance, "offsite construction" or "off-site construction".

Table 3.3 shows occurrences resulting in more than 3 times and total link strength in the OSC cluster. Off-site construction, prefabrication, and modular construction have a high link strength and this is also in line with results shown in Figure 3.5. The first four keywords in Table 3 were selected to identify the main papers for the qualitative analysis that is discussed in the following section.

Table 3.3 OSC keyword occurrences, more than 3 times in total

Keyword	Occurrences	Total link strength
Off-site construction, Offsite construction	34	27
Prefabrication	15	21
Off-site manufacturing, Off-site production	9	8
Modular construction, Modularization	9	9
Project management, Construction project management	8	7
Lean production, Lean construction	7	11
DFMA	4	6
Optimization	4	7
Mass customization	3	1
Panelized construction	3	2
Risk management	3	4
Robotics	3	4
Simulation	3	4

3.5 Qualitative Analysis

The qualitative analysis discussed in this study is part of an ongoing research project, which aims to identify critical success factors for the application of BIM and digital fabrication in OSM. Therefore, it is necessary to investigate and analyze the key articles in this domain to identify potential success factors. An analysis of keyword clusters in the domains of BIM and OSM helps to identify trends and the current status of the application of BIM and digital fabrication focusing on OSM. The classification of the research theme presented in Table 3.1 shows the direction and focus of each study based on the extracted keywords as well as the initial abstract reading. A keyword co-occurrence analysis could determine the core research focus in this domain (van Eck & Waltman, 2014). Figure 3.5 shows the direct and indirect relationships between keywords. Figure 3.5 is in accordance with Table 3.3, which shows that the integration of BIM and OSC has become more prominent during the past few years, mostly after the year 2016. In this section, the prominent research clusters identified by the bibliometric approach were qualitatively analyzed as discussed in the following subsection. In other words, quantitative and automatic keyword index clustering was combined with a qualitative analysis of the key publications based on all titles, abstracts and full paper sets.

3.6 Integration of BIM, Digital Fabrication and OSC

Selected key publications identified by the bibliometric approach were sorted by year of publication and then categorized into six research themes. All documents related to at least two of these themes were selected for more in-depth analysis. The main focus of the nominated articles was a integration of OSC and modern technologies such as BIM and digital fabrication in OSM. However, the pioneer scholars use different terminologies and approaches as we shall discuss below.

Off-site manufacturing is the process of manufacturing a construction project's component(s) at a location different from the final point of construction assembly (PCA). It involves the delivery of components to the PCA for installation at various stages of the project life cycle (Goulding et Rahimian, 2019a). In the literature, different terminologies describe off-site manufacturing i.e., OSC, modern method of construction (MMC), off-site production (OSP), and offsite prefabrication.

As stated by Lui et al. (2018), OSC integrates the application of modern technology and advanced machinery in a controlled facility at a location other than the final place of installation. The combination of manufacturing technologies and advanced machinery in prefabrication and OSM can increase efficiency (Liu *et al.*, 2018a). Moreover, the combination of Design for Manufacturing and Assembly (DFMA) with the parametric design of BIM can optimize design systems to be suitable for prefabricated buildings (Yuan, Sun et Wang, 2018).

Putting the accent on 'manufacturing', the Construction Industry Council defines off-site manufacturing as *"a delivery method that adds substantial value to a product and process through factory manufacture and assembly intervention*" (Abanda, Tah et Cheung, 2017). According to these authors, the main types of OSM are volumetric, hybrid, panellised, modular, and components & sub-assembly systems.

According to Agustí-Juan et al. (2017), the use of digital fabrication in OSM is a robotics-based production process using a computer-aided design (CAD) method (Agustí-Juan et Habert, 2017). This is further elabourated by Agkathidis (2010) who defines digital fabrication as a methodology of construction that is planned to be designed, manufactured, and assembled by utilizing digital tools (Agkathidis, 2010).

However, in order to transition from the traditional way of planning and onsite construction, advanced machinery for manufacturing such as computer-numeric-controlled (CNC) machines, need to understand data generated from drawings and BIM. Therefore, designers need to understand the process and interoperability between BIM and automated machinery to utilize digital fabrication in OSM (Iwamoto, 2009). Moreover, the industrial building system is a commonly used term in OSM and digital fabrication, especially in Asia. According to He et al. (2021), it is an innovative and advanced technology that shifts onsite traditional construction methodology to a controlled and factory-based location off-site, thereby improving productivity as well as efficiency in terms of production time (faster assembly), and thus reduced project cost (He *et al.*, 2021).

In automated construction systems, a widely used term is additive manufacturing (AM). AM can potentially be applied in the production of large structures in digital fabrication (Khoshnevis, 2004). It has been used in other sectors, such as automobile design, aerospace, and medical industries as well. However, as articulated by Ding et al. (2014), in the construction industry, the AM process is only suitable for small and medium-scale manufacturing parts due to limitations in delivering many kinds of building materials (Ding, Wei et Che, 2014).

Ding et al. (2014) introduced a new procedure for large-scale projects in AM techniques called BIM-based Automated Construction (BIMAC) in automated construction systems and digital fabrication. BIMAC integrates modern CAD, computer-aided manufacturing (CAM), Numerical Control (NC) technology, new material technology, and BIM to increase efficiency in AM for large-scale projects.

Melenbrink (2020) argued a gap between industry and academic research whereby academic proposals such as the BIMAC system concentrated on additive manufacturing or discrete assembly while industry efforts concentrated on automating conventional earthmoving equipment and embracing prefabrication (Melenbrink, Werfel et Menges, 2020).

There have been some efforts to increase automation in the construction sector but achieving full autonomy for the majority of construction tasks remains a thing of the distant future. Still, several important steps have been taken toward construction automation with the recent development of advanced machines designed for autonomous operation as well as a material-robot system for specific assembly tasks (Petersen *et al.*, 2019).

Ham and Lee (2019) studied the benefits of digital fabrication for construction management in terms of project management factors using the Project Management Body of Knowledge

(PMBOK). The study shows that the use of digital fabrication brings many advantages to the project. Some factors are considered challenges, such as cost reduction and control, but this does not mean that the use of digital fabrication is overall negative (Ham et Lee, 2019a).

Current literature explores the benefits and capabilities of optimizing construction efficiency by utilizing BIM and digital fabrication in OSM. Some of the important attributes noted to improve productivity are "ease of handling and assembly" as well as reducing the "weight of parts"(Gbadamosi *et al.*, 2019).

This can be supported by automation in construction and the use of robots for specific assembly tasks. On the other hand, BIM is capable of assisting designers in understanding design requirements for digital fabrication and robot-based assembly systems. Therefore, the integration of BIM, digital fabrication, and OSM is a way to improve construction efficiency and it is expected that future studies will investigate and develop a comprehensive system that integrates BIM and digital fabrication in OSC.

3.7 Conclusion and future work

This paper presents how the research on OSC and BIM has developed during the past decade. The study is crucial for understanding how to utilize BIM and digital fabrication in OSC and to provide research directions for further development in this domain. This research performs a systematic literature review, based on publications in BIM and OSC found in the Scopus database between 2010 and 2020. This review was limited to journal publications. Through the quantitative method, the bibliometric analysis approach deployed on BIM and OSC made it possible to establish the most recent subfields of study, namely, prefabrication, construction automation, and modular construction.

The dataset was then refined, and key publications related to the integration of BIM and OSM were selected for qualitative analysis. The classification of key articles into the following six main research themes, BIM, OSM/OSC, prefabrication, digital fabrication/construction automation, decision making, and literature review shows that there has been insufficient research on the integration of OSC, BIM, and digital fabrication.

Limited studies have been found linking BIM and digital fabrication for OSC in construction even though the benefits of BIM and digital fabrication in OSC were discussed by pioneer scholars and many studies during the past decade displayed the capability of BIM and digital fabrication in assisting the implementation of OSC activities such as planning, simulating, design evaluation, material processing, and manufacturing, transportation, and site assembly. Further research is needed to investigate what is required to integrate BIM, digital fabrication, and OSC. Aspects to be explored are interoperability and BIM design requirements for digital fabrication and its application to OSC, including identifying the uncertainties and differences between the latest academic research and current industry practices.

CHAPTER 4

IDENTIFICATION AND EVALUATION OF THE KEY DECISION SUPPORT FACTORS FOR SELECTING OFF-SITE CONSTRUCTION IN CANADA: A BUILDING INFORMATION MODELING (BIM)-ENABLED APPROACH

A. Mehdipoor[1], I. Iordanova[1], M. Al-Hussein[2]

[1]Department of Construction Engineering, École de Technologie Supérieure, 1100 Notre-Dame Ouest, Montréal, Québec, Canada H3C 1K3
[2] Department of Civil and Environmental Engineering, University of Alberta, Canada

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4.1 Abstract

The construction industry lags behind other sectors in terms of productivity performance, with many mega-projects experiencing cost overruns. While there are various reasons for this, the most significant one is the lack of efficiency. Adopting the off-site construction (OSC) methodology can improve productivity by enhancing project efficiency mainly in terms of time, cost and quality. Although OSC, off-site manufacturing (OSM), Industrialized Building System, prefabrication, modular, or other similar terms are not novel concepts, it is essential to shift any aspect of construction project activity from traditional onsite methods to a controlled, factory-based and manufacturing concept of production. Industrialization and digital fabrication have gained significant prominence in recent years, as they are perceived as viable solutions to the issues faced by the construction sector. As OSC is gradually gaining interest in building projects, it is crucial to identify and validate the key decision support factors (KDSFs) for selecting an appropriate OSC method from the early design stage. The purpose of this study is to identify, verify, and evaluate the KDSF for selecting OSC in Canada. This study utilized a mixed-methods design, comprising a systematic literature review (SLR) and pilot expert reviews through semi-structured interviews and surveys, to accomplish the research objectives and ensure the validity and reliability of the findings. Twelve interviews were conducted to validate and analyze the KDSFs, which were then prioritized using the mean score (MS) analysis and weighting function. Based on the research methodology, 32 KDSFs were validated and grouped into 7 ‘dimensions’. Further analysis concluded that the most important ‘dimension’ in selecting OSC for a building project in Canada is project time which consists of the design period, production time, mobilization and transfer time, as well as the assembly and construction periods.

Keywords: off-site construction, decision support system, success factors

4.2 Introduction

According to the scientific literature and industrial reports, many megaprojects suffer from cost overruns and delays (Van Vuuren, 2020; Jin *et al.*, 2018a). This is because of various reasons while poor productivity is the primary reason (Bertram *et al.*, 2019; Changali, Mohammad et van Nieuwland, 2015; de Laubier *et al.*, 2019). Moreover, the McKinsey Global Institute (2017) has also supported this finding, reporting that the construction sector has considerably lower average profit margins than other sectors. Bertram (Bertram *et al.*, 2019) suggested that shifting from traditional on-site construction methods to modular construction in Europe and North America could yield annual savings of up to $22 billion. Despite various factors causing the issue, adopting the construction (OSC) methodology has proven effective in enhancing efficiency in construction projects (Abdul Nabi et El-adaway, 2020). Various terminologies have been used to define the concepts of offsite construction.

Off-site Construction refers to a construction method that involves bringing on-site construction work to a controlled facility, where advanced machinery and manufacturing technologies are used to prefabricate buildings in a standardized and efficient manner (Liu *et al.*, 2017). OSC is a popular term in current use that refers to the preparation, design, fabrication, and assembly of building elements at a location other than their final installation plan to expedite and improve efficiency in the construction of a permanent structure.

In other words, OSC is to move the traditional on-site process to an industrial manufacturing environment.

Off-site manufacturing (OSM) is defined by the Construction Industry Council (CIC) (Kier Construction, 2018) as a delivery method that adds value to a product and process through factory manufacture and assembly intervention, with a focus on manufacturing. The main types of OSM include penalized, volumetric, hybrid, modular systems, and component and sub-assembly systems (Abanda, Tah et Cheung, 2017). Recently, digital fabrication and OSM have gained prominence in the construction industry as potential solutions to its problems (Wang *et al.*, 2020). However, there is a lack of research in this domain that links OSC to the concept of design for manufacturing and assembly (DfMA) (Jin *et al.*, 2018a).

While digital technology adoption can increase productivity in construction, research on construction automation is primarily related to the actual fabrication phase, and little attention has been given to technology development in construction (Bowmaster et Rankin, 2019a). In Canada, there has been limited research on the application of automation and robotics in construction, as automation technology for large-scale projects has been slow to develop and implement due to engineering constraints and the limited availability of suitable automation technology (Ding, Wei et Che, 2014).

The integration of these technologies should be considered from the planning and design phase, with a focus on their integration into a BIM environment and connection to IoT for real-time performance information (Tang, Chong et Zhang, 2019). A study was carried out in 2020 investigating the impact of digitalization technologies on productivity by examining case studies in Germany's building construction industry (Berlak, Hafner et Kuppelwieser, 2021). The study suggests that while companies may perceive the effects of digitalization as a mere platitude and a goal for manufacturers, it is crucial to consider user acceptance as a key factor in generating productivity improvements through the implementation of digitalization technologies.

Among various construction methods and technologies, selecting an appropriate concept is a challenging task. Decision-makers are required to consider different aspects and relevant factors to select a proper construction method. Therefore the process of selecting a suitable construction methodology is a multi-attribute and multi-objective process (Attouri, Lafhaj, Ducoulombier et Linéatte, 2022a).

As far as this research is concerned, validation and evaluation of the Key Decision Support Factors (KDSF) for OSC projects in Canada is yet to be established. Thus, the objective of this research is to identify, validate, evaluate and develop a systematic roadmap for relevant factors to select the proper construction methodology for building projects in Canada. The research aims to accomplish the following objectives:

- To identify, introduce, validate and evaluate KDSF for OSC projects in Canada
- To assess, analyze and rank the most relevant KDSF for OSC projects in Canada
- To define a roadmap through the development of a decision support system for OSC projects in Canada.

This research forms part of a Ph.D. project to develop a two-stage BIM-enabled Decision Support System for the selection of a suitable Industrialized Building System. The development of the proposed Decision Support System (DSS) involves two main aspects: 1) Identifying and evaluating Key Decision Support Factors (KDSF) for selecting the appropriate OSC approach, and 2) using a ranking system to choose the most suitable approach for a building project.

The outcome of this project will contribute to the body of knowledge by conducting an in-depth discussion of main trends in Off-site Construction, research gaps, and recommendations for near-future direction in Off-site Manufacturing. This research will identify the key success factors to improve construction efficiency through OSM. The findings of this research will form the first stage of qualitative and quantitative evaluation of KDSF for OSC projects in Canada.

For theoretical purposes, this research will constitute a comprehensive checklist of the most relevant factors tor for selecting OSC in building projects in Canada. In addition to theory, this project will contribute to the practice and managerial purposes by facilitating a roadmap to a better decision-support process in OSC projects in Canada.

4.2.1 Research background of OSC and Key Decision Support Factors (KDSF) for OSC projects

Effective decision-making plays a crucial role in the construction industry, and the utilization of computer technology can enhance the quality and efficiency of building projects (Marcher, Giusti et Matt, 2020). The significance of decision-making becomes prominent in a building project due to the variety and complexity of different techniques, technologies, and methods in the planning, designing, manufacturing and construction phase. The initial stage of this project is the identification of potential decision support factors for OSC by investigating the characteristics of prefabricated and modular Off-site Construction from the previous study.

Available research work studied different terminologies and related technologies integrated with OSC methodology. Previous studies used modern method of construction (MMC), Off-site production (OSP), and Off-site prefabrication (OSF) (Wang *et al.*, 2020; Rahman, 2014; Pan, Gibb et R.J. Dainty, 2007; Abu Hammad *et al.*, 2008; Hwang, Shan et Looi, 2018). Eventually, pioneer researchers introduced the integration of Automation, Digital Fabrication, Building Information Modelling and DMfA toward OSC project success. Prefabrication is the production of building components at a specialized facility, in a controlled environment, where different materials are assembled to create elements for the final installation on the project site. Contractors could benefit from the prefabrication method for fast-track projects which contains an extremely short schedule and complicated processes (Tatun *et al.*, 1987). The prefabrication method would reduce the overall project duration since on-site and off-site processes are carried out simultaneously (Lee *et al.*, 2019).

The United Kingdom (UK) government used the term modern method of construction (MMC) to describe a range of innovative techniques in housing construction, with many involving off-site technology that shifts the production process from the construction site to a factory (Gibb, 1999; Pan, Gibb et R.J. Dainty, 2007; Rahman, 2014). The terms Off-site Construction, Off-site manufacturing, and Off-site production (OSP) are often used interchangeably to describe a construction process that takes place away from the actual building site, such as a factory or production facility located close to the construction site (Blismas *et al.*, 2005).

Off-site prefabrication (OSF) refers to a process that involves the design and manufacture of units and modules, typically in a remote location, which is then assembled on-site as part of the final installation process (Gibb et Isack, 2003). Previous research has explored the decision-making factors related to OSC. The Off-site Construction approach during the initial design phase of a project can encourage all team members to adopt an "Off-site" mindset, which is crucial for project success (Attouri, Lafhaj, Ducoulombier et Lineatte, 2022).

Moreover, the selection of a proper IBS to improve project performance and building quality has increased recently (Daget et Zhang, 2019). There have been many types of IBS accessible in the market however there is a need to develop a comprehensive decision-making tool which assists decision-makers in making a quick and reliable choice during the early design stage (Attouri, Lafhaj, Ducoulombier et Linéatte, 2022a; Daget et Zhang, 2019). Decision-making factors related to the Off-site Construction domain were discussed by previous researchers. Wuni (Wuni et Shen, 2019) identified the top 5 decision-making factors in the selection of modular integrated construction (MiC) consisting of available skilled workers and management, project timeline, transportation, limitation in size and equipment availability.

4.3 Research methods and approach

The research adopted a mixed research method consisting of quantitative and qualitative research design. The mixed research methods have been used by previous researchers which allow interrogation and triangulation of data (Attouri, Lafhaj, Ducoulombier et Linéatte, 2022a). The technical know-how, opinion and experience of local experts constructed the basis for the validation and evaluation of data for this research. The significance of the KDSF is based on the value assigned to each criterion by local experts. Systematic Literature Review (SLR) as the first stage of the overall multistage methodological framework was adopted. Figure 4.1 shows the multistage methodological approach for this research.

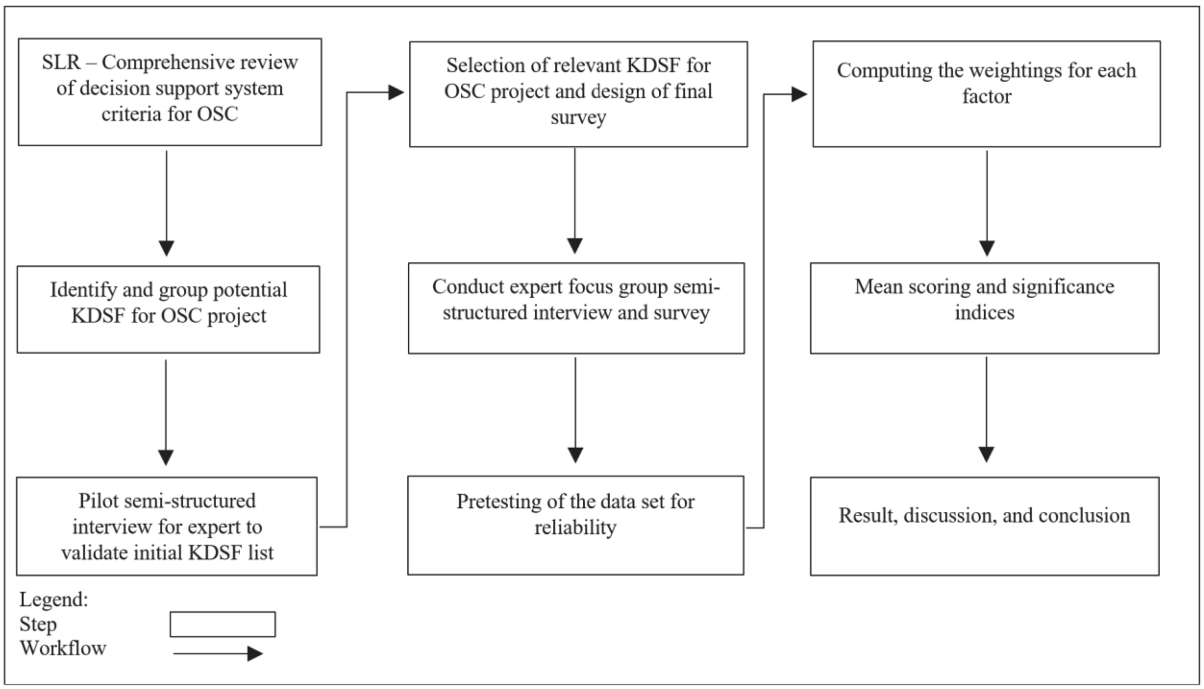

Figure 4.1 Multistage methodological approach

The main research focus was defined by investigating previous key studies related to OSC, BIM and Decision Making in OSC including a bibliometric approach and qualitative review. The Scopus database was used for the bibliometric approach. Compared with other databases the Scopus database is a better choice for sub-domains of digital fabrication, BIM, Decision Making, and OSC by covering a wider range of publications related to construction (Yin *et al.*, 2019). Scopus was preferred as well by Ruon Jin (Jin *et al.*, 2018a) as the search engine in the domain of construction compared to other databases such as Web of Science.

In the domain of bibliometric methodology, the technique of bibliometric mapping is a significant tool for visualizing the structural and dynamic features of scientific research.

VOSviewer is a program designed to efficiently display large bibliometric maps. It has the capability to produce a bibliometric map of authors or journals based on co-citation data, or a map of keywords based on co-occurrence data (van Eck et Waltman, 2010).

In collabouration with BIM-based construction networks, Oraee (Oraee *et al.*, 2017) employed VOSviewer for the purpose of bibliometric analysis. The current study conducted a bibliometric search on the topics of digital fabrication, BIM, and OSC using Scopus as the chosen search engine. The initial keywords were selected based on a review of prior research, including studies by Bowmaster (Bowmaster et Rankin, 2019a), Jin (Jin *et al.*, 2018a), Mengist (Mengist, Soromessa et Legese, 2020), Oraee (Oraee *et al.*, 2017), and Yin (Yin *et al.*, 2019), and all relevant English-language journal articles published from 2010 to 2020 were included in the analysis. The bibliometric data obtained from Scopus was imported into VOSviewer to generate network maps of the publications (Bowmaster et Rankin, 2019b; Jin *et al.*, 2018a; Mengist, Soromessa et Legese, 2020; Oraee *et al.*, 2017; Yin *et al.*, 2019). Figure 4.2 shows the SLR process applied in this research and Table 4.1 shows the Dimensions and Key Decision Support Factors for selection of OSC approach identified through SLR and expert interviews.

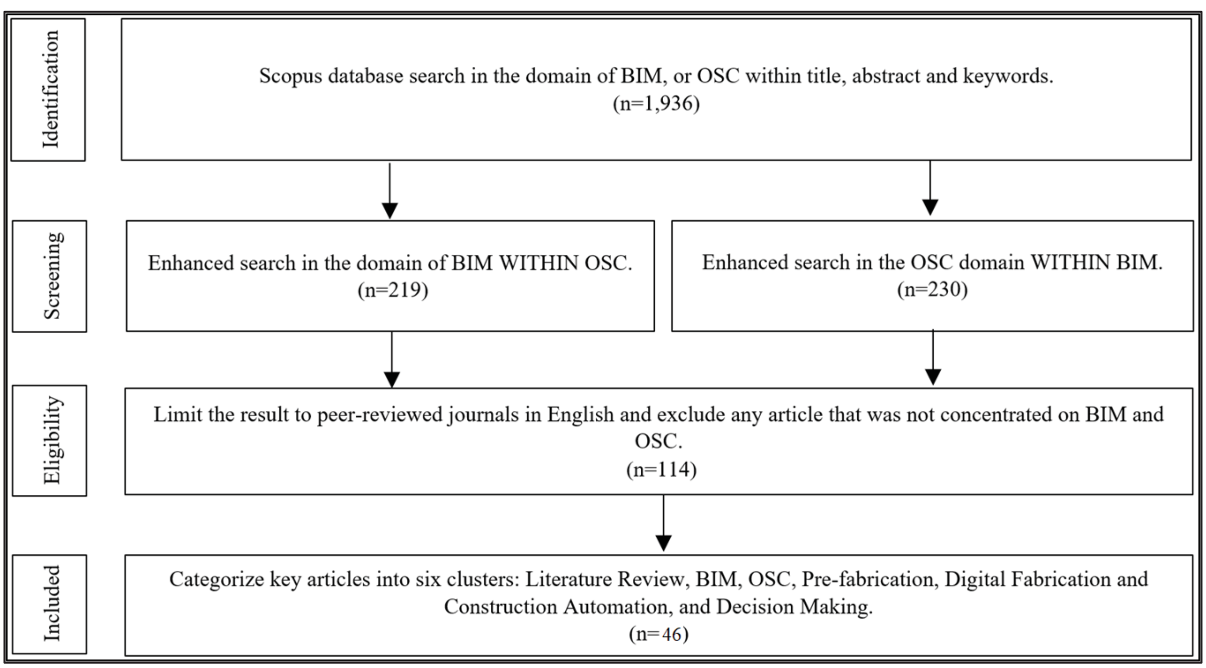

Figure 4.2 SLR process

The first step of SLR applied to this research is the initial search conducted within the database in the OSC domain, which was refined by using a set of BIM-related keywords. This dataset was utilized for in-depth discussion during the qualitative phase of the research. By searching for BIM-related keywords within the initial search results, OSC within the BIM-related results, and eliminating any duplicate, conference proceedings, book chapters, and editorial letters, the total number of relevant key articles was filtered down to 219.

These key articles were analyzed qualitatively which will be discussed in the discussion section. To narrow down the focus, a systematic approach was employed which involved reading the abstracts and skimming the main body of each article to exclude any irrelevant publications. This resulted in a total of 46 key journal papers for further analysis.

The main focus of the selected articles is the integration of OSC with modern technologies such as BIM and digital fabrication. However, there are various terminologies and approaches discussed by the leading scholars in the field, as outlined below.

Off-site manufacturing involves the production of components for a construction project at a location other than the final point of assembly. These components are delivered to the assembly location at various stages of the project's life cycle for installation (Goulding et Rahimian, 2019a). The literature uses different terms to describe off-site manufacturing, including Off-site Construction, modern methods of construction (MMC), off-site production (OSP), and off-site prefabrication.

OSC involves the integration of modern technologies and advanced machinery within a controlled facility. The combination of manufacturing technologies and advanced machinery in prefabrication and OSM can enhance (Liu *et al.*, 2018a). The Construction Industry Council (CIC) defines off-site manufacturing as "*a delivery method that adds substantial value to a product and process through factory manufacture and assembly intervention*."

CIC emphasizes the importance of manufacturing and defines off-site manufacturing as a delivery method that provides significant value to a product. According to these authors, the main types of OSC include volumetric, hybrid, panelized, modular system, and components & sub-assembly systems.

Digital fabrication in Off-site manufacturing is a production process that relies on robotics and Computer-Aided Design (CAD) techniques (Agustí-Juan et Habert, 2017). Digital fabrication can be defined as a construction methodology that involves designing, manufacturing, and assembling structures using digital tools (Agkathidis, 2010).

However, to transition from traditional planning and On-site construction to digitalized and automated OSC, advanced machinery such as computer-numeric-controlled (CNC) machines must interpret data generated from drawings and Building Information Modeling. Therefore, it is imperative for designers to comprehend the process and interoperability between BIM and automated machinery to utilize digital fabrication in OSM (Iwamoto, 2009).

Table 4.1 Dimensions and key decision support factors for selection of OSC

Dimension (D)	Factor's label	Key Decision Support Factors (KDSF)	Reference
Project characteristics (D1)	F1	Size	[1] [2] [3] [4] [5] [6]
	F2	Material	[1] [4] [5] [7]
	F3	Location	[1] [2] [4] [7]
	F4	Design complexity	[2] [3] [7]
	F5	Design flexibility	[1] [2] [3] [4]
Supply chain (D2)	F6	Financing	Expert interview
	F7	Available Manufacturer	[1] [2] [3] [4]
	F8	Raw material	[2] [3] [4]
	F9	Equipment	[1] [2] [3] [4]
	F10	Software	[2] [4]
	F11	Experts and skilled worker	[8] [2] [3] [4] [5]
Time (D3)	F12	Design period	[1]
	F13	Production time	[8]
	F14	Mobilization & transfer time	[1] [8] [3] [4]
	F15	Assembly & construction period	[1] [4]
Cost (D4)	F16	Design	[1] [2] [3] [4] [5]
	F17	Material	[1] [2] [3] [4] [5]
	F18	Production & Manufacturing	[8] [2] [3] [4]
	F19	Logistic	[8] [2] [4]
	F20	Assembly & construction	[2] [3] [4] [5]
	F21	Management	[2] [3] [4] [7]
	F22	Maintenance	[4] [7]
Quality (D5)	F23	DfMA + Disassembly	[8] [5]
	F24	Defect liability period	[2] [3]
	F25	Standards and protocols	[8] [3] [4] [5]
	F26	Sustainability (Carbon emission, Energy consumption, waste)	[2] [4] [7]
	F27	Construction safety	[2] [4]
Procurement (D6)	F28	Type of procurement & delivery method	[8] [4]
	F29	Number of tenderers	[8]
Socio-Cultural (D7)	F30	Lack of awareness among all stakeholders	[5]
	F31	Cultural resistance	[7]
	F32	Local authority regulation (Workers Union-Syndicat)	Expert interview
[1] FALLAHI et al., (2016), [2] HWANG et al., (2018), [3] WUNI et al., (2019), [4] DAGET et al., (2019), [5] HWANG, (2018), [6] FALLAHI, (2016), [7] YANG et al. (2013), [8] DUNCHEVA et al., (2019).			

Moreover, Industrial Building System is a frequently used term in OSC and digital fabrication, particularly in Asia. IBS is an innovative and advanced technology that shifts traditional On-site construction methodologies to a controlled factory-based location off-site. This approach increases productivity, and efficiency, reduces production time, accelerates assembly, and improves cost-effectiveness in projects (He *et al.*, 2021).

Additive Manufacturing (AM) is a common term in automated construction systems that has the potential to manufacture large structures in digital fabrication (Khoshnevis, 2004). Although AM has been successfully employed in other sectors such as automotive design, aerospace, and medical industries, Ding (Ding, Wei et Che, 2014) argued that in the construction industry, AM processes are only suitable for small and medium-scale manufacturing due to the challenge of delivering various kind of building materials.

BIM-based Automated Construction (BIMAC) in automated construction systems and digital fabrication is a new approach for large-scale AM projects. BIMAC integrates modern Computer-Aided Design (CAD), Computer-Aided Manufacturing (CAM), Numerical Control (NC) technology, new material technology, and Building Information Modeling to enhance the efficiency of AM for large-scale projects (Ding, Wei et Che, 2014).

However, there is a gap between industry and academia for the integration of OSC and digital fabrication. While academic proposals BIMAC system have emphasized additive manufacturing or discrete assembly, industry efforts have primarily focused on automating conventional earthmoving equipment and adopting pre-fabrication techniques (Melenbrink, Werfel et Menges, 2020). Therefore, it is necessary to develop and decision support system, able to integrate with BIM and other above-mentioned technologies, to assist a decision maker for the selection of proper IBS for OSC building projects.

4.4 Validation and Evaluation of Key Decision Support Factors (KDSF)

After completing a systematic literature review and administering a pilot study, the KDSF affecting the decision-making process in Off-site Construction, listed in Table 3.1, were validated by industry experts through semi-structured interviews. The semi-structured interview approach is considered an efficient practice in identifying relevant decision-making or support factors for OSC projects (Attouri, Lafhaj, Ducoulombier et Lineatte, 2022).

Moreover, to evaluate the importance of each factor, the experts were asked to indicate the importance of each criterion using a Likert scale from 1 to 5 (i.e., 1= least critical, 2= fairly critical, 3= critical, 4= very critical, and 5= extremely critical). This method is one of the most widely used survey instruments for data collection from experts' points of view in the construction management domain (Hosseini *et al.*, 2018; Wuni, Shen et Osei-Kyei, 2020).

Due to the lack of a central database for Off-site Construction experts, non-probability sampling methods using judgment/purposive sampling were used. This sampling method has been commonly used in expert surveys (Attouri, Lafhaj, Ducoulombier et Linéatte, 2022a; Wuni, Shen et Osei-Kyei, 2021). The identified factors were verified during semi-structured interviews. The interviews were conducted virtually using video conference and in person with 12 experts from different sectors in construction, such as architects, project managers, construction managers, mechanical and electrical engineers, structural engineers, and manufacturers, to ensure that different stakeholders' viewpoints were considered. All the experts possessed a minimum of 5 years and a maximum of 35 years of working experience in the construction industry.

Moreover, they were currently engaged in at least 3 different projects related to OSC and had up to 15 years of experience in Prefabricated and OSC projects. Although the number of participants was small due to the limitation of the scope of work that only included experts in Canada, it is considered an acceptable number since it is more than previous key studies that discussed relevant success and failure factors in OSC in Canada.

Wuni (Wuni, Shen et Osei-Kyei, 2021) evaluated the critical success factor for prefabricated prefinished volumetric construction projects internationally, while there were only 8 responses from Canada. Attouri (Attouri, Lafhaj, Ducoulombier et Linéatte, 2022a) conducted 10 semi-structured interviews to ensure the validity and reliability of the project's findings for decision-making factors in OSC. Another study by Wuni (Wuni, Shen et Osei-Kyei, 2020) on evaluating the critical failure factors for implementing modular projects is based on a total of 18 experts for North America. Therefore, in our opinion, the sample of this project, although small, is deemed adequate for analysis.

4.5 Data Analysis

The Statistical Package for the Social Science (IBM SPSS v.25) was employed to analyze the dataset. The reliability of both the data and survey instrument was evaluated using Cronbach's Alpha. To assess the internal consistency of the responses, Tavakol and Dennick (Tavakol et Dennick, 2011) recommended using Cronbach's alpha, which ranges from 0 to 1. An acceptable level of reliability is indicated by a Cronbach's alpha value of 0.7, where 0 represents no reliability and 1 indicates complete reliability (Tavakol et Dennick, 2011). The level of reliability corresponding to the alpha value is presented in Table 4.2.

Table 4.2 Level of reliability based on Cronbach's alpha

Cronbach’s alpha value	Internal Consistency
0.9 and above	Excellent
0.80 – 0.89	Highly reliable
0.70 – 0.79	Acceptable
0.60 – 0.69	Questionable
0.50 – 0.59	Poor
Below 0.50	Unacceptable

This DSR process includes six steps: problem identification and motivation, definition of the objectives for a solution, design and development, demonstration, evaluation, and communication. In this chapter, the different steps of the DSR methodology are explained in the context of this research.

The analysis generated a Cronbach's alpha value of 0.825 which is higher than the acceptable threshold and considered as highly reliable data set. Table 4.3 shows the variable and internal consistency value according to Cronbach's Alpha equation 4.1:

$$\alpha = \frac{K}{K-1}\left[1 - \frac{\sum S^2 y}{S^2 x}\right] \tag{4.1}$$

Table 4.3 Internal consistency

Variable	Description	Value	Internal Consistency
K	Number of KDSF	32	**0.825**
$\sum S^2 y$	Sum of each KDSF's variance	26.71	
$S^2 x$	Variance of sum of KDSF's value	132.90	

4.5.1 Mean scoring and ranking of Key Decision Support Factors (KDSF) for Off-site Construction projects

The Statistical mean scoring is widely used in the construction management domain to evaluate and rank performance indicators (Wuni, Shen et Osei-Kyei, 2020; Hussain *et al.*, 2017; Attouri, Lafhaj, Ducoulombier et Linéatte, 2022a). Mean score (MS), and standard deviation (SD) of each KDSF computed to assess the level of importance and the ranked factors are shown in Table 4.4.

$$\text{MS} = \frac{\sum(s \times f)}{n}, 1 \leq \mu \leq 5 \tag{4.2}$$

Mean score of KDSF was computed using equation 4.2 where MS = mean index of a KDSF, f = frequency of each rating (1-5) for each factor, S = score assigned to each factor by an expert using a scale system of 1 to 5, and n = total number of experts. In case of having two or more factors with sane MS (i.e. D2F10 Supply chain – Software and D2F11 Supply chain – Experts and skilled workers) the one with lower SD is considered to be more important. Table 4.4 shows the overall ranking for each KDSF based on the mean score and standard deviation in its relevant dimension.

Table 4.4 KDSF ranking (MS score)

KDSF	Dimension	MS	SD	Rank	KDSF	Dimension	MS	SD	Rank
F15	D3	4.75	0.45	1	F1	D1	3.67	1.15	17
F5	D1	4.50	0.41	2	F18	D4	3.67	0.98	18
F14	D3	4.50	0.45	3	F19	D4	3.58	1.08	19
F10	D2	4.42	0.67	4	F31	D7	3.58	0.79	20
F11	D2	4.42	0.70	5	F29	D6	3.42	1.24	21
F23	D5	4.42	0.72	6	F32	D7	3.42	1.08	22
F27	D5	4.42	0.79	7	F21	D4	3.25	0.97	23
F4	D1	4.33	0.65	8	F3	D1	3.08	1.31	24
F6	D2	4.25	0.75	9	F17	D4	3.08	1.42	25
F30	D7	4.25	0.77	10	F8	D2	3.00	1.13	26
F12	D3	4.17	0.83	11	F2	D1	2.83	0.72	27
F26	D5	4.08	0.90	12	F24	D5	2.83	0.83	28
F13	D3	4.00	1.13	13	F9	D2	2.50	1.38	29
F25	D5	4.00	1.28	14	F22	D4	2.50	1.00	30
F28	D6	3.92	0.79	15	F16	D4	2.17	1.11	31
F20	D4	3.75	0.87	16	F7	D2	1.83	1.03	32

The highest MS is for the F15D3 which is Time-related Dimension (D3) – Assembly & Construction Period (F15). Furthermore, the Time-related Dimension (D3) consisting of F6, F7 to F11 with an MS of 4.35 ranked first and was considered the most important dimension in the decision support process in the OSC project. Table 4.5 shows the result of the MS calculation for each dimension to determine its ranking.

Table 4.5 Dimension ranking (MS approach)

Dimension	Factors	Dimension MS	Dimension Rank
D1 – Project Characteristics	F1 – Size F2 – Material F3 – Location F4 – Design complexity F5 – Design flexibility	3.68	4
D2 – Supply chain	F6 – Financing F7 – Manufacturer F8 – Raw material F9 – Equipment F10 – Software F11 – Expert & skilled worker	3.40	6
D3 – Time	F12 – Design period F13 – Production time F14 – Mobilization transfer time F15 – Assembly & construction period	4.35	1
D4 – Cost	F16 – Design F17 – Material F18 – Production & Manufacturing F19 – Logistic F20 – Assembly & Construction F21 – Management F22 – Maintenance	3.14	7

Table 4.5 Dimension ranking (MS approach) (continued)

Dimension	Factors	Dimension MS	Dimension Rank
D5 – Quality	F23 – DfMA + Disassembly F24 – Defect liability period F25 – Standard and protocols F26 – Sustainability (Carbon emission & waste) F27 – Construction safety	3.95	2
D6 – Procurement	F28 – Type of procurement & delivery method F29 – Number of tenderers	3.67	5
D7 – Socio – Cultural	F30 – Lack of awareness among all stakeholders F31 – Cultural resistance F32 – Local Authority regulation	3.75	3

4.5.2 Sample Grouping and One-way Analysis of Variance

The dataset set was grouped to test whether significant differences exist among more than two groups of experts (Ostertagová et Ostertag, 2013). 12 experts were grouped into 3 categories i.e. Group A: Management such as project manager and construction manager, Group B: Manufacturer/Supplier/General Contractor and Group C: Design team such as Architect and Engineer. One-way Analysis of Variance (ANOVA) approach was carried out to test the significant difference. Furthermore, to test the consistency of the three different groups of respondents ANOVA was used. If a significant value is greater than 0.05, then there is no difference among the three different groups. Contrarily, a significant value of less than 0.05 recommends a high degree of difference in the expert's opinion (Hussain *et al.*, 2017). IBM SPSS v.25 was used to compute the P-value. In one-way ANOVA, the P-value is used to determine if the null hypothesis (H_0) is accepted or rejected (Kim, 2017). The null hypothesis assumed there was no significant difference among the three categories of respondents.

If the P-value is greater than 0.05, then the null hypothesis is true. Table 4.6 shows the grouping and P-value in one-way ANOVA.

Table 4.6 Group of respondent and One-way ANOVA analysis

Dimension	Factors	Mean Score (MS)			Total MS	Total SD	*Single Dimension P – Value*
		Group A	Group B	Group C			
D1	F1	4.0	4.0	3.2	3.67	1.15	**0.37**
	F2	2.5	3.0	3	2.83	0.72	
	F3	2.8	4.0	2.8	3.08	1.31	
	F4	4.0	4.7	4.4	4.33	0.65	
	F5	3.8	5.0	4.8	4.50	0.80	
D2	F6	4.0	4.7	4.2	4.25	0.75	**0.67**
	F7	2.5	2.0	1.2	1.83	1.03	
	F8	3.3	3.7	2.4	3.00	1.13	
	F9	2.3	3.0	2.4	2.50	1.38	
	F10	4.0	4.7	4.6	4.42	0.67	
	F11	4.3	4.7	4.4	4.42	0.67	
D3	F12	3.8	4.3	4.4	4.17	0.83	***0.20***
	F13	3.3	4.7	4.2	4.00	1.13	
	F14	4.5	4.7	4.4	4.50	0.67	
	F15	4.8	5.0	4.6	4.75	0.45	
D4	F16	1.3	2.0	3	2.17	1.11	**0.42**
	F17	2.0	4.0	3.4	3.08	1.16	
	F18	3.5	4.0	3.6	3.67	0.98	
	F19	3.8	3.7	3.4	3.58	1.08	
	F20	4.0	4.3	3.2	3.75	0.87	
	F21	4.0	3.3	2.6	3.25	0.97	
	F22	2.3	3.3	2.2	2.50	1.00	
D5	F23	4.8	4.3	4.2	4.42	0.67	**0.36**
	F24	2.5	3.3	2.8	2.83	0.83	
	F25	4.5	4.0	3.6	4.00	1.28	
	F26	4.3	4.3	3.8	4.08	0.90	
	F27	5.0	5.0	3.6	4.42	0.79	
D6	F28	4.8	3.7	3.4	3.92	0.79	**0.58**
	F29	3.3	4.0	3.2	3.42	1.24	
D7	F30	4.8	3.7	4.2	4.25	0.75	**0.26**
	F31	4.0	3.3	3.4	3.58	0.79	
	F32	3.8	3.7	3	3.42	1,08	
Overall P – Value							**0.10**

4.6 Discussion and research finding

The seven dimensions and their associated factors were used to develop a conceptual framework for decision support systems in OSC projects. Figure 4.3 shows the proposed framework of a decision support system based on key factors in OSC projects.

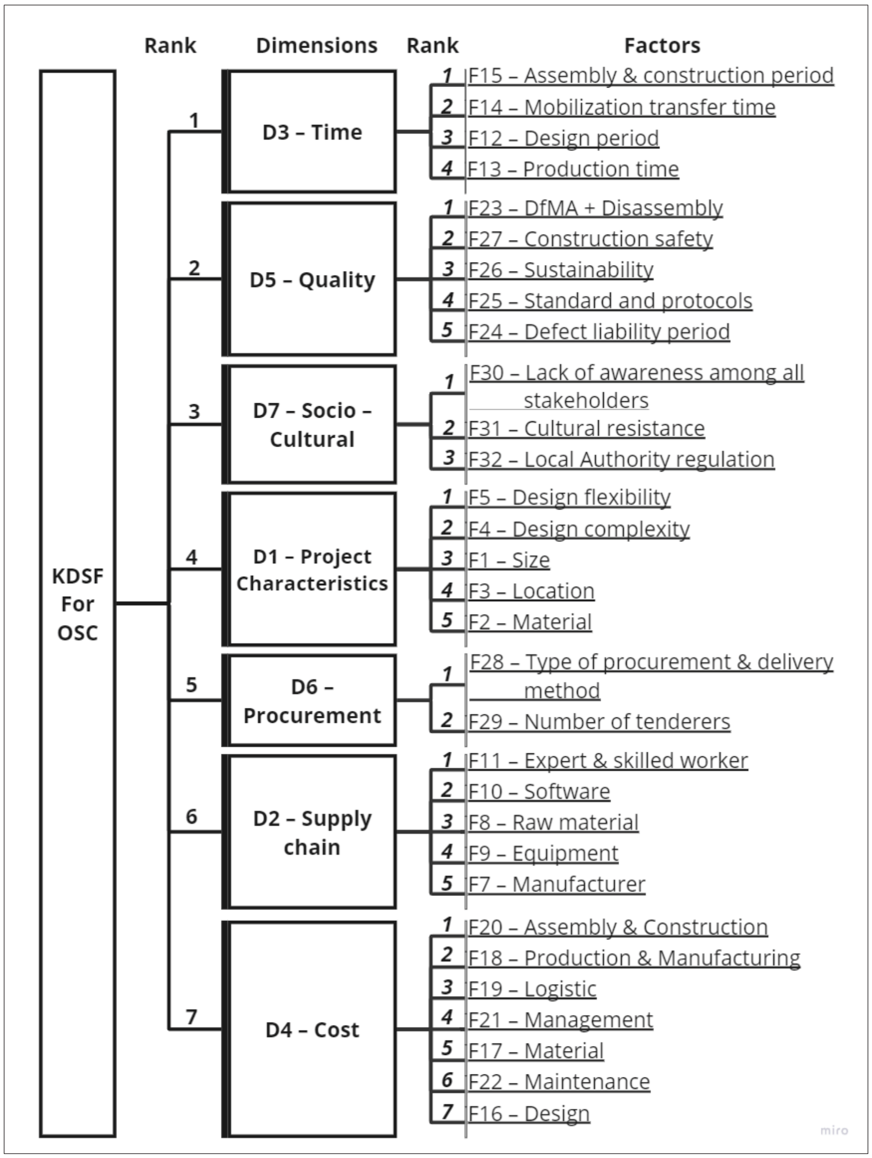

Figure 4.3 Proposed framework of a decision support system

The potential factors that could support decision-making were validated and merged into 32 key factors that influence the decision-support process. These KDSFs and the research findings have the potential to benefit all stakeholders in improving their decision-making process during the initial stage of project selection for OSC methodology. The importance and ranking of the relevant KDSFs have the potential to facilitate decision-making and guide industry players in prioritizing their preferences according to the nature of the project and the client's needs.

Overall, time-related factors (D3), such as design period, production time, mobilization and transfer time, and assembly and construction period, are considered the most important and relevant factors to consider when selecting OSC methodology for building projects. In contrast, cost-related factors (D4), such as design, material, production and manufacturing, logistics, assembly and construction costs, as well as management and maintenance, have the least influence on a decision-maker when selecting OSC methodology. Figure 4.4 shows the KDSF dimension ranking based on Mean Score. The findings are discussed in more detail below.

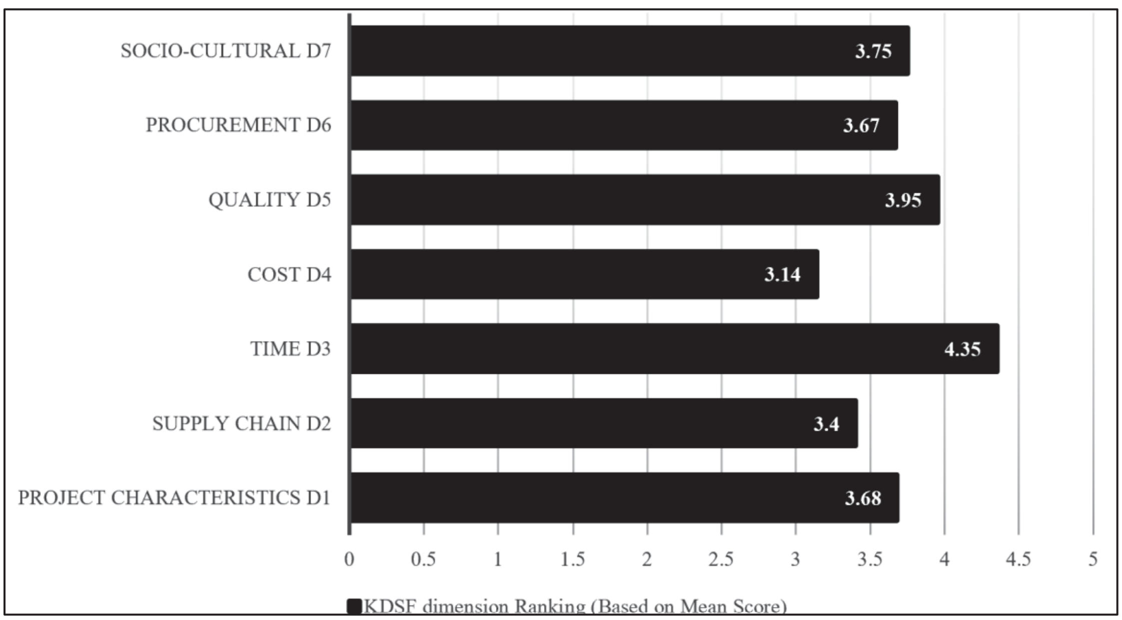

Figure 4.4 KDSF dimension bar chart

4.6.1 Time factors (D3)

The validated time-related factors (D3) are the design period, production time, mobilization and transfer time, and assembly and construction period. D3 scored a total mean of 4.35, making it the most important dimension for selecting OSC methodology for building projects. According to an expert's opinion (translated from French), "time is the most critical factor.

It is decisive for a general contractor or project manager because this is where a client is willing to pay more to save time." This statement aligns with the overall ranking, which shows that cost-related factors ranked the least important KDSF with a score of 3.14.

The literature also discusses and proposes selecting OSC methodology as a solution for overcoming construction project delays. (Hussain *et al.*, 2017; Abu Hammad *et al.*, 2008; Gusmao Brissi, Debs et Elwakil, 2020). Brissi (2020) states that time is one of the most important factors influencing decisions regarding the use of OSC in multifamily housing in the US.

Table 4.7 displays the scoring and MS among D3 factors for each group of experts. The results indicate that the assembly and construction period, with an MS of 4.75, was considered the most relevant and important criterion for selecting OSC.

Additionally, mobilization and transfer time ranked second. The experts evaluated production time and design period as the least significant factors among other time-related KDSFs. The single dimension P-value of D3 is 0.20, indicating that there is no difference between the opinions of the different groups of experts, namely Group A (management, such as project managers and construction managers), Group B (manufacturers/suppliers/general contractors), and Group C (design teams, such as architects and engineers).

Table 4.7 Time related factors (D3) scoring

Time related factors (D3)					
Groups	Design period (F12)	Production time (F13)	Mobilization & transfer time (F14)	Assembly & construction period (F15)	Total MS
Group A	4	1	5	5	4.06
	4	4	5	5	
	5	5	5	5	
	2	3	3	4	
Sub-MS	3.75	3.25	4.50	4.75	
Group B	5	5	5	5	4.67
	4	4	5	5	
	4	5	4	5	
Sub-MS	*4.33*	*4.67*	*4.67*	*5.00*	
Group C	4	4	5	4	4.40
	4	4	4	4	
	4	4	5	5	
	5	4	4	5	
	5	5	4	5	
Sub-MS	*4.40*	*4.20*	*4.40*	*4.60*	

4.6.2 Quality factors (D5)

The D5 factors consist of Design for Manufacturing and Assembly (DfMA) + Disassembly, Defect Liability Period, Standards and Protocols, Sustainability (Carbon Emission, Energy Consumption, and Waste Management), and Construction Safety. The data analysis revealed that quality-related factors ranked second highest among the seven dimensions of the Key Decision Support Factors (KDSF). According to experts, "*choosing Off-site Construction not only reduces carbon emissions and saves energy due to fewer logistics and transportation, but* *also results in significant energy savings in Canada, particularly in winter when it eliminates the need to keep construction sites warm*".

Among the D5 factors, DfMA + Disassembly scored the highest Mean Score (MS) of 4.42 and a Standard Deviation (SD) of 0.67, making it the most important KDSF for quality-related factors, with a total MS of 3.95.

Qualitative analysis of expert semi-structured interviews revealed that the ability of an OSC project to meet the client's quality requirements and satisfaction is one of the most important factors for selecting the appropriate construction methodology in building projects. This finding is supported by other researchers who have identified improving project quality performance as a critical indicator for meeting client satisfaction in construction projects (Wuni, Shen et Osei-Kyei, 2021; Attouri, Lafhaj, Ducoulombier et Linéatte, 2022a; Abu Hammad *et al.*, 2008; Al-sarafi *et al.*, 2022).

Experts indicate that in Quebec, the Société d'habitation du Québec (SHQ) is launching the development of a digital model for prefabricated affordable housing based on OSC methodology in 2023 (SHQ, 2023). As part of the mandate, the energy performance of the proposed building project must meet the Novoclimat program and be at least 10% more efficient than the requirements of Chapter I.1-Energy efficiency of building construction code RLRQ, chapter B-1.1, R2 (Novoclimat, 2020). Therefore, it can be concluded that government agencies are selecting OSC methodology to ensure that high quality building projects that meet standards and sustainability requirements are achievable, which is consistent with the results of the data analysis in this research.

4.6.3 Socio-Cultural factors (D7)

The D7 factors, with a total MS of 3.75, ranked third among the other dimensions. It consists of three KDSFs, namely: Lack of awareness among stakeholders, Cultural resistance, and Local authority regulation. The factor of Lack of awareness among all stakeholders, with an

MS of 4.25 and an SD of 0.75, is considered by the interviewees to be the most important and relevant factor related to the Socio-Cultural dimension.

Qualitative analysis of expert interviews reveals that "The client's understanding and perception of OSC is a key factor in proceeding with the offsite concept." The statement is further supported by the expression of the term "interested in a real building but it won't happen by OSC," which shows that a lack of understanding is an important barrier to selecting OSC.

According to Wuni (Wuni, Shen et Osei-Kyei, 2020), poor client understanding, receptivity, and acceptance of modular projects in OSC concepts are considered key critical failure factors. The single dimension P-value of 0.26 shows that there is no variance among different groups of respondents to determine the importance and relevancy of KDSF related to D7.

Furthermore, cultural norms can play a significant role in the decision-making process, as they are capable of dictating design aesthetics and construction practices that may be preferred or prohibited in a particular region. Therefore, understanding the local environment and taking these factors into account is essential when selecting the appropriate construction methodology.

4.6.4 Project characteristics factors (D1)

The dimension related to project characteristics (D1) scored a total MS of 3.68, with the most important KDSF being design flexibility (F5) with an MS of 4.50 and SD of 0.80.
Design flexibility in the Off-site Construction domain has been frequently discussed in the literature, mainly regarding adaptable buildings for sustainable built environments, which is also related to D5.

The KDSF of design flexibility, which drives "change of use", is a specific criterion in adaptable building within the OSC cluster (Manewa *et al.*, 2016). According to expert opinion, *"using prefabricated building systems, which are designed based on adaptable building* *concepts, will enhance the level of flexibility in design (design flexibility), therefore adaptable buildings enhance building's life cycle value."* This is translated into a technical example of using hollow-core slab and delta beam in OSC methodology, which gives more flexibility to a building by reducing the number of columns as well as the floor thickness to host fully modular pods (Peikko, 2023).

The second important KDSF in D1 is design complexity (F4) with an MS of 4.33, which is respectively followed by the size of the project in terms of footprint and height (F1) with an MS of 3.67 and SD of 1.15, the location of the project (F3) with an MS of 3.08 and SD of 1.31, and the material (F2) with an MS of 2.83 and SD of 0.72. Table 4.8 shows the distribution of scoring among different groups of respondents for factors related to D1.

It should be mentioned that the KDSF of design flexibility (F5) has the highest score by Group B: Manufacturer/Supplier/General Contractor, then Group C: Design. Analysis of expert opinion showed that *"in the Canadian context, there is a lack of designers who can design based on prefabricated systems. Not many designers are familiar with the procedure for the certification of prefabricated buildings (CSA A277)."* Therefore, manufacturers and suppliers would need to transform conventional design into prefabrication design according to their product's specifications and client's needs.

This statement supports the MS scoring by Group B and Group C. The P-value of 0.37 from ANOVA showed that the null hypothesis (H_0) is rejected; thus, there is no difference between different groups of respondents evaluating KDSF in D1.

Table 4.8 Project characteristics (D1) scoring

Dimension	Factors	Mean Score (MS)			MS	SD	*Dimension* *P* Value	Dimension MS	Dimension Rank
		Group A	Group B	Group C					
D1	F1	4.0	4.0	3.2	3.67	1.15	0.37	3.68	4
	F2	2.5	3.0	3	2.83	0.72			
	F3	2.8	4.0	2.8	3.08	1.31			
	F4	4.0	4.7	4.4	4.33	0.65			
	F5	3.8	5.0	4.8	4.50	0.80			

4.6.5 Procurement factors (D6)

The factors related to the procurement dimension, with a total MS score of 3.67, are Type of procurement & Delivery method (F28) with an MS of 3.92 and SD of 0.79 and Number of tenderers (F29) with an MS of 3.42 and SD of 1.24. D6, which pertains to procurement, ranked fifth among the dimensions.

Although the delivery method is frequently discussed as one of the critical success factors in OSC projects in the literature (Wuni et Shen, 2019), according to experts, *"the majority of government projects are based on conventional contracts, and collabourative methods such as Integrated Project Delivery (IPD) or Design and Build (D&B) are mainly acceptable for private projects."* The results still support the importance of project delivery methods and the benefits of collabourative contracts in OSC projects.

However, the decision-making process for construction methodology could be significantly influenced by clients' needs and regulations, which may not consider OSC.

4.6.6 Supply chain factors (D2)

The supply chain dimension, which consists of six KDSFs, namely Availability of Software (F10), Expert and Skilled Workers (F11), Financing (F6), Raw Material (F8), Equipment (F9), and Manufacturer (F7), received a total MS score of 3.40 and ranked sixth among the dimensions. Despite the proven benefits of automation and digitalization in OSC projects (An *et al.*, 2020), the majority of prefab suppliers, modular manufacturers, and prefabricators in Canada are not yet fully digitalized, according to experts.

The availability of software and high-tech equipment, such as robotic arms and 3D printers, are not considered critical factors in selecting OSC methodology for building projects. However, as the amount of automation and digitalization in the construction industry increases, particularly in the OSC domain, the importance and necessity of the availability of software and equipment will increase correspondingly.

Moreover, the qualitative analysis revealed that the availability of local manufacturers (F7) was not considered a critical factor, as some successful OSC projects have been completed using international prefab suppliers or manufacturers. This finding also holds for the factors of raw material (F8), which in some cases (such as imported Cross-Laminated Timber (CLT) panels and glulam beams) were even more economical compared to similar locally provided products.

4.6.7 Cost related factors (D4)

The Cost dimension (D4) comprised of KDSFs related to the Cost of Design, Material, Production and Manufacturing, Logistic, Assembly and Construction, Management, and Maintenance, which ranked the lowest with a total MS of 3.40. Despite frequent discussions in the literature on the cost-saving benefits of OSC projects (Abanda, Tah et Cheung, 2017; Pan et Sidwell, 2011; García de Soto *et al.*, 2018), cost reduction was not considered as important as other factors for the selection of OSC methodology.

The study investigated several cases where clients were willing to pay more to ensure a certain level of quality or meet a specific timeline to complete the project. This could be due to the perception that the use of OSC methodology is capable of resulting in higher quality, more efficient construction, and faster completion times.

Additionally, due to site location, weather conditions, and accessibility in Canada, the OSC methodology was considered an appropriate approach, regardless of any associated cost or expensive logistics and transportation.

The single dimension P-value of 0.42 indicated that there is not enough evidence to reject the null hypothesis (H_0), suggesting no variance among the different groups of respondents evaluating KDSFs in D4. Therefore, there was no significant difference between the different groups of expert opinions in evaluating cost-related factors. This suggests that there is a general consensus among experts in Canada that cost reduction is not a primary driver for the selection of OSC methodology.

However, the construction industry is highly localized, and factors such as government regulations, labour costs, and cultural norms can significantly impact the decision-making process for construction methodology.

4.7 Conclusion, contributions, and limitation of the research

The Off-site Construction approach is rapidly gaining popularity as a preferred methodology for many construction projects. However, previous studies have mainly focused solely on the aspect of cost savings, without considering other dimensions such as time, quality, and value of the project itself (Attouri, Lafhaj, Ducoulombier et Linéatte, 2022a; Siggner, 2011; Ham et Lee, 2019b; Van Vuuren, 2020; Wuni et Shen, 2019; Jin *et al.*, 2018a; Wang *et al.*, 2020).

This paper aims to identify and assess seven major dimensions comprising 32 key decision support factors to help decision-makers understand and recognize the factors that should be considered when making a quick and reliable decision about the use of OSC early in the project definition process.

Different aspects that affect the process of decision making are covered in this research including project characteristics, supply chain, time, cost quality, procurement and socio-cultural factors to achieve the objectives. The factors were identified and validated through a comprehensive SLR and semi-structured expert interviews.

To assess, analyze the factors, a mixed-method of qualitative and quantitative approach was applied. Twelve (12) experts with extensive experience in OSC and with different background such as project manager, architect, engineer, contractor and manufacturer were asked to rank the importance and performance of each factor.

The result of this research shows that time related factors i.e. design period, production time, mobilization and transfer time, and assembly and construction period are the most important factors in decision making process for OSC projects.

In addition, although there have been numerous studies in the literature highlighting the cost-saving advantages of using Off-site Construction methodology, the importance of reducing costs was found to be outweighed by other factors in the selection of OSC methodology. The research examined various instances where clients were willing to pay extra to ensure that a certain level of quality was achieved or to meet specific project completion deadlines.

This research constitutes a component of a Ph.D. project that aims to create a two-stage BIM-enabled Decision Support System for the selection of a proper Industrialized Building System in OSC projects.
However, the primary focus of this paper is to identify, validate, and analyze the key decision support factors (KDSF) and establish a conceptual framework for the selection of the Off-site Construction methodology for building projects.

The research has developed a conceptual framework for the selection of the OSC methodology based on validated key decision support factors for building projects. Therefore, this research is considered an initial guideline for OSC practitioners to determine the most important and relevant indicators to select the OSC approach to ensure the success of the project.

In summary, this research contributes to the understanding of OSC methodology selection by emphasizing the importance of time-related factors and considering a comprehensive set of key decision-supporting factors beyond cost saving.

It should be noted that this research is limited by certain constraints. First, although the sample size was larger than most previous studies in this domain, increasing the number of participants could affect the generalizability of the results. Second, this research was limited to the Canadian context. The construction industry is known for being highly localized, meaning that various factors such as government regulations, labour costs, and cultural norms can significantly influence the selection of construction methodology.

These factors vary significantly across regions and can often be a critical consideration in the decision-making process. Therefore, it is suggested that future research endeavors focus on increasing the sample size and examining a wider range of contexts. Future research should encompass a broader range of context beyond the confines of the Canadian construction industry to account for the localized nature of this sector. Furthermore, comprehensive lifecycle analyses should be conducted to assess the environmental, social, and economic impacts of OSC, encompassing factors such as energy consumption, waste reduction, social acceptance, and economic feasibility.

CHAPTER 5

ENHANCING DECISION-MAKING IN OFF-SITE CONSTRUCTION: A TWO-STAGE BIM-ENABLED DECISION SUPPORT SYSTEM FOR THE SELECTION OF A SUITABLE INDUSTRIALIZED BUILDING SYSTEM

A. Mehdipoor[1], M. Al-Hussein[2], N. Nabipour[3], M. Shayegan[1], I. Iordanova[1]

[1]Department of Construction Engineering, École de Technologie Supérieure, 1100 Notre-Dame Ouest, Montréal, Québec, Canada H3C 1K3
[2] Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Canada T6G 2R3
[3] Department of Building, Civil and Environmental Engineering, Concordia University, Montréal, Canada H3G 1M8

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5.1 Abstract

An effective strategy for bolstering productivity within the construction sector is to integrate Off-site Construction (OSC), Building Information Modelling (BIM), and digitalization. In this regard, the use of Industrialized Building Systems (IBS) within OSC has experienced a notable upward surge, contributing to improved productivity and project success. OSC and IBS have established a growing presence within the construction domain in recent years. However, the selection of a suitable construction method and corresponding techniques are critical in ensuring the success of an OSC project incorporating IBSs. This decision-making process is of particular importance during the early design phase of a project, where comprehensive data may be lacking. Decision-makers must consider all primary factors and make timely, judicious decisions. Nevertheless, stakeholders in the construction sector, such as designers and developers, often encounter difficulties in choosing an appropriate IBS for implementation in OSC. Despite the availability of various types of IBSs in the market, the development of a validated, comprehensive Decision Support System (DSS) is needed in order to foster the application of IBS in OSC. The aim of the research presented in this paper is to

enhance construction efficiency by advancing OSC techniques and their integration with BIM through informed decision-making. In specific, the objective is to develop a two-stage BIM-enabled DSS for the selection of a suitable IBS in OSC, where the DSS targets prefabricated components and/or specific sections of buildings. In this regard, this paper proposes a decision-making method consisting of two stages. Stage 1 determines whether OSC should be used in the given building project, and Stage 2 evaluates and selects a suitable IBS solution based on relevant decision-making factors for the given project.
Keywords: decision support system, decision making, off-site construction, industrial building system.

5.2 Introduction

Canada's housing shortage has reached a critical level, as insufficient housing has persisted for over a decade (Conference Board of Canada, 2024). A 2024 report by the Canada Mortgage and Housing Corporation (CMHC) projects a housing supply gap of 3 million units by 2030. This gap could widen to 4 million units, exacerbated by current economic and immigration trends. Additionally, the construction industry lags behind other sectors in terms of productivity, often resulting in cost overruns and project delays (Van Vuuren, 2020; Jin *et al.*, 2018). One promising solution is the transition from traditional on-site construction methods to modular construction. It has been estimated that, in Europe and North America, this shift could result in annual savings of up to $22 billion (Bertram *et al.*, 2019). Off-site construction methods—involving moving traditional on-site processes to an industrial manufacturing site—have proven to be effective in improving productivity and efficiency (Liu *et al.*, 2017). Additionally, the increased adoption of Industrialized Building Systems (IBSs) within OSC has significantly enhanced productivity and project outcomes (Kamar *et al.*, 2011). Furthermore, BIM provides new opportunities to enhance the computerized design and fabrication of industrialized buildings, leading to increased productivity and cost-effectiveness (He *et al.*, 2021). Consequently, integrating BIM with OSC can maximize these benefits for the construction industry and improve construction efficiency (Yin *et al.*, 2019).

However, despite the potential productivity increase through the use of digital technologies such as BIM, research on construction automation has primarily focused on the design phase, with little attention given to technological advancements in other areas. One such area is decision-making (Bowmaster et Rankin, 2019; Tang, Chong et Zhang, 2019). Effective decision-making is crucial, given the complexity of construction processes and the variety of techniques and methods involved in planning, manufacturing, and constructing building projects (Daget & Zhang, 2019). Therefore, the growing interest in OSC highlights the critical importance of selecting appropriate construction methods and techniques to ensure a project's success (Marcher, Giusti et Matt, 2020).

In this context, the aim underlying the research presented in this paper is to enhance construction efficiency by advancing OSC techniques and their integration with BIM through informed decision-making. This paper proposes a two-stage decision-making method, where Stage 1 is to determine whether OSC should be used in the given building project, and Stage 2 (if applicable) is to evaluate and select suitable IBS solutions based on relevant decision-making factors for OSC projects. By utilizing a two-stage BIM-enabled DSS (BeDSS) and a mixed-methods approach that includes a Systematic Literature Review (SLR) and expert validation, this research addresses gaps and develops innovative solutions. The proposed BeDSS, a multi-criterion DSS integrated as a software plugin within BIM tools, aims to provide a computerized framework that combines mathematical programming, automated data extraction, decision analysis, and statistical procedures.

5.3 Literature Review

In the construction industry, decision-making is a critical task that can be supported by the use of computer technology to improve quality and efficiency in building projects (Marcher, Giusti et Matt, 2020). Due to the complexity of the construction process and the variety of different techniques and methods involved in planning, manufacturing, and constructing a building project, decision-making plays a particularly critical role.

Scholars have examined the various decision-making elements associated with OSC. For instance, Wuni and Shen (2019) identified five primary factors involved in the selection of modular integrated construction (MiC), these being the availability of skilled labour and management, project timelines, transportation, limitations in size, and equipment availability. The process of decision-making in the construction management domain based on multi-criterion decision-making (MCDM) techniques, meanwhile, has been reviewed by pioneer researchers such as (Aboelmagd, 2018; Alhumaidi, 2015; An *and al.*, 2020; Daget and Zhang, 2019; Ordoobadi, 2009; Wuni and Shen, 2019). Moreover, Aboelmadg (2018) used the Analytic Hierarchy Process (AHP) as a tool in MCDM for selecting the best construction bid price. In the OSC domain, Daget & Zhang (2019) developed a decision-making model for the assessment of IBSs using MCDM techniques, with the scope of their research being limited to housing projects in Ethiopia.

There are multiple techniques within the MCDM approach. For instance, Ordoobadi (2009) applied fuzzy logic for the selection of a supplier capable of meeting the client's requirements. Daget and al. (2019) used AHP to develop a decision-making model for OSC. Wuni & Shen (2020) developed a fuzzy modelling-based decision-making framework for evaluating the critical failure factors for OSC projects, identifying poor design and lack of proper supervision and management as key failure factors for modular projects. Ishuzaka (2014) compared the most widely used techniques in MCDM (i.e., fuzzy logic, AHP, fuzzy AHP and hybrid fuzzy AHP), identifying the integration of fuzzy logic with AHP as a promising solution for overcoming challenges and uncertainties within the MCDM approach (Ishizaka, 2014).

Fuzzy set theory has been integrated with conventional AHP methods in numerous applications within the construction management domain, such as selecting the best location for a construction project (Rezaei *and al.*, 2013), assessing the sustainability indicators for green building manufacturing (Yadegaridehkordi *and al.*, 2020), assessing construction project risk (Zeng, An and Smith, 2007), decision-making problems in construction (Lee, 2016) and selecting alternatives in construction project management (Prascevic and Prascevic, 2017).

This research focuses on applying fuzzy logic within the MCDM approach to evaluate and rank alternatives in a case study based on relevant factors that influence the decision-making process in OSC projects. There are two alternatives that this research takes into consideration, called Alternative 1 and Alternative 2 in each stage. In Stage 1, Alternative 1 is a conventional method (on-site construction), and Alternative 2 is an OSC method, while in Stage 2 the comparison is between IBS 1 - Volumetric modular unit (Alternative 1) and IBS 2 - Panelized unit (Alternative 2).

5.4 Methodology

The objective of this study is to create a two-stage decision support system (DSS) aimed at aiding decision-makers in assessing the feasibility of OSC, and, if OSC is chosen, identifying the appropriate IBS for the project. If the project is deemed to be compatible with OSC (i.e., Stage 1), the decision maker will proceed to Stage 2, where different IBS alternatives are assessed to select the most appropriate system based on clients' needs. The key decision-support factors (KDSFs) that formed the foundational development of the proposed system were identified through various approaches such as a systematic literature review, networking with domain experts and professionals, questionnaires, and semi-structured interviews. As a result, 32 KDSFs across 7 factors were identified, validated, and assessed to be utilized in the proposed system (Mehdipoor, Iordanova and Al-Hussein, 2023a). To streamline the pairwise comparison approach, 11 KDSFs with similar interpretations were merged together, resulting in 21 total KDSFs.

The decision-making process within construction management has been extensively studied by leading researchers, particularly when utilizing MCDM techniques. These researchers include Aboelmagd (2018), Alhumaidi (2015), An *and al.* (2020), Daget and Zhang (2019), and Ordoobadi (2009). Aboelmadg (2018) employed AHP, a tool within MCDM that breaks down hierarchical problems, to select the most advantageous construction bid price, thereby illustrating the benefits of MCDM techniques. In the OSC sector, Daget and Zhang (2019) devised a decision-making model for evaluating the IBS using MCDM techniques.

Additionally, the MCDM approach encompasses various techniques. For instance, Ordoobadi (2009) used fuzzy logic to select an appropriate supplier capable of fulfilling a client's needs and expectations. Meanwhile, Daget and Zhang (2019) employed AHP to create a decision-making model for OSC.

Often, decision-makers can only provide subjective and uncertain judgments rather than precise decisions. These judgments need to be quantified. In this regard, traditional AHP methods are not suitable for real-world decision-making problems when presented with vague data. To manage such uncertainties and vagueness, fuzzy logic—introduced by Zadeh (1965)—can be employed. Consequently, merging the fuzzy logic with AHP can be more practical and effective than the traditional AHP alone in solving real-world problems.

Wuni & Shen (2020) established a decision-making framework that uses fuzzy modelling to assess the critical failure factors in OSC projects. Such approaches integrating fuzzy logic with AHP—referred to as “fuzzy AHP” or FAHP—help to address the uncertainties inherent in MCDM (Ishizaka, 2014).

5.4.1 Ontology

In this research, an ontology is developed to structure and formalize the knowledge required for enhancing decision-making in OSC using a BIM-enabled Decision Support System. The ontology provides a comprehensive framework for understanding and utilizing the various concepts, relationships, and factors involved in selecting suitable Industrialized Building Systems (IBS) for OSC projects. Key concepts and definitions are as follows:

OSC: Also known as Off-site Manufacturing or off-site production, involves the preparation, design, fabrication, and assembly of building elements at a separate location from their final installation site. This approach aims to expedite and improve construction efficiency by shifting the construction process to an industrial manufacturing environment and utilizing advanced machinery and manufacturing technologies. Combination of definitions provided by Iordanova (2020), Liu et al. (2017), and Gibb and Pendlebury (2006).

BIM: Construction of a model that contains information about a building from all phases of its life cycle including operation and maintenance (ISO 16757-1: 2015).

IBS: An innovative technology that offers greater automation, higher productivity, increased cost efficiency, and improved site safety by shifting building activities from traditional construction sites to off-site factory-based manufacturing environments (He *et al.*, 2021)

Decision Support System (DSS): A computerized system used to support decision-making activities. In this context, the DSS is integrated with BIM to assist in the selection of appropriate IBS for OSC projects.

Key Decision-Support Factors (KDSFs): Factors that influence the decision-making process in selecting suitable construction methodologies and IBS. These factors are identified through systematic literature reviews, expert consultations, and empirical studies.

Furthermore, the ontology organizes the decision-making process into a hierarchical structure, reflecting the stages, factors, and alternatives involved:

Overall Goal: to enhance decision-making in OSC through the selection of suitable IBS.

Stages: stage 1 goal: Assess the feasibility of using OSC for the project. stage 2 goal: Select the most suitable IBS for the project if OSC is deemed feasible.

Main Factor (Dimensions): Seven dimensions that represent the primary considerations in the decision-making process consisting of Project characteristics (D1) Supply chain (D2) Time (D3) Cost (D4) Quality (D5) Procurement (D6) Socio-Cultural (D7) (Mehdipoor, Iordanova and Al-Hussein, 2023a).

Sub-Factor: Specific factors under each main criterion that contribute to the evaluation process. For example, under "Time (D3)," sub-factor include Design period (F7), Production time (F8), Mobilization & transfer time (F9) and Assembly & construction period (F10).

Alternatives: In stage 1, the alternatives are different construction methodologies. In this research, in stage 1, Alternative 1 is the conventional method (onsite construction) and Alternative 2 is OSC method. In Stage 2, the alternatives are different IBS systems. In this project in stage 2, Alternative 1 is a volumetric modular unit and Alternative 2 is a panelized unit.

The methodological approach consists of the Fuzzy Analytical Hierarchy Process as an extension of the traditional AHP that incorporates fuzzy logic and integrates with BIM, specifically Revit, to use BIM data to support the decision-making process

5.4.2 Fuzzy AHP

FAHP is a fuzzy extension of Saaty's pairwise comparison method to incorporate subjective judgments and uncertainty (van Laarhoven and Pedrycz, 1983). The FAHP approach is based on the following steps:

Step 1- Define the objective: In the context of the present study, the problem involves appropriately selecting between conventional construction and OSC (Stage 1). If the decision is made to proceed with OSC, the objective shifts to selecting a suitable IBS for the project (Stage 2). This delineation of the problem and objective provides a clear direction for the decision-making process (Saaty, 1987).

Step 2- Establish the hierarchical structure: Following the problem definition, the hierarchical structure of the decision factor is established. The hierarchy begins with the overarching goal, which, in the present case, is divided into two stages: selecting a suitable construction method and (if applicable) selecting an IBS for the project. This goal is then broken down into 7 main factors that are essential for evaluating the alternatives. These main factors are further expanded into 21 sub-factors, which represent specific factors that contribute to the evaluation process.

Finally, at the bottom of the hierarchy are the alternatives themselves. This hierarchical structure provides a systematic framework for organizing the decision factor and alternatives (Saaty, 1987). Figure 5.1 shows the FAHP Hierarchical Structure.

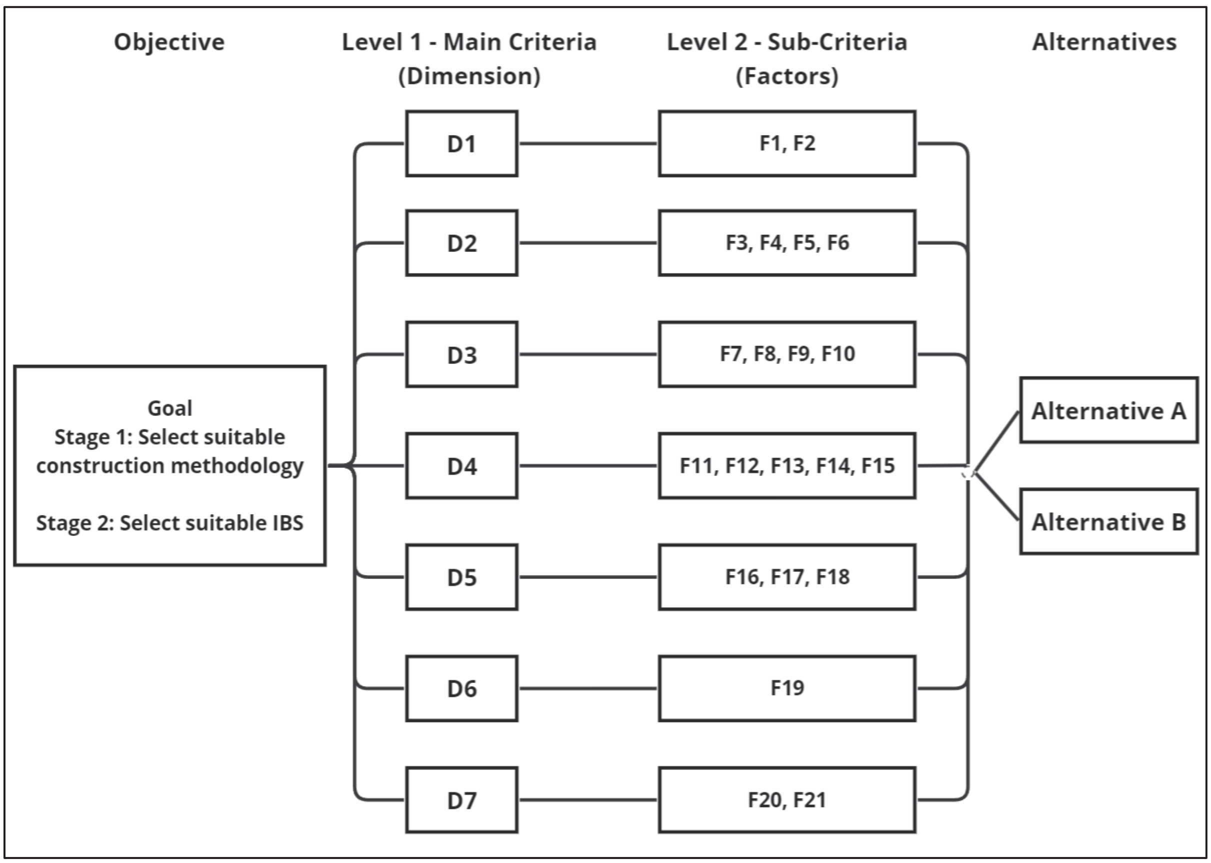

Figure 5.1 FAHP Hierarchical Structure

<u>Step 3- Determine the fuzzy scale:</u> A crucial aspect of FAHP is the use of a fuzzy scale to quantify the importance of one element over another. The fuzzy scale consists of three fuzzy numbers that represent different levels of importance. For instance, (1,1,1) denotes equal importance, (2,3,4) signifies weak importance, (4,5,6) indicates fair importance, (6,7,8)

represents strong importance, and (9,9,9) reflects absolute importance. Assigning fuzzy numbers according to the perceived importance of elements facilitates a nuanced assessment of their relative significance in the decision-making process (Chang, 1996). Table 5.1 shows the linguistic terms and corresponding triangular fuzzy numbers adapted from Ayhan (2013) and Chang (1996).

Table 5.1 Linguistic terms and corresponding triangular fuzzy numbers adopted from Ayhan, (2013), Chang, (1996) and Oguztimur (2011)

Saaty scale	Definition	Fuzzy Triangular Scale	Definition
1	Equally important	(1,1,1)	*i* and *j* are equally important
3	Weakly important	(2,3,4)	*i* is weakly more important than *j*
5	Fairly Important	(4,5,6)	*i* is fairly more important than *j*
7	Strongly important	(6,7,8)	*i* is strongly more important than *j*
9	Absolutely important	(9,9,9)	*i* is absolutely more important than *j*
2	The intermittent values between two adjacent scales	(1,2,3)	Used when a compromise is needed
4		(3,4,5)	
6		(5,6,7)	
8		(7,8,9)	

<u>Step 4- Perform pairwise comparison:</u> In this step, pairwise comparisons are conducted for each pair of elements within a given level of the hierarchy. Decision-makers assign fuzzy numbers to each main factor and sub-factor based on their subjective judgments regarding the relative importance of the elements being compared. These pairwise comparisons are carried

out systematically for all main factors (dimensions), sub-factors, and alternatives, ensuring a comprehensive assessment of their interrelationships (Chang, 1996).

Step 5- Calculate the fuzzy synthetic extent: Following the pairwise comparisons, the fuzzy synthetic extent is calculated for each element in the hierarchy. The fuzzy synthetic extent serves as a measure of the overall importance of an element, considering its relative importance across all pairwise comparisons. This calculation involves summing the fuzzy numbers assigned to each element and normalizing the values to ensure consistency throughout the hierarchy (Chang, 1996).

$Si = \sum Aij / \sum \sum Aij$ where;

Si: This is the fuzzy synthetic extent for a specific element i. It represents the overall importance of that element when compared to all other elements at the same level in the hierarchy.

Aij: This is the fuzzy number assigned to the pairwise comparison of element i with element j. It represents the relative importance of element i over element j.

$\sum Aij$: This is the sum of the fuzzy numbers for all pairwise comparisons involving element i.

$\sum \sum Aij$: This is the sum of the fuzzy numbers for all pairwise comparisons at the same level in the hierarchy.

Step 6- Determine the fuzzy weights: The fuzzy synthetic extents having been obtained, the next step is to determine the fuzzy weights for each element. The fuzzy weight of an element is calculated by dividing its fuzzy synthetic extent by the sum of synthetic extents for all elements within the same level of the hierarchy.

This calculation yields fuzzy weights that reflect the relative importance of each element in contributing to the overall decision (van Laarhoven et Pedrycz, 1983).

The formula for this step is: $W_i = S_i / \sum S_i$

W_i: This is the fuzzy weight for a specific element i. It represents the relative importance of that element when compared to all other elements at the same level in the hierarchy.

S_i: This is the fuzzy synthetic extent for element i, calculated in step 5.

$\sum S_i$: This is the sum of the fuzzy synthetic extents for all elements at the same level in the hierarchy.

<u>Step 7- Defuzzify the fuzzy weights:</u> The fuzzy weights obtained from the previous step are then defuzzified to convert them into crisp values. Defuzzification enables decision-makers to obtain precise numerical values representing the weights of each element, facilitating quantitative analysis and comparison (Chang, 1996). Defuzzification methods such as the centroid method or the maximum membership principle are employed for this purpose.

<u>Step 8- Calculate the consistency ratio:</u> Ensuring the reliability of the decision-making process is crucial, and the consistency of pairwise comparisons is evaluated to achieve this. The consistency ratio (Saaty, 1987) is calculated to assess the consistency of judgments made during the pairwise comparisons. A consistency ratio less than 0.1 indicates that the judgments are consistent and can be considered reliable for use in further analysis.

The formula for the Consistency Ratio is (Saaty, 1987): $CR = CI / RI$

CR: This is the Consistency Ratio. It is a measure of the consistency of the pairwise comparisons. If the CR is less than 0.1, the judgments are considered consistent.

CI: This is the Consistency Index. It is a measure of the deviation from consistency in the pairwise comparisons. The formula for the Consistency Index is: $CI = (\lambda max - n) / (n - 1)$

λmax: This is the maximum eigenvalue of the pairwise comparison matrix. It is a measure of the overall consistency of the pairwise comparisons.

n: This is the number of elements being compared at the same level in the hierarchy.
RI: This is the Random Index as per table 5.2. It is the average Consistency Index for a large number of random pairwise comparison matrices. The values of RI depend on the number of elements being compared.

Table 5.2 Random Index (RI) (Lu et al., 2009)

N	1	2	3	4	5	6	7	8
RI	0	0	0.58	0.96	1.12	1.32	1.41	1.45

Step 9- Calculate the overall scores: Using the fuzzy weights obtained for the factor and alternatives, the overall scores for each alternative can be calculated by multiplying their respective weights. This process results in a ranking of alternatives based on their overall scores. The alternative with the highest score is the most suitable choice according to the established factor (Saaty, 1987).

Step 10- Review and validate the results: The final step involves reviewing and validating the results in consultation with decision-makers and experts. This validation process ensures that the ranked alternatives align with the goals and objectives defined at the beginning of the decision-making process. In the present case, three experts were consulted to validate the results in this step.

5.4.3 Decision Making Process

This section presents a novel decision-making system that employs the FAHP method. This system is designed to assess and rank alternatives, providing a robust and efficient tool for decision-makers. The system is integrated using Revit, a robust BIM software widely used by professionals in architecture, engineering, and construction (Sacks *and al.*, 2018).

Figure 5.2 shows the BeDSS decision-making process. It commences with the decision maker accessing the user interface (UI) and defining alternatives for comparison (Step 1).

Subsequently, the system accesses the BIM model, extracting pertinent information such as building size, location, and distance (Step 2). The system then gathers the decision maker's judgments, utilizing a linguistic scale to establish pairwise comparisons (Step 3). Default values are suggested by the system based on a fuzzy triangular scale and the decision maker's linguistic judgment (Step 4). The decision maker is then prompted to review and revise the system's suggestions in consideration of the project's requirements and the information available from the BIM model (Step 5).

The system proceeds to calculate the normalized weights of the factor (Step 6), and then defuzzify the fuzzy pairwise comparison (Step 7). The consistency rate (CR) is then calculated (Step 8). If the CR is less than 0.1, indicating satisfactory consistency, the system computes the weights for pairwise comparison, ranks each alternative (Step 9), and suggests the most suitable alternative to the decision maker (Step 10). If the CR is greater than or equal to 0.1, the system returns to the stage of collecting the decision maker's judgments, and the process is iterated until a satisfactory level of consistency is achieved. This system provides a comprehensive and systematic approach to decision-making in construction projects, enhancing efficiency and accuracy.

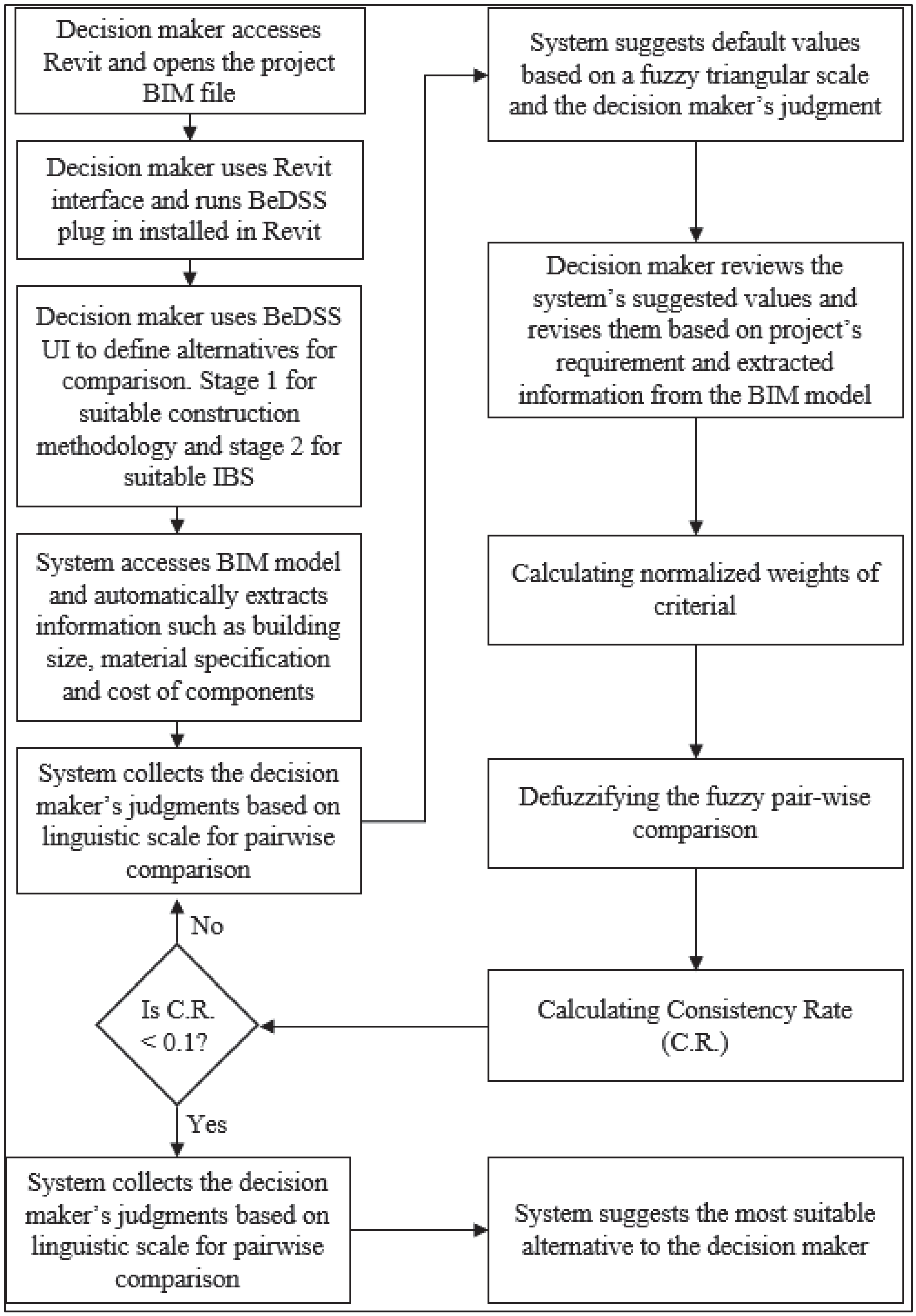

Figure 5.2 BeDSS decision-making process

5.4.4 User interface: BIM-enabled Decision Support System (BeDSS Plug-in) for Revit

The UI provides a powerful tool that communicates with the BIM model to generate information and perform the required analysis of data extracted from BIM model as well as data input by the decision maker. It assists the decision maker in following a systematic approach in order to make an informed and sound decision. The UI is programmed as a decision support plugin to Revit using Dynamo and Python to interact with the Revit Application Programming Interface (API). To maximize the potential of the UI, custom plugins are developed. The proposed system uses Dynamo as the primary mode of communication with Revit. All the tasks and developments are performed within the Python Script node available in Dynamo by employing methods provided by Revit API.

The UI development consists of the following steps:

Step 1: Understanding the basics and selection of suitable tools

The first step in UI development involves understanding the fundamental concepts and selecting the appropriate tools that will best suit the needs of the decision-maker. Dynamo, a visual programming tool, integrates with Revit to build custom functionality using visual logic, eliminating the need for text-based coding (Kossakowski, 2023). Python, meanwhile, a high-level programming language, is well suited to automation and data analysis (Van Rossum and Drake, 2009). The Revit API facilitates interaction with Revit's database and task automation (Autodesk, 2022). Therefore, the integration of Dynamo, Python, and the Revit API applied in this research is a powerful synergy for enhancing and customizing the proposed BeDSS plug-in.

Step 2: Develop the plugin

The development process begins with defining the plugin's functionality, which can be broken down as follows.

First, the user interacts with the Revit software to open the project BIM file and access the BeDSS plug in. The plug in must communicate with the model to extract the required information. In the present study, data extraction encompasses generating the required family types, the elements associated with those family types, and the parameters embedded in them. This is achieved by using Revit API methods to generate information on floor area, materials used, or thermal data available in the Revit family types' parameters.

Next, the extracted information is analyzed to provide the user with an appropriate amount of information. In the context of the present case, two levels of analysis are conducted. The first level of analysis involves generating raw data from the model to gain further insights, such as calculating the gross area of the project. The second level of analysis inspects the raw fuzzy weights of user inputs and evaluates the suitability of the alternatives. This analysis primarily employs the Pandas and NumPy libraries. Pandas is a powerful data manipulation and analysis library for Python. It provides rich data structures and functions designed to make working with structured data fast, easy, and expressive (McKinney, 2010). NumPy is a fundamental package for scientific computing with Python. It provides support for large, multi-dimensional arrays and matrices, along with a large collection of high-level mathematical functions (Oliphant, 2015).Therefore, in this step, Pandas and NumPy are employed to handle, process, and analyze the data extracted from the Revit model. Pandas enhances data manipulation capabilities, while NumPy provides the necessary computational power for numerical analysis.

Finally, a user-friendly interface is developed to facilitate the interaction of the user with the plugin, as well as to illustrate the analyzed data to the user in an accessible format. Moreover, where necessary, help and guides are provided to the user to avoid confusion.

To evaluate user inputs dynamically and avoid inputting inconsistent data, two dynamic input assessment functions are developed within the UI. These functions dynamically check the consistency and format of user inputs and inform the user if any incompatible data is flagged in the user inputs. The main library employed to develop the UI is Windows Forms, given its high functionality and flexibility.

A visual script is created using Dynamo to extract this data. Dynamo's node-based interface allows for manipulation and extraction of data from Revit elements (Collao *and al.*, 2021). Python nodes within Dynamo are used to run Python scripts for complex tasks, providing more flexibility and power. Python scripts are used to interact with the Revit file via the Revit API. Classes and methods provided by the API, meanwhile, are used to access and manipulate the Revit model.

Step 3: Testing and deployment

After development, the plugin is tested by running it on different Revit files to ensure it extracts the correct data. The results are compared with those of an Excel-based approach for data analysis to identify any errors. Any bugs or issues are addressed during this step. The plugin can then be used to extract data from Revit files and compare alternatives. Figure 5.3 shows a screenshot of the developed UI.

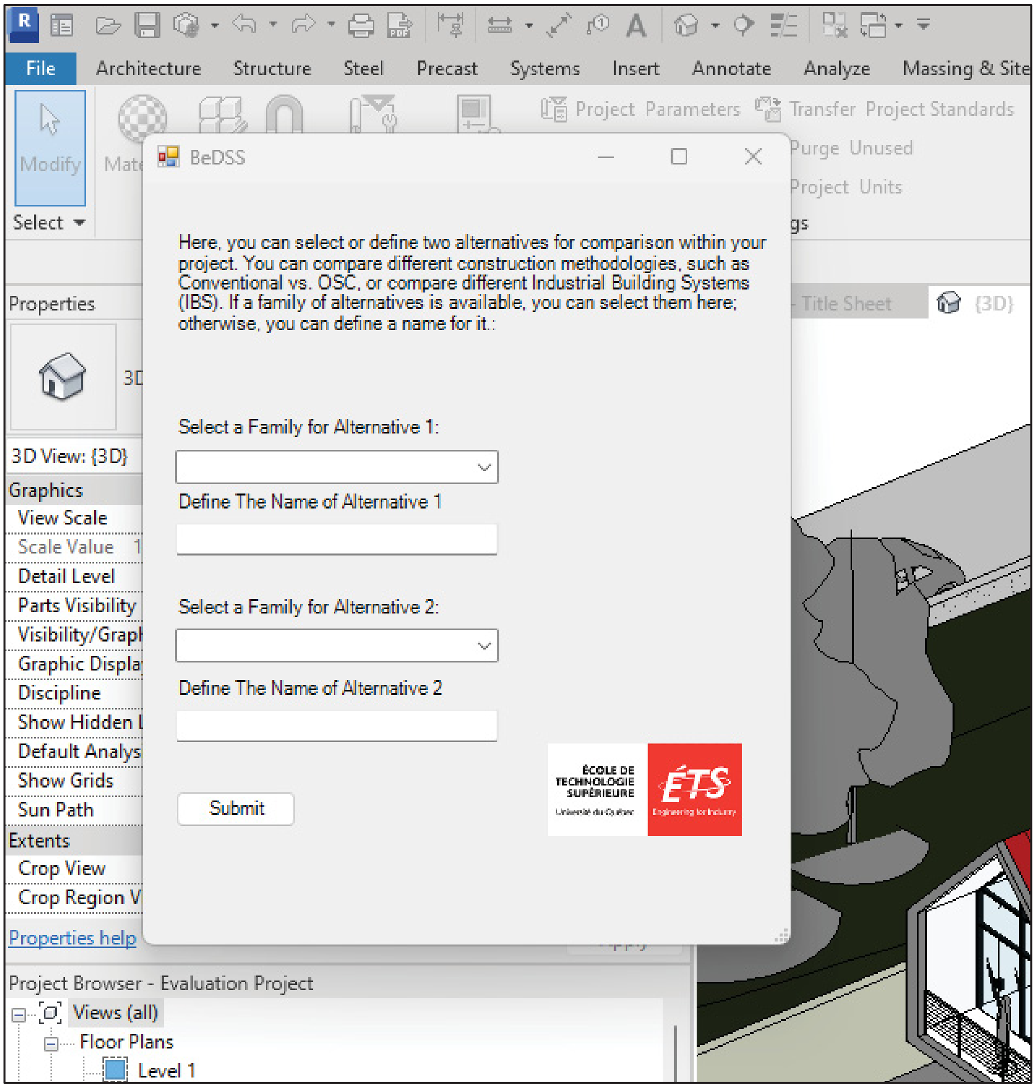

Figure 5.3 BeDSS Plug in user interface in Revit

5.4.5 UML Class Diagram for BeDSS Plug-in for Revit

Unified Modeling Language (UML) plays a crucial role in the decision-making process, particularly due to its comprehensive applications across various stages of system development. UML excels in providing a clear visual representation of complex systems, which enhances the understanding of how different components interact and relate to each other. Additionally, UML aids in problem-solving by deconstructing a system into manageable parts, making it easier to identify and address potential issues.

This breakdown also contributes to thorough documentation, which proves invaluable for ongoing maintenance and future development of the system. In the context of decision-making systems such as the BeDSS plugin for Revit in this project, UML helps to model the decision logic, data flow, and user interactions, ensuring that the system is well-designed to support complex decision processes. The UML class diagram for the BeDSS plugin for Revit provides a comprehensive overview of the system's architecture. It serves as a guide by which for developers and stakeholders to better understand the plugin's structure and functionality. By encapsulating the FAHP method within a user-friendly interface, the BeDSS plugin supports the integration of DSSs and BIM to enhance the selection IBSs for OSC projects.

System Architecture and Design

The following subsections correspond to the UML class diagram that represents the structure of the BeDSS plugin, detailing the classes, attributes, operations, and relationships that constitute the system.

Class Structure Overview

The UML class diagram for the BeDSS plugin is a blueprint that illustrates the object-oriented architecture of the system. It is a critical component of the system design, offering a clear and organized view of the plugin's structure. The diagram is composed of several classes that encapsulate the data and behaviors necessary to perform FAHP within the Revit software. The primary classes and their roles in the system are as follows:

- **BeDSS_Plugin**: This central class acts as the controller for the plugin. It initializes the UI, which is the primary point of interaction with the decision-maker. It also coordinates the flow of commands and data between various components of the system.
  Attributes: userInterface, projectData, decisionMatrix
  Operations: Initialize(), ExecuteFAHP(), DisplayResults()

- **ProjectDataExtractor**: This class is responsible for interfacing with the Revit API to extract relevant data from the BIM model.
  Attributes: revitDocument, elementFilters
  Operations: ExtractBimData(), RetrieveElementProperties()

- **FactorManager**: This class manages the factor and sub-factor used in the FAHP method.
  Attributes: mainFactor, subFactor
  Operations: LoadFactor(), Sub-FactorFactor()

- **DecisionMakerInterface**: This class provides the interface through which the decision-maker interacts with the system.
  Attributes: inputFields, suggestedValues
  Operations: CollectJudgments(), SuggestDefaultValues()

- **PairwiseComparisonMatrix**: This class represents the matrix used for pairwise comparisons in the FAHP method.
  Attributes: comparisonData, fuzzyScale
  Operations: PerformPairwiseComparison(), CalculateConsistencyRatio()

- **FuzzyLogicProcessor**: This class handles the fuzzy logic operations required for the FAHP method.
  Attributes: linguisticTerms, triangularFuzzyNumbers
  Operations: DefuzzifyWeights()

- **AlternativeRanker**: This class calculates the final ranking of the IBS alternatives based on the weighted factor.
  Attributes: alternativeScores
  Operations: RankAlternatives(), CalculateWeights()

Relationships and Interactions

The classes within the BeDSS plugin are interconnected through various types of relationships, including associations, aggregations, and compositions. The “BeDSS_Plugin” class acts as the central coordinator, associating with the “ProjectDataExtractor” to obtain project-specific data from Revit. It aggregates the “FactorManager” to manage decision factor and uses the “PairwiseComparisonMatrix” for evaluating the alternatives. The “FuzzyLogicProcessor” is built within the “PairwiseComparisonMatrix” to handle the fuzzy logic calculations. The “DecisionMakerInterface” is associated with the “BeDSS_Plugin” to facilitate user input and interaction. The “AlternativeRanker” is used to compute the final rankings of the IBS alternatives, and the “ResultValidator” ensures the decision-making process's integrity.

Diagram Representation

The UML class diagram visually represents these classes as rectangles divided into compartments listing the class name, attributes, and operations. Lines between the classes indicate relationships, with arrows denoting the direction of association and diamonds representing aggregation or composition. Figure 5.4 shows the UML class diagram for the BeDSS in this project.

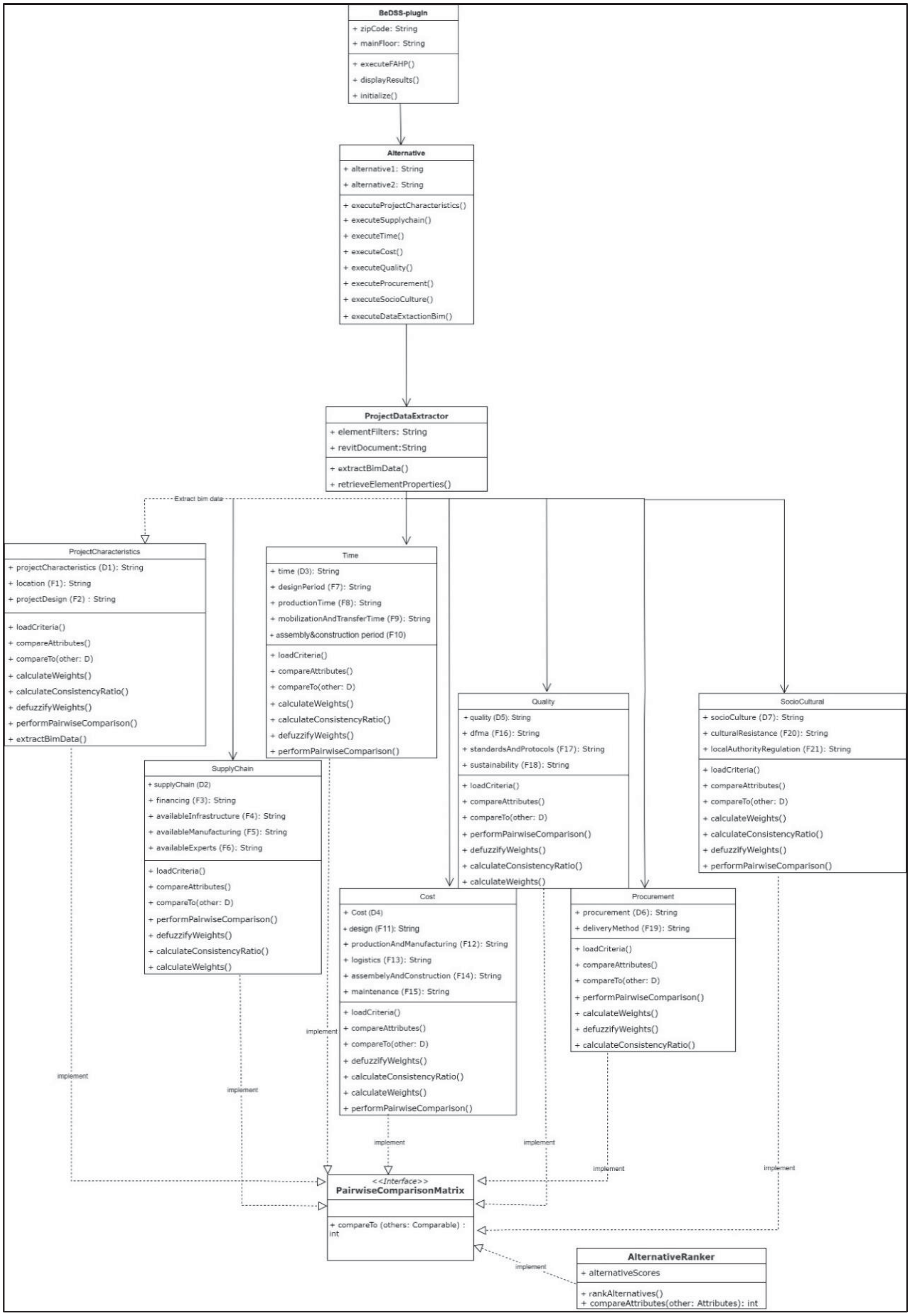

Figure 5.4 UML class diagram of BeDSS

5.5 Results and discussion

This section describes the application of the proposed procedural framework to a real-world project in Canada involving the construction of an administrative complex encompassing a gross floor area of nearly 28,000 sq ft. The case study has distinct attributes in terms of geographic location, climatic conditions, accessibility, and project delivery timeline. The climatic conditions of the case study area are marked by cold winters and relatively short summers. The site's accessibility presents a significant challenge, and the client's primary objective was to construct a building capable of efficiently operating under the conditions noted above, meaning that the building must have adequate thermal insulation, the project must be delivered expeditiously, and energy consumption during building operation must be minimal.

In order to fulfill the client's expectations and accomplish the goals of this construction project, the proposed framework and associated software were employed by an industry expert. The initial objective was to select the most fitting construction method (Stage 1), with the aim of determining the suitability of OSC for this particular project. Stage 2 involved selecting an appropriate IBS that was in alignment with the project's attributes and the client's stipulations.

5.5.1 Stage 1 – Selection of appropriate construction methodology

In Stage 1, the user referred to the list of validated KDSFs in assessing the impact of selecting OSC to ensure the success of the project. The list of KDSFs consisted of seven dimensions that were divided into 21 factors. These had been previously validated by 12 experts through interviews (Mehdipoor, Iordanova and Al-Hussein, 2023a). The user then assigned a linguistic importance level to each factor according to Table 3. The MCDM model was then applied using FAHP to categorize the alternatives as either conventional (Alternative 1) or OSC (Alternative 2).

Table 5.3 Key Decision Support Factor (Main and sub-factor) taken from Mehdipoor, Iordanova et Al-Hussein, (2023)

Main Factor (Dimensions)	**Key Decision Support Factor (KDSF) Sub-factors**	**Weights**
Project characteristics (D1)	Project Location (F1) Project Design (Size, complexity and flexibility) (F2)	w_1 w_2
Supply chain (D2)	Financing (F3) Available Manufacturer (F4) Available Infrastructure (Hardware & Software) (F5) Available experts and skilled workers (F6)	w_3 w_4 w_5 w_6
Time (D3)	Design period (F7) Production time (F8) Mobilization & transfer time (F9) Assembly & construction period (F10)	w_7 w_8 w_9 w_{10}
Cost (D4)	Design (F11) Production & Manufacturing (F12) Logistics (F13) Assembly & Construction (F14) Maintenance (F15)	w_{11} w_{12} w_{13} w_{14} w_{15}
Quality (D5)	DfMA + Disassembly (F16) Standards and protocols (F17) Sustainability (Carbon emission, Energy consumption, waste) (F18)	w_{16} w_{17} w_{18}
Procurement (D6)	Type of procurement & delivery method (F19)	w_{19}
Socio-Cultural (D7)	Cultural resistance (F20) Local authority regulation (Workers Union-Syndicate) (F21)	w_{20} w_{21}

Table 5.4 shows the pairwise comparison of the dimensions, which is the aggregated fuzzy decision matrix of dimensions with respect to the goal of Stage 1 (i.e., the selection of a suitable construction method). (In this stage, Alternative 1 refers to the conventional method of cast-in-place concrete construction, while Alternative 2 refers to OSC).

Table 5.4 Pairwise comparison of main factors (dimensions)

	D1			D2			D3			D4			D5			D6			D7		
D1	*1.00*	*1.00*	*1.00*	**1.00**	**1.00**	**1.00**	**0.25**	**0.33**	**0.50**	**2.00**	**3.00**	**4.00**	**0.25**	**0.33**	**0.50**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
D2	1.00	1.00	1.00	*1.00*	*1.00*	*1.00*	**0.25**	**0.33**	**0.50**	**2.00**	**3.00**	**4.00**	**0.25**	**0.33**	**0.50**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
D3	2.00	3.00	4.00	0.25	0.33	0.50	*1.00*	*1.00*	*1.00*	**6.00**	**7.00**	**8.00**	**1.00**	**1.00**	**1.00**	**2.00**	**3.00**	**4.00**	**2.00**	**3.00**	**4.00**
D4	0.25	0.33	0.50	0.25	0.33	0.50	0.13	0.14	0.17	*1.00*	*1.00*	*1.00*	**0.13**	**0.14**	**0.17**	**0.25**	**0.33**	**0.50**	**0.25**	**0.33**	**0.50**
D5	2.00	3.00	4.00	2.00	3.00	4.00	1.00	1.00	1.00	6.00	7.00	8.00	*1.00*	*1.00*	*1.00*	**2.00**	**3.00**	**4.00**	**2.00**	**3.00**	**4.00**
D6	1.00	1.00	1.00	1.00	1.00	1.00	0.25	0.33	0.50	2.00	3.00	4.00	0.25	0.33	0.50	*1.00*	*1.00*	*1.00*	**1.00**	**1.00**	**1.00**
D7	1.00	1.00	1.00	1.00	1.00	1.00	0.25	0.33	0.50	2.00	3.00	4.00	0.25	0.33	0.50	1.00	1.00	1.00	*1.00*	*1.00*	*1.00*

The pairwise comparison of the main factors (dimensions) having been completed, the geometric mean of each main factor was then calculated. Following this calculation, the normalized weight of each factor was computed (see table 5.5).

Table 5.5 Calculation of main factors normalized mean

Main Factor (Di)	Geometric Mean			Fuzzy Weight			Mean	Nor.Mean	
D1	0.74	0.85	1.00	0.08	0.11	0.15	0.112	**0.107**	**WD1**
D2	0.74	0.85	1.00	0.08	0.11	0.15	0.112	**0.107**	**WD2**
D3	1.43	1.81	2.21	0.15	0.23	0.34	0.237	**0.226**	**WD3**
D4	0.25	0.31	0.40	0.03	0.04	0.06	0.042	**0.040**	**WD4**
D5	1.92	2.47	2.97	0.20	0.31	0.45	0.321	**0.306**	**WD5**
D6	0.74	0.85	1.00	0.08	0.11	0.15	0.112	**0.107**	**WD6**
D7	0.74	0.85	1.00	0.08	0.11	0.15	0.112	**0.107**	**WD7**
sum	6.57	8.01	9.58				1.048	1.000	
Inverted value	0.152	0.125	0.104						
Increasing Order	0.104	0.125	0.152						

The next step was to generate the defuzzified matrix in order to calculate the consistency rate. The final defuzzidied matrix is shown in table 5.6.

Table 5.6 Defuzzidied matrix of dimensions

	D1	D2	D3	D4	D5	D6	D7
D1	1	1	0.361	3	0.361	1	1
D2	1	1	0.361	3	0.361	1	1
D3	2.769	2.769	1	7	1	3	3
D4	0.333	0.333	0.142	1	0.144	0.361	0.361
D5	2.769	2.769	1	6.904	1	3	3
D6	1	1	0.333	2.769	0.333	1	1
D7	1	1	0.333	2.769	0.333	1	1

The consistencies of fuzzy judgment matrices are evaluated by calculating the CR.

Table 5.7 CR calculation

Di	Weight	Overall Score
D1	0.101	0.713
D2	0.101	0.713
D3	0.281	1.973
D4	0.036	0.256
D5	0.281	1.970
D6	0.098	0.689
D7	0.098	0.689
λmax		7.006
C.R.		**0.00085**

The results indicate that the CR was found to be lower than 0.1. Therefore, the decision matrix was deemed to be consistent. The CR having been deemed acceptable, the pairwise comparison matrix of sub-factors (Fi) was then defined in order to calculate the weights of the sub-factors. Calculation of the sub-factors' weights was done in a similar manner to the calculation of the main factors' weights. Table 8 shows the calculations of the weights of the sub-factors (Wi).

Table 5.8 Weight of each subfactor in FAHP

Di – Main Factors (Dimension)	WDi	Sub-Factor (Fi)	WFi	**Wi**	
D1	0.107				
		F1	0.168	**0.018**	**W1**
		F2	0.831	**0.089**	**W2**
D2	0.107				
		F3	0.445	**0.048**	**W3**
		F4	0.327	**0.035**	**W4**
		F5	0.043	**0.005**	**W5**
		F6	0.183	**0.020**	**W6**
D3	0.226				
		F7	0.321	**0.073**	**W7**
		F8	0.075	**0.017**	**W8**
		F9	0.321	**0.073**	**W9**
		F10	0.281	**0.064**	**W10**
D4	0.040				
		F11	0.070	**0.0028**	**W11**
		F12	0.075	**0.0030**	**W12**
		F13	0.211	**0.0084**	**W13**
		F14	0.490	**0.0196**	**W14**
		F15	0.152	**0.0061**	**W15**
D5	0.306				
		F16	0.402	**0.123**	**W16**
		F17	0.118	**0.036**	**W17**
		F18	0.478	**0.146**	**W18**
D6	0.107				
		F19	1	**0.107**	**W19**
D7	0.107				
		F20	0.742	**0.07946**	**W20**
		F21	0.257	**0.02757**	**W21**

The next step was to compare the alternatives (i.e., Alternative 1 – Conventional method, and Alternative 2 – OSC method) with respect to each sub-factor.

Here, the user compared the factors and alternatives in order to understand the most important factor and the best corresponding alternative. These matrices were normalized and checked for consistency (similar to in previous steps).

Table 5.9 summarizes the results of the pairwise comparison between two construction methods: Alternative 1 (Conventional method) and Alternative 2 (OSC method)—across a range of sub-factors (F1 to F21). As can be seen, each sub-factor in the table was assigned a weight (Wi) based on its importance, these weights having been determined in earlier steps of the decision-making process. The weights for each alternative with respect to each sub-factor (Wi-Alt1.i and Wi-Alt2.i), it should be noted, represent how well each alternative performs in relation to the specific sub-factor.

Table 5.9 Results of a pairwise comparison between two construction methods

Fi	Wi	Wi-Alt1.i	Wi-Alt2.i		Alt.1 score	Alt.2 score
F1	0.018	0.125	0.874		0.002	0.015
F2	0.089	0.1	0.9		0.007	0.080
F3	0.048	0.1	0.9		0.004	0.042
F4	0.035	0.125	0.874		0.004	0.030
F5	0.005	0.742	0.257		0.003	0.001
F6	0.020	0.1	0.9		0.002	0.017
F7	0.073	0.1	0.9		0.007	0.065
F8	0.017	0.125	0.874		0.002	0.015
F9	0.073	0.1	0.9		0.007	0.065
F10	0.064	0.1	0.9		0.006	0.057
F11	0.002	0.257	0.742		0.000	0.002
F12	0.003	0.125	0.874		0.000	0.002
F13	0.008	0.125	0.874		0.001	0.007
F14	0.019	0.125	0.874		0.002	0.017
F15	0.006	0.257	0.742		0.001	0.005
F16	0.123	0.1	0.9		0.012	0.110
F17	0.036	0.257	0.742		0.009	0.026
F18	0.146	0.1	0.9		0.014	0.131
F19	0.107	0.125	0.874		0.013	0.094
F20	0.079	0.1	0.9		0.007	0.071
F21	0.028	0.126	0.874		0.003	0.024
				Sum Rank	0.115 2	0.885 1

The weighted scores in Table 9 were analyzed for each alternative across all sub-factors in order to arrive at the optimal decision. The scores were calculated by multiplying the weight of each sub-factor (Wi) by the performance of each alternative for that sub-factor, with the sum of these scores being the total score for each alternative.

Table 9 shows that Alternative 2 was found to generally have higher weighted scores across most sub-factors, indicating superior performance compared to Alternative 1. For sub-factors such as F2 (Project Design), F3 (Financing), and F6 (Available experts and skilled workers), Alternative 2 was found to significantly outperform Alternative 1, with scores of 0.080, 0.042, and 0.017 respectively, compared to Alternative 1's scores of 0.008, 0.004, and 0.002.

The only sub-factor with respect to which Alternative 1 was found to have a higher score than Alternative 2 was F5 (Available Infrastructure), with a score of 0.003 (compared to 0.001 for Alternative 2). However, this sub-factor had a relatively low weight (0.005), so its impact on the overall decision could be considered relatively limited.

The most heavily weighted sub-factors, such as F16 (DfMA + Disassembly), F18 (Sustainability), and F19 (Type of procurement & delivery method), were all found to favor Alternative 2, with scores of 0.110, 0.131, and 0.093, respectively. These high-impact areas are critical to the decision-making process, so these scores suggested Alternative 2 to be more aligned with the priorities of the case project.

The scores for each alternative having been aggregated, Alternative 1 was found to have a total score of 0.116, while Alternative 2 achieved a significantly higher score of 0.883. This substantial difference showed Alternative 2 to be the more appropriate construction method for the project, according to the weighted evaluation of sub-factors.

Based on the analysis of the pairwise comparison matrix and the weighted scores, Stage 1 concluded with Alternative 2 being identified as the preferable option (see Figure. 5.5). This selection of the OSC method was supported by a systematic and quantitative evaluation process, ensuring a sound and justifiable decision.

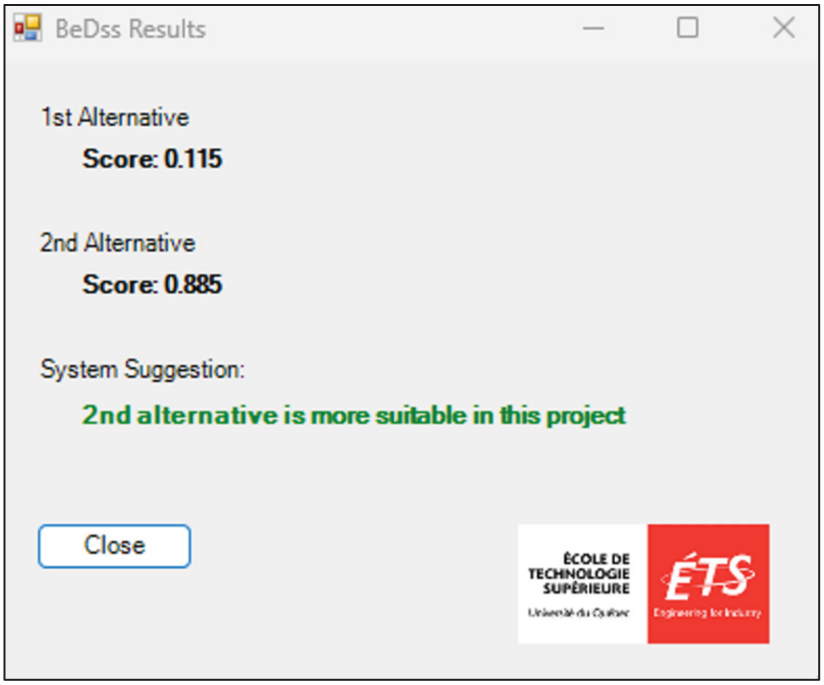

Figure 5.5 Screen shot of BeDSS recommendation in Stage 1

5.5.2 Stage 2 – Selection of suitable IBS solution

Since the OSC method was deemed appropriate for the project, the user proceeded to Stage 2 to determine the most suitable IBS for maximizing the efficiency of the construction method and ensuring the success of the project. The methodology and steps in Stage 2 were similar to those in Stage 1.

The user compares two applicable IBS systems for the project. The first IBS (Alternative 1) was a volumetric modular unit, while the second IBS (Alternative 2) was a panelized unit (a closed light-gauge steel panel).

Table 5.10 provides a comparative analysis of the two alternatives with respect to the project's seven main factors based on the relevant literature and expert knowledge and experience.

Table 5.10 Comparative analysis of the two alternatives with respect to seven main factors (dimensions)

Main Factor (Dimension)	**Alternative 1 (IBS No.1- Volumetric modular unit)**	**Alternative 2 (IBS No.2 - Panelized unit)**
D1: Project Characteristics	These are 3D modules that are produced in a factory and then transported to the construction site. They are typically fully finished with internal fittings, fixtures, and services before arrival. This system is well-suited for this project, since uniformity and repetition are involved.	This system involves flat panel units that are produced off site and assembled on site. The panels can include walls, floors, and roofs, and are made of light-gauge steel. This system allows for design flexibility and can be adapted to this project.
D2: Supply Chain	The supply chain for volumetric modular units is typically streamlined, as the majority of the construction is completed off site by a single manufacturer. This can reduce the number of suppliers and subcontractors involved	The panelized system may involve a more complex supply chain, with different suppliers for the panels, services and other components. However, it can also allow for more local sourcing of materials and labour for the on-site assembly.
D3: Time	Volumetric modular construction can significantly reduce the overall project timeline, as modules are manufactured concurrently with site work. This parallel processing can lead to faster occupancy and return on investment.	Panelized units also offer time savings when compared to traditional construction, but the time advantage may be less pronounced than with volumetric modular units since more on-site assembly and finishing are required.

Table 5.10 Comparative analysis of the two alternatives with respect to seven main factors (continued)

Main Factor (Dimension)	Alternative 1 (IBS No.1-Volumetric modular unit)	Alternative 2 (IBS No.2 - Panelized unit)
D4: Cost	While the initial cost for volumetric modular units can be higher due to the extensive factory work, the overall project cost can be lower when factoring in the reduced construction time and potential for fewer on-site labour hours.	Panelized units can be cost-effective, especially if the design leverages the standardization of panels. However, costs can escalate if extensive customization is required, or if there are delays in the assembly process.
D5: Quality	Quality control is often higher for volumetric units since they are produced in a controlled factory environment. This can lead to better consistency and performance of the finished building.	Panelized systems benefit from factory production, but the final quality also depends on the skill of the on-site assembly team. There is potential for quality issues if the panels are not assembled correctly.
D6: Procurement	Procurement for volumetric modular units is typically straightforward, with a single manufacturer providing the complete module. This can simplify the procurement process, but may limit flexibility in terms of design changes.	Procurement for panelized units can be complex, involving multiple suppliers and coordination. However, this can also allow for more competitive bidding and potential cost savings.
D7: Socio-Cultural	Volumetric modular construction can face socio-cultural barriers, such as resistance from local labour markets due to the perception of job losses in factories. However, it can also be seen as innovative and environmentally friendly.	Panelized construction may be more readily accepted, as it requires a significant amount of on-site labour, which can be beneficial for the local economy. It can also be perceived as a more traditional form of construction, which may be more culturally acceptable in certain areas.

The UI depicted in Figure 5.6 facilitated the decision-making process by allowing the selection of two IBS alternatives from the Revit model for pairwise comparison, following the same methodology and steps as those outlined in Stage 1. In this case, the BeDSS plugin identified two IBS options: 'Volumetric Module' and 'Prefab Wall Panel.' The user designated 'Volumetric Module' as Alternative 1 and 'Prefab Wall Panel' as Alternative 2.

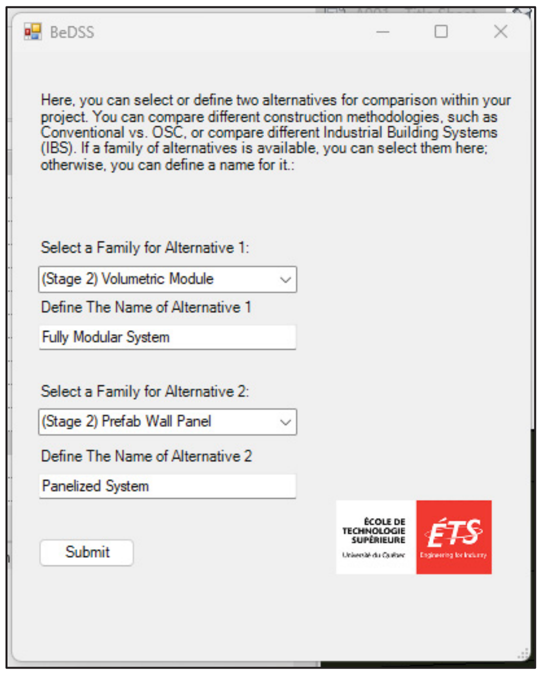

Figure 5.6 Screenshot of IBS selection in BeDSS stage 2

Figure 5.7 illustrates the process of assigning importance to main and sub-factors. In this regard, the user assessed the significance of each main factor (dimension) and sub-factor in selecting a suitable IBS for the project.

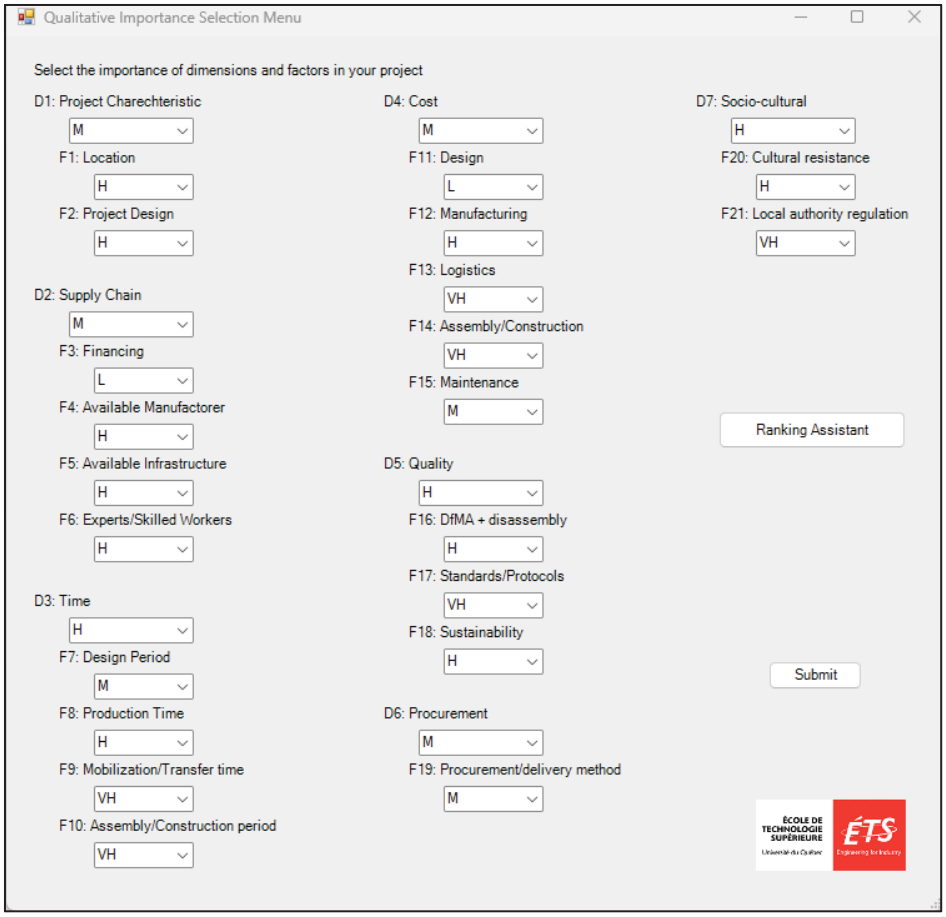

Figure 5.7 BeDSS user interface for assigning importance to factors

Based on the user's input regarding the importance of each main factor (dimension) and sub-factor, the software automatically populates the recommended values for the pairwise comparison. Table 5.11 shows the mapping of the BeDSS's recommended pairwise rating, taken from Ishizaka (2014).

Table 5.11 Mapping of recommended pairwise ratings by BeDSS

Mapping of default pairwise rating by DSS				
Pairwise		Fuzzy AHP		
VH	VH	1	1	1
VH	H	2	3	4
VH	M	6	7	8
VH	L	9	9	9
H	H	1	1	1
H	M	2	3	4
H	L	6	7	8
M	M	1	1	1
M	L	2	3	4
L	L	1	1	1

This functionality aids the decision maker in reviewing the scores and making appropriate adjustments. The system also performs automatic checks of the consistency of the scoring, notifying the user if the CR is deemed unacceptable. BeDSS is programmed to extract data automatically, and the user can access this information by clicking on the 'BIM Information' button. Figure 5.8 shows the automatic scoring of the pairwise comparison of main factor analyzed by BeDSS for the case project, as well as an example of the CR check.

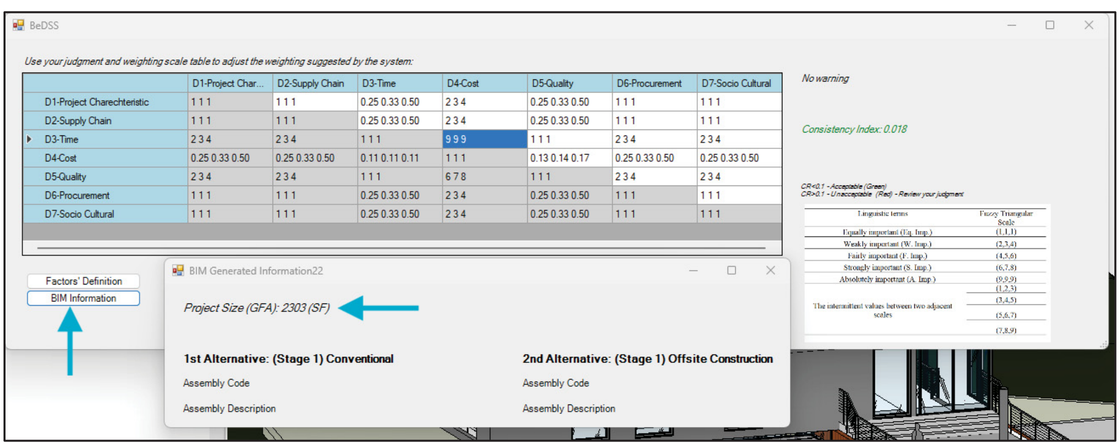

Figure 5.8 Automatic scoring by BeDSS

Moreover, BeDSS can automatically extract various parameters from the Revit model for each alternative. Figure 5.9 compares the extracted data from both alternatives side by side, including the total project gross floor area. This information assists in making informed judgments as part of the pairwise comparison.

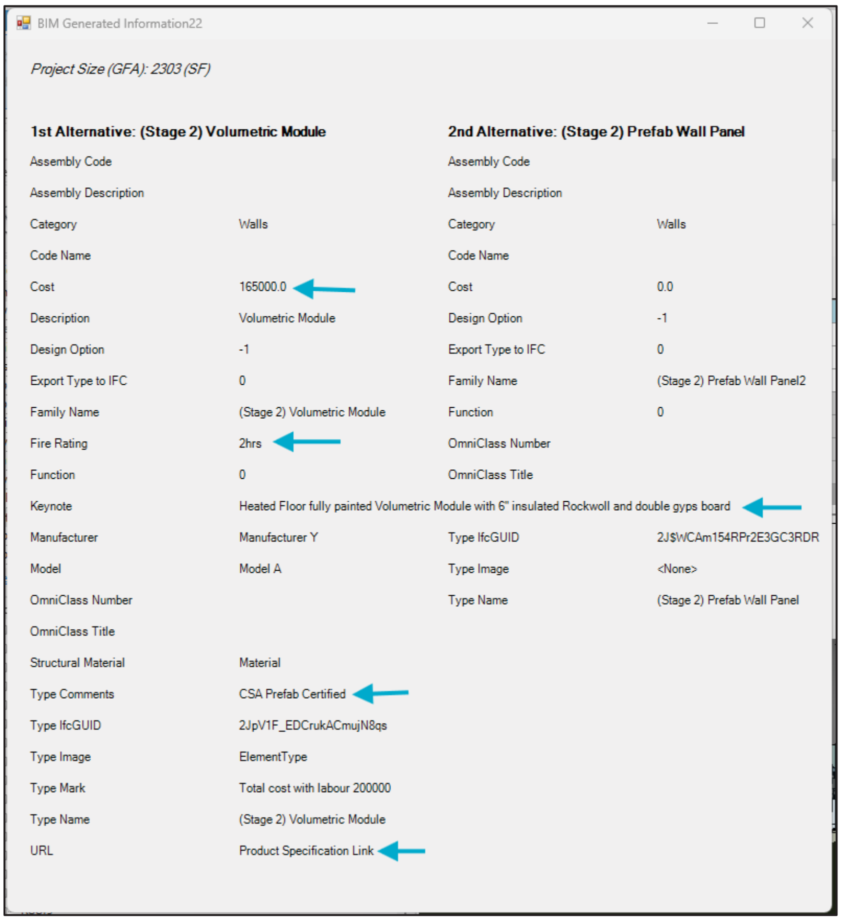

Figure 5.9 Extracted data from BIM model for alternatives

During the pairwise comparison of factors within each dimension, the user evaluated the performance of each alternative with respect to these factors. Figure 5.10 shows the comparison between F1 (Location) and F2 (Project Design). Given the considerable distance between the project site and the factory, the user deemed the panelized method (Alternative 2) to be significantly superior to the modular method for this particular case, assigning scores of

(7, 8, 9) for this pairwise comparison. Regarding F2 (Project Design), the user favored the modular method due to its repetitive layout design, resulting in scores of (1/4, 1/3, 1/2) in the F2 matrix.

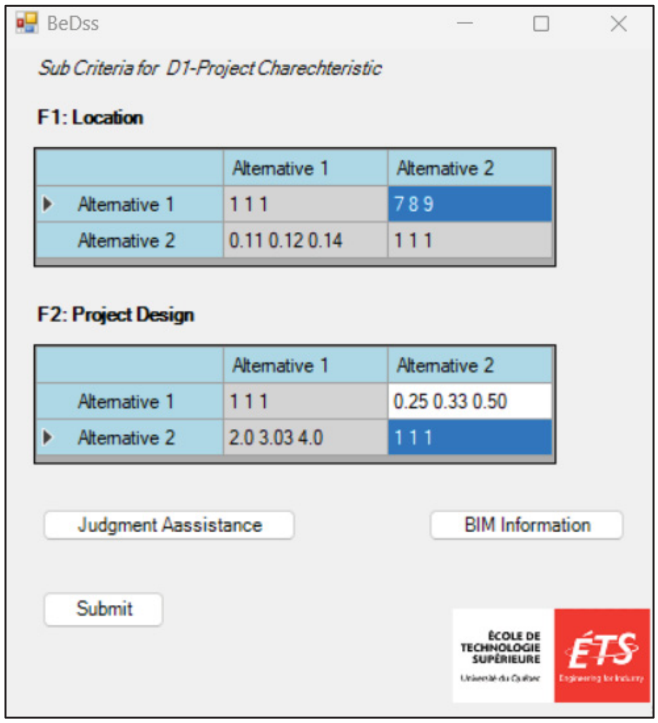

Figure 5.10 Pairwise comparison of
F1 and F2 within D1

Once the scoring had been completed for all factors, the BeDSS determined and displayed the most suitable IBS system for the case project—Alternative 2 (see figure 5.11).

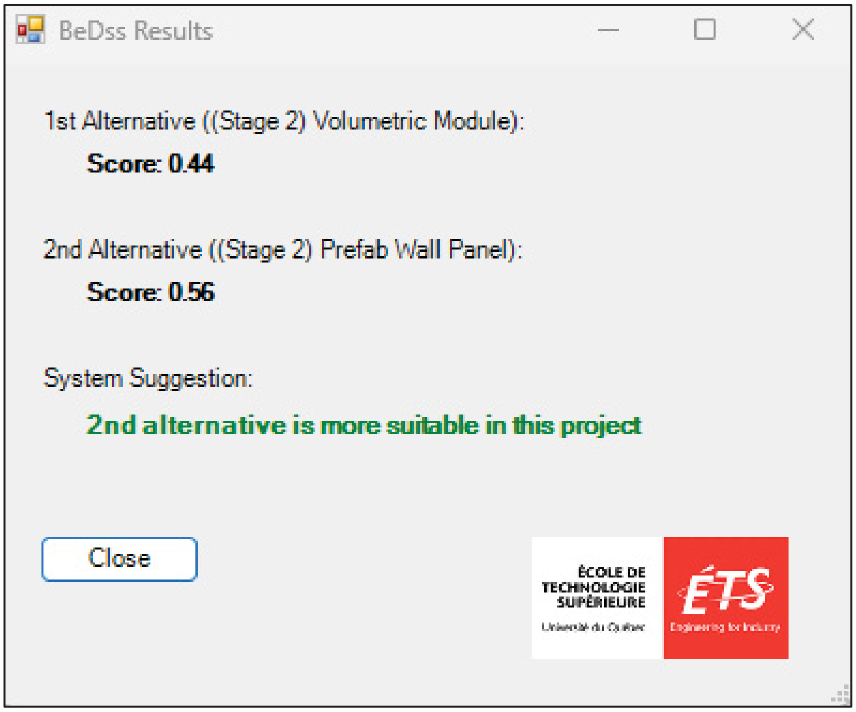

Figure 5.11 Screenshot of BeDSS recommendation in Stage 2

5.5.3 Evaluation of the proposed BeDSS

Following the development and initial testing of the BeDSS software, a group of industry experts was invited to evaluate the software and provide feedback. The purpose of this evaluation was to assess various aspects of the software, including its usability, functionality, decision-making process, and overall satisfaction. Fifteen experts from diverse backgrounds—representing fields such as structural engineering, mechanical, electrical and plumbing (MEP) engineering, architecture, environmental science, project management, and software engineering—participated in the evaluation. These experts came from different organizations, including consulting firms, contractors, academic institutions, government agencies, and non-profit organizations. To ensure the reliability of the data obtained, Cronbach's alpha was used as a measure of internal consistency. This statistical method, which is used to validate the internal consistency of a questionnaire or survey, was employed to validate the KDSFs proposed by Mehdipoor and al. (2023a) in a previous study and employed in the present study.

The analysis yielded a Cronbach's alpha value of 0.76, which falls within an acceptable threshold for dataset reliability. Table 5.12 presents the results of the Cronbach's alpha test:

Table 5.12 Cronbach's alpha test for BeDSS evaluation

Variable	Description	Value	Internal cconsistency
K	Number of evaluation items	13	0.76
$\sum S^2 y$	The sum of each items' variance	4.89	
$S^2 x$	The variance of a sum of items' value	16.51	

Furthermore, the statistical mean scores for various aspects of the software, including its usability, functionality, decision-making process, and overall satisfaction were used to determine the level of satisfaction and performance of the software. The decision-making aspect was ranked the highest, where this aspect encompasses the explanation of factors influencing the decision, their relevance to the decision-making process, and the level of assistance the user may require in order to make informed decisions. The next aspect, usability of the software, includes factors such as ease of installation, UI, integration of plugins with Revit, and the overall user experience. The experts highlighted areas for improvement regarding the usability aspect, such as providing a more user-friendly scoring dashboard and simplifying the data entry method for pairwise comparisons. Overall, the proposed software received a satisfaction rating of 3.93 on a scale ranging from 1 (very dissatisfied) to 5 (very satisfied). This indicates an acceptable level of satisfaction among the experts.

In summary, the BeDSS software was evaluated by industry experts from various backgrounds and organizations and was deemed to be satisfactory, with the reliability of the expert feedback (i.e., satisfaction ratings) having been confirmed via statistical analysis. The decision-making aspect received the highest rank, while usability was identified as an area for improvement.

5.5.4 Post Validation of the proposed BeDSS

To validate and verify the results obtained by the developed BeDSS, they results were compared to the results obtained when employing fuzzy logic in the selection of a suitable method for the case study. It should be noted in this regard that Rezaei and al. (2013) employed a similar approach in running both standard AHP and FAHP for the purpose of comparison and validation of a proposed FAHP decision support tool for selecting locations for underground dam infrastructure. Mehdipoor and al. (2023b) presented the results of using fuzzy logic for the same KDSFs and case study in a previous work. As reported there, using fuzzy logic in selecting the most suitable alternative helped to reduce the vagueness and uncertainty inherent in the problem. Table 5.13 summarizes the results obtained for both BeDSS and fuzzy logic:

Table 5.13 Results obtained from BeDSS and fuzzy logic

Alternatives	Crisp scores (Fuzzy Logic)	Rank using Fuzzy Logic	FAHP score by BeDSS	Rank using BeDSS
Conventional Method	46.04	2	0.11	2
OSC Method	70.32	1	0.88	1

In employing both BeDSS and fuzzy logic to rank the alternatives, OSC was identified by both approaches as the most suitable method for the case project.

To summarize, the validation of the BeDSS involved comparing its results with those obtained through fuzzy logic. The use of fuzzy logic helped to account for the inherent vagueness and uncertainty in the problem. The comparison of rankings between BeDSS and fuzzy logic confirmed OSC method to be the most suitable alternative for the project.

5.6 Conclusion

This paper presented a two-stage BIM-enabled DSS that enhances the decision-making process in OSC projects. The outcomes of this research advance the integration of OSC with BIM to improve construction efficiency and assist decision-makers in making more reliable decisions in the selection of suitable construction methodologies and IBS for a given project. This is accomplished by gaining insight regarding the potential benefits of OSC and the adoption of a suitable IBS for a given project, with the goal of improving productivity and project outcomes through the selection of a suitable construction method and IBS.

This paper outlined both the two-stage decision-making process and the development of the BeDSS. During the first stage, the user evaluates the suitability of using OSC for the given building project based on a set of validated KDSFs, these factors having been identified and validated through systematic literature reviews and expert interviews. The proposed BeDSS uses MCDM techniques, such as FAHP, to recommend the most suitable construction method. During the second stage, the user selects a suitable IBS solution for the given OSC project. The BeDSS plugin, integrated with BIM tools, is capable of checking the consistency of the user's input throughout the process and extracting relevant data from the BIM model. Moreover, it facilitates the decision-making process by supporting the selection of IBS alternatives and conducting pairwise comparisons in order to determine the most suitable IBS system for the given project. The proposed BeDSS was implemented in a real-world scenario in Canada. The outcome of the Stage 1 analysis was that OSC was deemed the most appropriate construction method for the project based on weighted evaluations of KDSFs. In Stage 2, the prefabricated wall panel system was deemed to be the most suitable IBS for the project.

Following the development and initial testing of the BeDSS software, a panel of industry experts from diverse backgrounds and organizations was engaged to evaluate the software and provide feedback through interviews and questionnaires. The reliability of the collected data was ensured through rigorous statistical analysis, and the software's performance was assessed based on experts' satisfaction ratings. Notably, the decision-making capability of the developed plugin received the highest satisfaction ranking, signifying its efficacy. However, the usability aspect was identified as an area warranting improvement in terms of user-friendliness. Overall, the level of satisfaction was deemed satisfactory.

Finally, to post-validate the outcomes generated by BeDSS, a comparative analysis was conducted, comparing the results obtained by BeDSS to those obtained when employing fuzzy logic to determine an appropriate construction method for the case study, the fuzzy logic results having been obtained in a previous study. The use of fuzzy logic to select the most suitable alternative for the case project is an effective strategy for mitigating the imprecision and uncertainty inherent in the decision making process. Examining the ranking of alternatives using both the BeDSS and fuzzy logic methods, the OSC method was confirmed to be the most suitable approach for the project.

One limitation of this study is the reliance on expert judgment for the assessment and pairwise comparison of the KDSFs through BeDSS. While their judgment provides valuable insights, experts may be subject to individual biases and limitations. The effectiveness of the BeDSS also relies on the availability and accuracy of data inputs. However, in practice, obtaining comprehensive and reliable data for decision-making can be challenging. The lack of standardized data collection processes and the reluctance of stakeholders to share sensitive project information may limit the accuracy and reliability of the proposed system. Moreover, the BeDSS relies on the integration of BIM tools and software plugins. While BIM has gained significant traction in the construction industry, there may still be limitations in terms of interoperability and compatibility among different BIM platforms and software applications. These technological constraints may hinder the integration and functionality of the BeDSS.

Future areas of research can include addressing these technological limitations and developing standardized protocols for BIM integration to enhance the usability and effectiveness of DSSs in OSC. To further enhance the applicability and effectiveness of the proposed BeDSS, future research could focus on the integration of real-time data and advanced analytics. Incorporating real-time data from construction projects, such as cost data, schedule information, and performance metrics, could provide decision-makers with more accurate and timely insights for selecting a suitable construction method and IBS. Additionally, the leveraging of advanced analytics techniques, such as machine learning and predictive modeling, could enable the BeDSS to continuously learn and improve its decision-making capabilities over time. This would enhance the system's adaptability and responsiveness to changing project requirements and industry dynamics.

CHAPTER 6

ENHANCING THE MANUFACTURING PROCESS IN LIGHT-GAUGE STEEL OFF-SITE CONSTRUCTION USING SEMI-AUTOMATION

A. Mehdipoor[1], I. Iordanova[1], M. Al-Hussein[2]

[1]Department of Construction Engineering, École de Technologie Supérieure, 1100 Notre-Dame Ouest, Montréal, Québec, Canada H3C 1K3
[2] Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Canada T6G 2R3

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6.1 Abstract

Purpose – This study introduces a digitalized workflow for light-gauge steel off-site construction projects to reduce task duration, enhance data flow, and improve project cost assessment. With technological advancements, digitalization and building information modeling have become crucial in off-site construction to boost productivity. This research systematically integrates these technologies within the off-site construction framework, aiming to decrease manufacturing duration and enhance the accuracy of the bill of quantities for cost assessment during the manufacturing phase. The study addresses the knowledge and practice gap by presenting a comprehensive workflow tailored for light-gauge steel off-site construction projects.

Design/methods/approach – The study employs a design science research approach to develop the proposed workflow. Two hypotheses are tested: (1) A digitalized workflow significantly reduces task duration and improves project cost assessment, and (2) Semi-automation is a financially feasible investment with a payback period shorter than the total project duration. A real modular project with 47 modules and a total gross floor area of 2,500 m² is used to apply and evaluate the workflow. The hypotheses are tested by comparing task durations and bill of quantities accuracy before and after implementing the workflow. The economic feasibility is assessed through a cost–benefit analysis referencing the case project.

Findings – Three months of data post-implementation show a 66% reduction in task duration and a 45% improvement in bill of quantities accuracy. On average, the workflow resulted in a 38% reduction in production and assembly duration and a 11% improvement in measurement accuracy. The cost–benefit analysis indicates a payback period of 10 months and 26 days for the initial investment.

Research limitations/implications – The results are validated within the Canadian construction industry context. This paper focuses on the design and manufacturing phases, suggesting further studies should cover the installation and operation stages.

Keywords: off-site construction, digital fabrication, off-site manufacturing, automation

6.2 Introduction

The Construction Industry Council (Kier Construction, 2018) defines off-site manufacturing (OSM) as a delivery method that adds value to a product and process through factory manufacture and assembly intervention, with a focus on manufacturing. OSM can also be understood to refer to the production and prefabrication phase of the off-site construction (OSC) approach (Goulding & Rahimian, 2019). OSC, in turn, is a construction approach wherein most on-site construction operations are transferred to a controlled off-site production facility. Within this controlled environment, sophisticated machinery and manufacturing principles are employed to prefabricate building components with a focus on standardization and efficiency (Liu et al., 2017). The principal categories of OSM within OSC are panelized, volumetric, hybrid, and modular systems, as well as component and sub-assembly systems (Abanda et al., 2017).

It is well documented that cost and schedule overruns are common within the construction sector (Jin et al., 2018; Van Vuuren, 2020). The primary contributor to these overruns is productivity issues, which encompass a range of specific problems such as inefficient workflows, labour shortages, rework due to errors, and poor coordination among different trades (Bertram et al., 2019; Changali et al., 2015; de Laubier et al., 2019). In this regard, digital fabrication and OSM have emerged as promising solutions for addressing these persistent challenges within the construction industry (Wang et al., 2020).

However, the realization of the potential benefits of OSC in practice has been limited. Scholars have noted that the various forms of process waste and inefficiencies in OSC point to a gap between theory and practice (Ayinla et al., 2022; Zhang et al., 2020). For instance, Ayinla et al. (2022) conducted a process waste analysis of off-site production methods in house construction, identifying significant inefficiencies in factory wall panel production. Their study found that OSM methods that merely replicate the manual methods typical of on-site construction but in an off-site production facility do not necessarily provide marked improvements over conventional on-site methods.

They argued that the production process must follow a structured workflow and incorporate automation in order to achieve a significant improvement in productivity.

Similarly, Zhang et al. (2020) introduced a process-oriented framework to improve manufacturing performance in OSC. They integrated value stream mapping (VSM) with a production line breakdown structure (PBS) in order to analyze current-state production line performance and assess proposed solutions for improved performance. Their findings underscored that the construction manufacturing domain may not fully benefit from modular construction and lean implementation when employing methods similar to those of conventional on-site construction. It is also noted in the literature that the critical factors influencing success in OSC projects primarily revolve around time/schedule. These factors include the duration of the design phase, the time required for production, mobilization, and transfer, as well as the assembly and construction period (Mehdipoor et al., 2023).

Moreover, it has been observed that project success in OSC is contingent upon effective implementation of the integrated project delivery approach, where the OSC contractor is tasked with effectively managing the premanufacturing phases of design, planning, and procurement. This involves design, material procurement, and the generation of shop drawings for both off-site production and on-site installation. In undertaking these activities, the OSC contractor assumes a substantial amount of risk transferred from the client, taking responsibility for all activities from engineering services to the partial or complete execution of the project (Barkokebas et al., 2023).

Design for Manufacture and Assembly (DfMA) has emerged as a prominent paradigm coinciding with the growing prominence of prefabrication and the industrialization of construction. DfMA encompasses a nuanced interplay of opportunities and challenges, serving as a dynamic means to enhancing construction productivity (Lu et al., 2021). It entails harnessing advancements in construction materials, production, and assembly technologies, along with ongoing improvements in logistics and supply chain management (Goulding & Rahimian, 2019).

The adoption of DfMA has been limited, however, and there is a shortage of documented evidence of its successful implementation in construction in the literature (Bao et al., 2022; Wasim et al., 2020). The adoption of DfMA in OSC in particular remains relatively modest, and there is little data available concerning its prevalence in the industry (Rankohi et al., 2022). Moreover, there is little information available in the literature concerning the linkages between OSM in construction and the overarching concepts of digitalization, automation, and DfMA (Jin et al., 2018).

While the construction industry, particularly OSC, has seen the application of automation and digitalization technologies (Alwisy et al., 2019; Bowmaster & Rankin, 2019; Ilhan et al., 2019), the present study stands out in its systematic integration of these technologies within the OSC framework, bridging the gaps in knowledge and practice by presenting a comprehensive workflow specifically designed for light-gauge steel (LGS) OSC projects.

For the purposes of the present study, semi-automation is defined as a hybrid approach that combines automated processes with human intervention. In the present context, it refers to an approach in which automated machinery is incorporated for tasks such as cutting and assembly of LGS components, while human oversight, as well as manual tasks such as feeding the steel roll into the framing machine, stacking the studs produced during the production phase, and assembling panels during the product assembly phase, are still required.

Overall, this study presents a systematic approach to tackling process uncertainties and boosting productivity in OSC, recognizing the existing use of automation in LGS construction. It adds valuable insights to the expanding literature on digitalization and automation in OSC, underscoring the significance of custom-made workflows for distinct construction scenarios.

The specific goals included reducing task duration, enhancing data flow, and improving project cost assessment. The research sought to overcome the limitations of current practice by providing insights into the implementation of digitalized and automated techniques in the context of OSC, with a focus on the design, manufacturing, and assembly phases. The literature review that follows provides a summary of existing studies, linking the theoretical underpinnings to the practical application of digitalized and automated approach in the design, manufacturing, and assembly phases of OSC. By addressing the gap between theoretical benefits and practical realization, this study aims to contribute to the body of knowledge on OSC and provide a practical solution to enhance productivity and efficiency in LGS construction projects.

6.3 Literature review

6.3.1 Digitalization and automation in construction

The construction industry, particularly OSC, has been slow to embrace digitalization (e.g., computer-aided design, automation technologies) compared to sectors such as aerospace and automobile manufacturing. (Antwi-Afari et al., 2018; Ilhan et al., 2019; Petersen et al., 2019). This literature review summarizes the reasons for the slow adoption of digitalization and automation in OSC as identified in existing scholarship. One of the notable barriers identified in the literature is that the upfront investment required for purchasing and implementing advanced digital and automation technologies can be prohibitively high for many construction firms, particularly small and medium-sized enterprises (SMEs) (Oesterreich & Teuteberg, 2016).

Moreover, there is a significant skills gap in the construction industry, with a shortage of workers proficient in the use of advanced digital tools and automation technologies. This lack of expertise can impede the effective implementation and utilization of these technologies (Shojaei et al., 2023). Furthermore, in terms of the industry's culture the construction sector tends to be conservative, with a strong preference for established methods and practices. This cultural resistance to change can be a major barrier to the adoption of new technologies (Whyte, 2019). Moreover, different digital tools and automation systems may not be compatible with one another, leading to interoperability issues.

This lack of standardization can complicate the integration of various technologies and limit their effectiveness (Pan & Zhang, 2021).

In the context of OSC in particular, automation refers to the use of technology to perform tasks without human intervention within a controlled factory environment. This can encompass various stages of the construction process, such as design, production, and assembly (Agkathidis, 2010; Caneparo, 2014; Ham & Lee, 2019). Automation in OSC differs from on-site construction automation in several ways:

Design Automation: Involves the use of software tools such as Building Information Modeling (BIM) to create detailed digital representations of building components. This allows for precise planning and coordination before production begins (Eastman et al., 2011).

Production Automation: Refers to the use of machinery and robotics to fabricate building components in a factory setting. With regard to LGS construction, this could include tasks such as cutting, welding, and assembling LGS components (Bock & Linner, 2015).

Assembly Automation: Involves the use of automated systems to assemble prefabricated components into final structures, either in the factory or on site (Cheng et al., 2023).

Automation faces limitations in terms of the capacity to accommodate diverse materials and designs, and this has inhibited its application in construction, as has the considerable cost associated with acquiring and maintaining automation equipment (Petersen et al., 2019). Moreover, the scarcity of skilled labour has been identified as a hindrance to the effective implementation of automation technologies.

Furthermore, the dynamic nature of construction sites, which are characterized by unexpected conditions, adds a layer of complexity to the integration of automation. Frequent design changes in construction projects is another factor challenging the effective implementation of automation (Ilhan et al., 2019).

Communication challenges represent yet another factor impeding the smooth adoption of automation technologies in construction. Finally, some of the tools and techniques associated with automation are impracticable to adopt within the construction context (O'Connor et al., 2014).

Beyond these challenges, the manual and ad hoc decision-making paradigm that predominates the boarding design of light-frame buildings contribute significantly to material waste. This highlights the urgent need to explore and adopt automated design and planning strategies to minimize waste and enhance efficiency in the OSC sector (Liu et al., 2018).

To overcome these barriers, not only are advancements needed in terms of the technological capabilities of automation, but a paradigm shift in the industry's mindset is required. Such a shift can facilitate the establishment of a culture that embraces the benefits of automation and effectively addresses its limitations through strategic integration and adaptation.

6.3.2 Integration of BIM, Digital Fabrication and automation in OSC

Agustí-Juan et al. (2017) define the application of digital fabrication as an automated and robotics-based production approach employing computer-aided design methods (Agustí-Juan & Habert, 2017). Agkathidis (2010) further expounds on the concept of digital fabrication, characterizing it as a construction method that involves the use of digital tools for planning, manufacturing, and assembly (Agkathidis, 2010).

However, to facilitate the transition from conventional planning and on-site construction methods to digital fabrication, the integration of advanced manufacturing machinery, such as computer numerical control (CNC) machines, is essential. Moreover, proficiency in interpreting data derived from drawings and BIM is crucial in the effective operation and control of these machines.

Consequently, designers must possess a comprehensive understanding of the processes involved and the interoperability between BIM and automated machinery in order to effectively implement digital fabrication (Iwamoto, 2009).

Numerous studies have investigated the advantages of optimizing construction efficiency through the integration of BIM and digital fabrication and automation. Recent studies highlight several key benefits associated with this approach in OSC:

Improved coordination and collabouration: Ham & Lee explored the advantages of digital fabrication in construction management, assessing its impact on project management aspects through the lens of the Project Management Body of Knowledge. Their findings revealed numerous benefits associated with the adoption of digital fabrication in construction projects. They argued that, while there are challenges related to the adoption of digital fabrication (e.g., cost reduction and control), these do not negate the overall positive impact of digital fabrication (Ham & Lee, 2019).

2.2.2 Enhanced Efficiency and Productivity: Automation in off-site construction significantly reduces the time required for building processes. By utilizing advanced robotics and automated machinery, tasks that traditionally took weeks can now be completed in a matter of days. This efficiency not only accelerates project timelines but also allows for the simultaneous execution of multiple projects, thereby increasing overall productivity (Petersen et al., 2019).

Additionally, Significant advancements have been achieved in the domain of construction automation, such as the recent development of advanced machines designed for autonomous operation and material–robot systems tailored for specific assembly tasks (Petersen et al., 2019). Key attributes of digital fabrication for enhancing productivity within the OSC domain, such as ease of handling and assembly, have been highlighted (Gbadamosi et al., 2019).

Moreover, the integration of robotics into flexible manufacturing systems (FMS) has been identified as a potential strategy for increasing modular construction flexibility. By incorporating robotics into FMS, prefabricated building component manufacturing systems gain flexibility, allowing for real-time adjustments, improved equipment utilization, reduced set-up times, and varying speeds, which collectively enhance productivity and reduce manpower requirements (Castaneda et al., 2023).

2.2.3 Improved Quality and Precision: Automated systems ensure a higher level of precision and consistency in construction tasks. This leads to improved quality of the final product, with fewer defects and a reduced need for rework. The use of computer-aided design and manufacturing technologies ensures that components are produced to exact specifications, enhancing the overall structural integrity and aesthetic appeal of buildings (Chea et al., 2020).

These enhancements can be supported by automation in construction and the use of high-tech machines for specific manufacturing and assembly tasks. Meanwhile, BIM is capable of assisting designers in understanding design requirements for digital fabrication and automated manufacturing and assembly systems, with this paradigm commonly referred to as DfMA (Abd Razak et al., 2022).

Long term cost benefit: While the initial investment in automation technology can be substantial, the long-term cost savings are significant. Barkokebas et al. (2023) highlights the integration of digitalization and automation as a cornerstone for improving processes and enhancing communication across the construction industry. Despite the challenges and uncertainties in implementing digitalization approaches, particularly in OSC companies, a digitalization-based workflow can significantly reduce the duration and increase the accuracy of premanufacturing phases. By developing and implementing a digitalization plan and automation implementation, OSC companies can identify waste in current practices and propose suitable improvement measures.

This approach not only reduces task durations but also provides more accurate estimates, leading to substantial cost savings over time (Barkokebas et al., 2023).

Safety Improvements: Automation reduces the need for human labour in hazardous environments, thereby enhancing worker safety. A study by Gusmao Brissi et al (2022) discussed that the interactions of robotic systems and lean construction in OSC can significantly improve safety outcomes. The study identified various interactions, including the use of robots, automated equipment, wearable devices, unmanned aerial vehicles (UAVs), automated guided vehicles (AGVs), and digital fabrication/computer numerical control (CNC) machines. These technologies can perform dangerous tasks such as heavy lifting, welding, and working at heights, which reduces the risk of accidents and injuries on construction sites. This not only protects workers but also reduces the costs associated with workplace accidents (Gusmao Brissi et al., 2022).

Environmental Benefits: Integration BIM, digitalization and automation in off-site construction can contribute to sustainability goals by optimizing material usage and reducing waste (de Laubier et al., 2019). Precision manufacturing ensures that materials are cut and assembled with minimal waste, and the controlled environment of off-site facilities allows for better management of resources and energy consumption. Additionally, the reduced need for transportation of materials and workers to and from construction sites lowers the carbon footprint of construction projects (Goulding & Rahimian, 2019).

Moreover, one of the least used aspects of BIM is the ability to obtain the energy model of the building using the BIM methodology known as BIM 6D. This digital information model allows simulating the real energy behavior of the building and improving the building's lighting systems, both natural and artificial. BIM 6D enables design and operation decisions that enhance energy efficiency, particularly in Nearly Zero-Energy Buildings (NZEB) and the rehabilitation of existing buildings.

For instance, in public buildings such as hospitals, BIM 6D can lead to significant energy savings and improved lighting efficiency, contributing to the decarbonization of high energy consumption buildings and enhancing their energy certification (Montiel-Santiago et al., 2020).

As summarized above, the integration of BIM, automation, and digital fabrication represents a critical pathway towards improving the efficiency of manufacturing and assembly in OSC. The present study focuses on design and production automation, whereas the assembly phase in the proposed workflow remains a manual process. As such, it is considered a semi-automated workflow. The following section discusses the methodology underlying the implementation of each phase of the proposed workflow.

6.4 Research Methods

This study implements the design science research (DSR) method to develop a workflow for improving the manufacturing process in LGS-OSC projects. The steps outlined by Rocha et al. for the implementation of DSR in lean construction are adopted (Rocha et al., 2012). The steps are as follows:

Step 1 – Problem Identification: Acquire a comprehensive understanding of the topic and identify practically relevant issues.

Step 2 – Solution Design: Propose a potential design and develop an artifact/prototype capable of addressing the identified problem.

Step 3 – Validation and Assessment: Evaluate and assess the performance of the proposed solution through its application in real case studies.

Two assumptions are tested:

Research assumption 1: The implementation of a digitalized workflow in LGS-OSC projects significantly reduces task duration and improves project cost assessment by enhancing data flow and accuracy of the bill of quantities.

Research assumption 2: The application of semi-automation and digitalization in the manufacturing process of LGS-OSC projects is a financially feasible investment, with a payback period less than the total project duration, leading to improved productivity and cost-effectiveness in the construction industry.

Figure 6.1 provides an overview of the DSR method employed in this research. The method is applied to the design and development of a workflow for implementing a semi-automation process to enhance the manufacturing phase through digitalization. A real project is used as a case study to demonstrate the successful implementation of the workflow and to evaluate the hypotheses.

The case study focuses on the manufacture and assembly of LGS components as part of an OSC project. This involves the production of custom LGS panels designed to meet specific project requirements, incorporating unique dimensions and configurations as dictated by the project's architectural and structural needs.

This customization necessitates a more flexible and precise manufacturing process, where the proposed digitalized and semi-automated workflow plays a crucial role. The primary problem identified in this context is inefficiencies in the manufacturing process, leading to extended task durations and inaccuracies in the bill of quantities, ultimately resulting in increased operational costs and project delays.

To test the assumptions, the durations of tasks and the accuracy of the bill of quantities are compared before and after the implementation of the proposed workflow for different components of the case study. By applying the proposed digitalized and semi-automated workflow to a real OSC project, we can ensure that the solution is not only theoretically sound but also practically viable.

According to Yin (2018), case studies provide rich, detailed insights into the implementation process, including the challenges encountered and the solutions adopted. Therefore, this real-world application offers empirical evidence of the workflow's effectiveness in reducing task durations and improving the accuracy of the bill of quantities. It is important to acknowledge the exploratory nature of this case study.

The research aims to both test specific hypotheses and build a deeper understanding of the impact of digitalization and semi-automation on LGS-OSC projects. This dual approach enhances the overall rigour and clarity of the research. Furthermore, a cost-benefit analysis (CBA) is employed to investigate the economic feasibility of the proposed solution. CBA, it should be noted, provides a means of assessing economic feasibility and selecting effective projects in the investment decision-making domain (Huang, 2021; Kim et al., 2022).

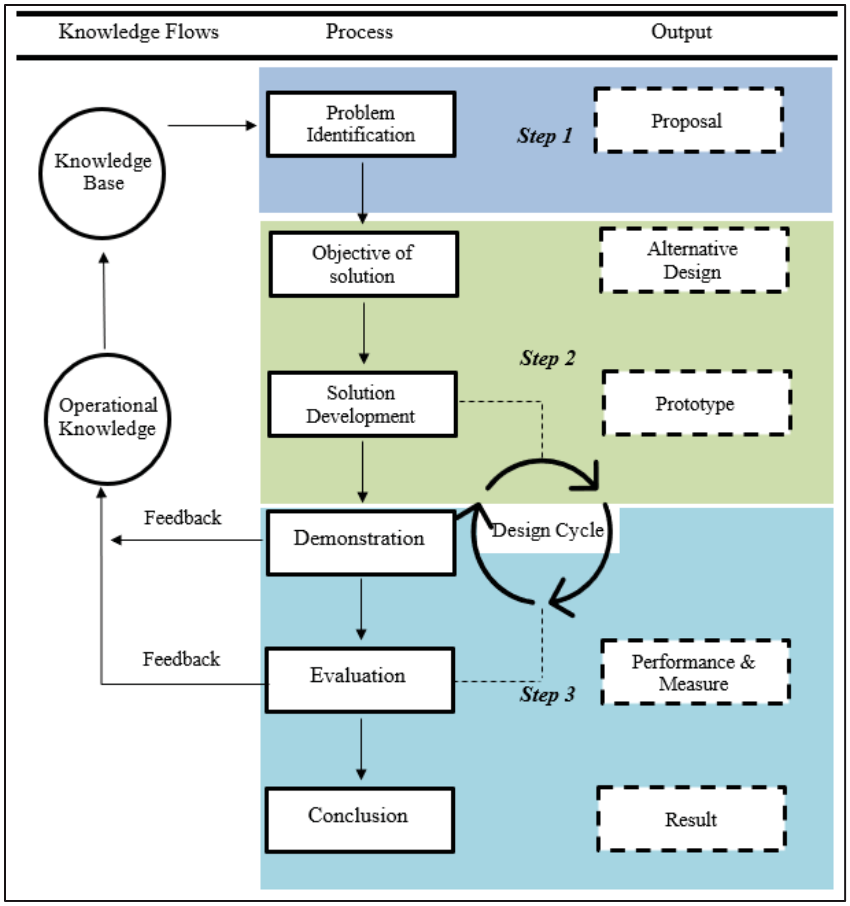

Figure 6.1 Overview of DSR method

6.4.1 Business Process Model and Notation

In a typical design process that adheres to established rules, the steps can be characterized as a series of connected activities, events, and steps within a model. The standard known as Business Process Model and Notation (BPMN) is employed to illustrate this concept (ISO/IEC 19510:2013 - Information Technology - Object Management Group Business Process Model and Notation, 2013). BPMN helps to depict each part of the design process, including actions, important events, and the logical order of steps, in a clear manner. Through the use of BPMN, a visual representation can be created that makes it easier to understand how the design process works.

Moreover, it serves as a graphical representation tool for illustrating business processes in a standardized and easily understandable manner, providing a comprehensive set of process elements specifically designed for articulating policy content or rules within an organization (Häußler et al., 2021).

This standard is widely accepted and ensures a structured and clear way of presenting the steps, promoting consistency in the overall process (Häußler et al., 2021). Within the Architecture, Engineering, and Construction (AEC) field, BPMN is frequently employed to depict the processes involved in model creation, collabouration, and data exchange throughout the planning, execution, and handover phases of a project (Alreshidi et al., 2016).

The fundamental components of BPMN are events, which denote significant occurrences in a process, such as the initiation or completion of a task (start- and end-points); tasks, which represent the specific actions or work performed, ranging from user tasks involving human interaction to script tasks; and gateways, which act as decision points, allowing for divergent or convergent paths in the process. Examples of gateways include exclusive gateways, indicating mutually exclusive choices, and parallel gateways, allowing for simultaneous execution of tasks. The connections between these elements are facilitated by edges, exemplified by elements such as sequence flow.

These edges establish the relationships and dependencies between different nodes, forming a seamless and continuous representation of the entire process. This graphical connectivity is crucial for visualizing the flow of activities and decision points within the business process (ISO/IEC 19510:2013 - Information Technology - Object Management Group Business Process Model and Notation, 2013). BPMN also offers a hierarchical organizational feature by enabling the aggregation of sub-processes into a higher-level structure. This functionality allows for the categorization and grouping of related tasks and activities, enhancing the overall clarity and manageability of complex business processes.

6.4.2 Proposed workflow

Figure 6.2 illustrates the proposed workflow, where BPMN is integrated with the Project Execution Plan (PEP) to enhance manufacturing processes. The assessment of this proposed workflow involved measuring the impact of digitalization and automation during the manufacturing, production, and assembly phases in particular (i.e., from Phase 3 to Phase 5 as depicted in Figure 6.2).

The evaluation of this workflow was conducted by comparing time savings and the accuracy of quantity takeoffs before and after applying the proposed workflow to a light-gauge steel OSC case project. This comparative analysis quantified the tangible benefits of implementing digitalization and automation integrating BPMN and PEP, providing valuable insights into the efficiency gains to be achieved in terms of both temporal considerations and precision in quantity assessments.

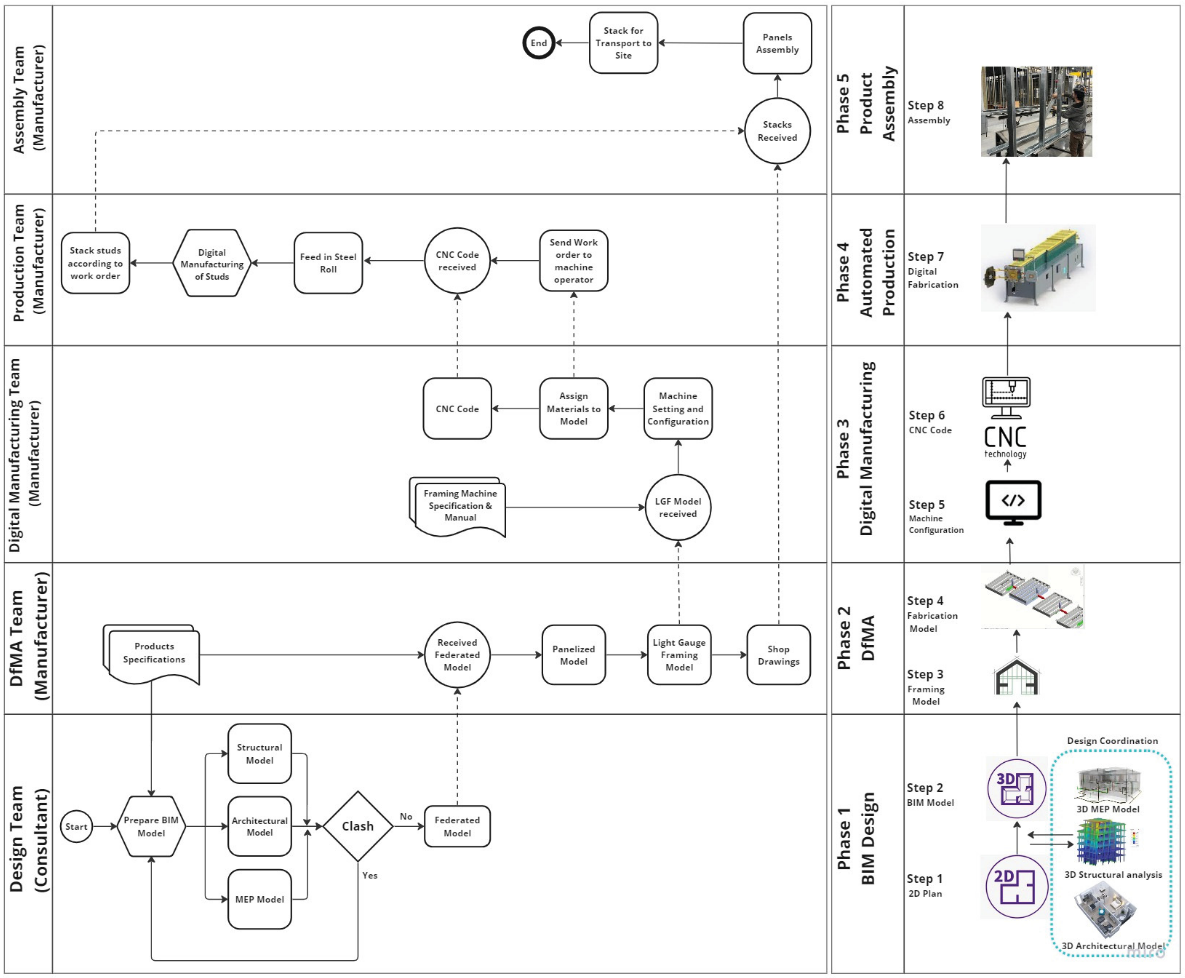

Figure 6.2 Proposed semi-automation workflow

The proposed workflow as shown in Figure 6.2 comprises five distinct teams, each playing a crucial role in the seamless execution of a given project. The first of these teams is the design team, composed of professionals such as architects, structural engineers, civil engineers, geotechnical engineers, and mechanical, electrical, and plumbing (MEP) engineering consultants. This collective expertise ensures a comprehensive approach to the conceptualization and planning phases of the project.

The DfMA team is responsible for optimizing the manufacturability and assembly of components, employing advanced methods to enhance efficiency and reduce costs. This team works collabouratively with the design team to integrate manufacturability considerations into the early stages of the design process, fostering a concurrent engineering approach.

The digital manufacturing team focuses on leveraging cutting-edge technologies to enhance manufacturing processes. By incorporating digital tools, simulations, and advanced analytics, this team seeks to streamline production workflows, improve precision, and minimize resource wastage, where the integration of digital technologies enables a more agile and adaptive manufacturing environment.

The production team, playing an important role in the manufacturing phase, oversees the actual fabrication of components in accordance with the optimized designs. This team ensures that the manufacturing processes align with the specifications outlined by the design and DfMA teams, maintaining a seamless transition from design to production.

Finally, the assembly team, an integral part of the manufacturing phase, is responsible for the careful and precise assembly of fabricated components. This team plays a crucial role in ensuring that the final product meets quality standards and specifications, contributing to the overall success of the project.

As summarized above, the BPMN provides a sophisticated and collabourative framework involving diverse teams, each contributing specialized skills and expertise at different stages of the manufacturing process. This comprehensive approach not only fosters efficiency but also ensures the optimization of resources and the delivery of high-quality outcomes in the realm of design and manufacturing.

The proposed workflow is intricately aligned with PEP, encompassing 8 steps within 5 phases. Phase 1, also referred to as BIM design, is the responsibility of the design team and encompasses two sequential steps.

The first step involves the preparation of the initial plan, typically rendered in 2D format. The second step, meanwhile, entails the generation of a BIM model based on the previously formulated 2D plan. While the conventional approach is to undertake BIM design and BIM model generation as two successive steps, the best practice is to amalgamate Steps 1 and 2, whereby the generation of the BIM model is directly coupled with the extraction of the 2D plan from the said model. This streamlined method enhances efficiency and is recognized as a superior approach in contemporary BIM workflows.

During this phase, effective coordination is paramount. Coordination necessitates effective collaboration among various trades, including architectural, structural, and MEP BIM models. The overarching objective in this regard is to mitigate clashes and conflicts within the design, ensuring a harmonious integration of diverse components. The creation of a clash-free federated model in Phase 1 lays the foundation for a seamless transition to subsequent phases of the workflow.

By prioritizing coordination and clash mitigation in the BIM design phase, the subsequent stages benefit from a well-structured and cohesive model, facilitating a more efficient and effective execution of the project. This strategic emphasis on coordination and clash resolution underscores the holistic and integrative nature of the proposed workflow, aligning with contemporary standards and best practices in the realm of design and project execution. It is imperative to note that this research did not delve into the quantitative measurement of the coordination phase. Nevertheless, it underscored the critical importance of generating a clash-free federated model, an output that is subsequently transmitted to the DfMA team in Phase 2.

DfMA (Phase 2) comprises two crucial steps: generation of framing models and generation of fabrication models. At this stage, the DfMA team is tasked with developing a panelized model based on the product specifications and detailed designs provided by the consultant team. In the context of the present study in particular, a light-gauge framing (LGF) model is used as the framing model, where the StrucSoft MWF software is employed to facilitate the creation of the automated framing model.

The adoption of automated framing design techniques is advantageous primarily in terms of time savings and a significant reduction in modeling errors. Through the automated process facilitated by the StrucSoft MWF software, the framing model can be efficiently and accurately generated, contributing to a streamlined workflow. The use of StrucSoft MWF software allows for the automation of framing design.

This software integrates with BIM platforms to generate precise framing models directly from the architectural and structural designs. The automation process includes the placement of studs, tracks, and other framing elements according to predefined rules and standards. This reduces the need for manual intervention, minimizing errors and expediting the design process. Once the initial framing model is generated, it undergoes a coordination process to ensure that all components fit together without conflicts.

The software performs clash detection to identify and resolve any potential issues between different building systems (e.g., structural, mechanical, electrical). This step is crucial for creating a clash-free federated model that can be seamlessly transitioned to the manufacturing phase. It is important to note that the proposed workflow is not confined to the use of these particular software tools. For the purposes of the present project, though, Revit and StrucSoft MWF are selected as a representative case to address the interoperability challenges that may be encountered among various models, including design, framing, and fabrication models.

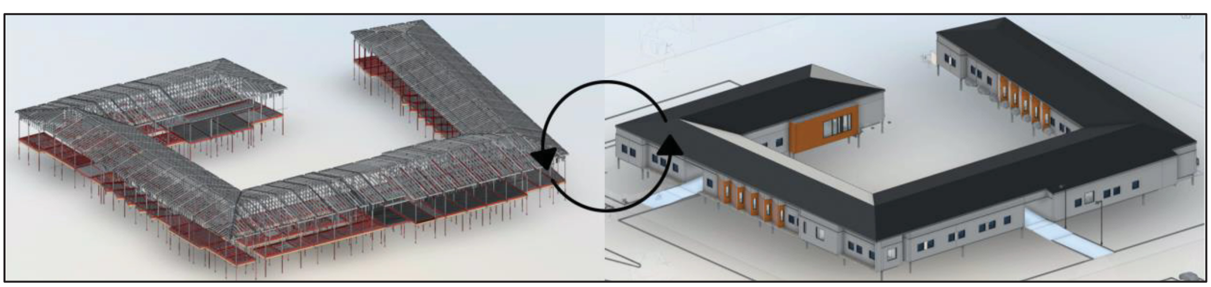

Figure 6.3 Framing the LGF model through the deployment of automation tool

Once the framing models are complete (Figure 6.3), the DfMA team generates fabrication models.

These models include detailed shop drawings that are directly extracted from the LGF models. The shop drawings provide comprehensive representations of the design, offering a detailed blueprint for production and assembly. The use of automated tools in this phase ensures precision and consistency, which are crucial for the subsequent manufacturing processes.

The fabrication models are also used in Phase 3 to generate CNC codes that control the automated manufacturing machines. The CNC codes are derived directly from the fabrication models, ensuring that the manufacturing process is aligned with the design specifications. This integration reduces the risk of errors and enhances the efficiency of the production process.

To ensure a seamless transition to Phase 3, the coordinated LGF model is transmitted to the digital manufacturing team. This collabourative approach leverages a common data environment (CDE), a centralized platform utilized by the project team to ensure the rapid and accurate transformation of documents and information. In the case study, a custom CDE platform is utilized as a shared repository, facilitating efficient communication and collabouration among team members.

The custom CDE platform supports a variety of data formats to accommodate the diverse needs of the project team. These formats include industry-standard BIM formats such as IFC (Industry Foundation Classes) and RVT (Revit files). These formats are essential for sharing detailed 3D models and ensuring interoperability between different software tools used by the design and manufacturing teams.

Moreover, the platform supports DWG and PDF formats for 2D drawings and shop drawings. These files provide detailed plans and instructions for the manufacture and assembly processes. Furthermore, the platform is used to share the CNC-specific file formats that are used to control automated manufacturing machinery.

These files are generated by the BIM models and are crucial for the automated production phase. The CDE platform employs several data-sharing processes to ensure efficient and secure collabouration, including version control, access control and permission, and automated notifications alerting team members of new uploads, changes to existing files, and upcoming deadlines. By incorporating this structured and technology-driven method, not only is the efficiency, accuracy, and overall effectiveness of the design and manufacturing processes be enhanced, but the important role of a unified digital platform in fostering seamless data exchange throughout the entire manufacturing process is demonstrated.

Phase 3, dedicated to the development and implementation of automation throughout the entire workflow, is a critical stage in the overall process. The coordinated LGF models received by the DfMA team must be translated into CNC code. However, before this can occur, the operational tools must be configured in accordance with the framing machine specifications and manual requirements.

This phase unfolds in two distinct steps: in the initial step of machine configuration (Step 5), careful attention is given to setting up the operational tools based on the framing machine specifications. This step ensures that the machine is set up correctly to perform the necessary operations, such as cutting, swaging, and notching. The machine having been configured, the system generates the CNC codes. These codes are derived from the LGF models, and are used to control the automated manufacturing process. The CNC codes specify the precise operations that the machine will perform on the LGS components (Step 6).

Table 6.1 shows an example of operational tool configurations corresponding with CNC codes. These configurations facilitate the automated manufacture of light-gauge steel studs, enabling precision and efficiency in the automated manufacture of steel studs.

Table 6.1 Operational tool configurations for auto-framing steel stud manufacturing machine (X5 Infinity)

Operation	Tool number
Swage	2
Crimp	7
Web Notch	5
Lip Notch	4
Chamfer Notch	6
Flange Notch Left	91
Flang Notch Right	92
Dimple Punch	1
Service Hole	3
Slot Hole	93
Index Hole	97
Triple Web Hole	94
Generic Hole 1	95
Generic Hole 2	96

Figure 6.4 illustrates the positioning of and operations performed on a light-gauge steel stud, as well as presenting the setup of the manufacturing framing machine (in this case, X5 Infinity was used) and the CNC codes.

This visual guide clarifies the intricate relationship between system parameters and CNC instructions, enhancing comprehension of the procedures for shaping and positioning operations. The graphical representation facilitates a comprehensive understanding of the synthesis between system configuration and CNC programming, contributing to the overall operation of the manufacturing system.

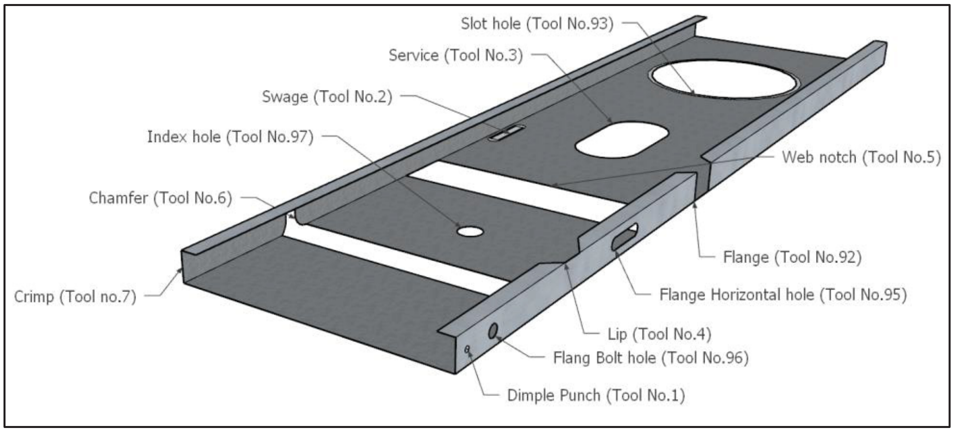

Figure 6.4 Design of operational tools in machine configuration setup (authors' work)

This crucial preparatory step ensures the seamless translation of LGF models into CNC code. Subsequently, in Step 6, the CNC code is generated, laying the digital foundation for the automated production of panels (Figure 6.5).

Following the configuration of the machine, the next task involves inputting material information for panel production into the system. This multifaceted process includes the preparation of a work order for the production team.

The purpose of this preparatory step is to provide the production team with detailed instructions, ensuring they are well-prepared to feed the machine in accordance with the work order. This careful planning is essential to mitigate the risk of delays in preparing the manufacturing machine to receive the CNC code for automated production.

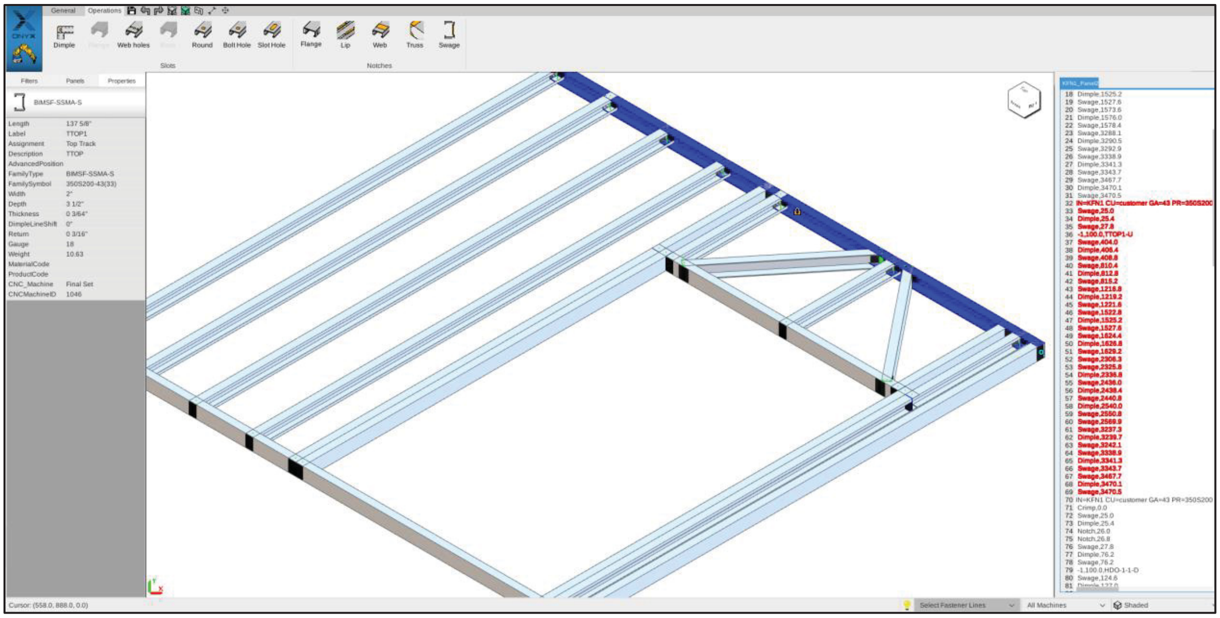

Figure 6.5 CNC code editor visualized through a cloud-based manufacturing tool

Upon completion of the work orders, the generated CNC codes (in Step 6) are transmitted to the production team. This marks the initiation of the digital fabrication phase, wherein the panels are manufactured automatically. The purpose of these steps is to optimize efficiency, minimize delays, and enhance precision in the production process, ultimately contributing to the successful integration of automation in the manufacturing workflow.

In Phase 4 (automated production), the production team engages in the manufacture of studs through the deployment of CNC codes to the framing machine. This phase comprises five primary tasks: receiving the work order, obtaining the CNC codes, feeding the steel roll, manufacturing studs, and stacking the manufactured studs. In this phase, the workflow is systematically arranged, commencing with the reception of the work order, followed by the acquisition of CNC codes essential for the automated manufacturing process. These documents provide detailed instructions for the automated production process.

Subsequently, the production team proceeds to feed the steel roll into the framing machine in accordance with the parameters specified in the work order. The heart of the operation lies in the automated manufacture of studs, a process executed with precision and efficiency through the utilization of CNC codes. The framing machine, controlled by the CNC codes, performs various operations, such as cutting, swaging, and notching, to manufacture the LGS studs. This automation ensures high precision and efficiency, significantly reducing the labour hours compared to a manual approach. Upon completion of the manufacturing process, the studs produced are systematically stacked in adherence to the specifications outlined in the work order. This systematic approach ensures the seamless execution of Phase 4, underscoring the effective use of advanced technologies such as CNC codes and automated machinery to achieve optimal results in stud production.

The final phase, Phase 5, involves product assembly, during which the assembly team receives stacks of studs and assembles them in accordance with the provided shop drawings. Each component is tagged and numbered during the production phase, while every sheet of the shop drawings features embedded QR codes for direct access to the 3D models of panels in the CDE. By scanning QR codes embedded in shop drawings with a smartphone, tablet, or similar device, assembly team can access the BIM model of the panels, allowing them to navigate through and explore the various components of each model.

These practices enhance comprehension of the assembly process and facilitate installation. It is noteworthy that some framing elements, such as the top and bottom tracks of the wall panels, doors, and window openings, undergo pre-lip-cutting and pre-drilling during the automated production phase. This machining of select framing elements supports the correct and precise positioning of the connecting joists, thereby streamlining the assembly process.

This approach not only ensures accuracy but also streamlines the overall manufacturing process. Through the incorporation of QR codes and pre-engineered features, the assembly team is equipped with valuable tools that contribute to the efficient realization of the intended design, ultimately enhancing the structural integrity and aesthetic quality of the assembled product.

In the implementation of the proposed workflow, several challenges are encountered. These challenges, and the corresponding solutions, are discussed as follows:

Technology Integration: Integrating new automated machinery with existing systems poses significant technical challenges, and ensuring compatibility among different software and hardware components requires careful planning and execution. To address this, a phased approach is adopted in which initial integration tests are conducted in a controlled environment. This allows for the identification and resolution of compatibility issues prior to full-scale implementation. Moreover, collaboration with technology vendors ensures that the machinery and software are properly configured to work seamlessly together.

Workforce Training: The introduction of semi-automation necessitates that the workforce acquire new skills and adapt to new processes. This transition is challenging, particularly for workers accustomed to traditional manual methods. Comprehensive training programs are developed to equip the workforce with the requisite skills. These programs include hands-on training sessions, workshops, and continuous support to ensure an adequate comfort level and proficiency with the new technology. The training is also tailored to different roles, ensuring that each team member receives relevant and practical instruction.

Project Coordination: Coordination among various teams (design, DfMA, digital manufacturing, production, and assembly) is inherently complex, particularly where the introduction of new processes and technologies is concerned. Effective communication channels and project management tools are established to facilitate this coordination. Moreover, regular meetings and progress reviews are conducted to ensure alignment and to address any issues promptly. The use of a common data environment also plays a crucial role in enhancing collaboration and information-sharing among the various teams.

Human Oversight and Manual Tasks: Despite the automation of certain tasks, human oversight and manual intervention are still required for some operations, such as feeding the steel roll into the framing machine and stacking the studs produced. Clear protocols and standard operating procedures are developed to guide these manual tasks. Training is provided to ensure compliance with these protocols. Moreover, feedback from workers is actively solicited as a means of encouraging continuous improvement and addressing practical challenges encountered by workers.

Initial Investment and Cost Management: The initial investment in automated machinery and training programs is substantial, posing financial challenges. As such, a detailed CBA is conducted to justify the investment. Such an analysis aids in the securing of the necessary funding and support from stakeholders.

By addressing these challenges through strategic planning, effective training, and robust project management, the implementation of the semi-automation workflow is successfully achieved. These efforts not only facilitate a smooth transition but also ensure that the benefits of the new workflow are fully realized, leading to significant improvements in productivity and accuracy in LGS-OSC projects.

6.5 Results

This section presents the comparative analysis of outcomes between the workflow previously implemented by the case company for managing the manufacturing process and the proposed semi-automation workflow, focusing on time reduction and enhancement of accuracy in the bill of quantities. The empirical data used in the comparison was extracted from the project case study datasheet, which spanned periods both prior to and three months following the implementation of the proposed workflow.

Figure 6.6 illustrates the workflow process prior to the implementation of the proposed workflow.

As the figure shows, the existing process consisted of three phases and four steps. Due to the absence of DfMA and automation, the quality of the final product and the productivity of the process were not reaching optimal levels. The comparative discussion that follows provides further details in this regard.

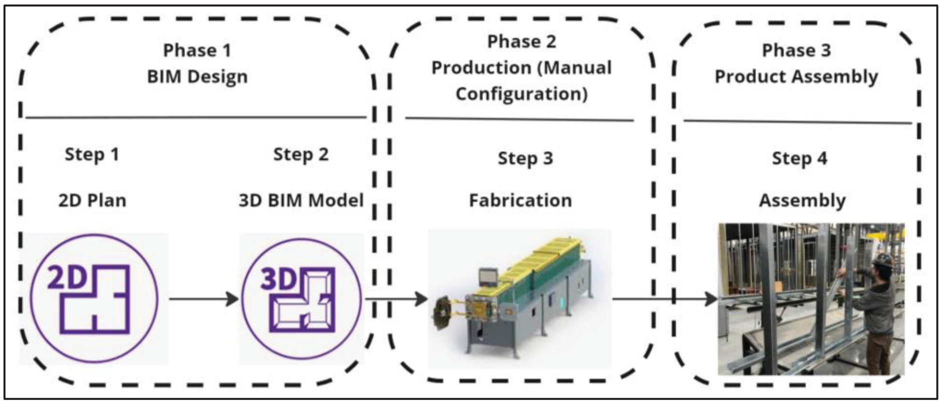

Figure 6.6 Initial workflow process
(before implementation of proposed workflow)

6.5.1 Effects of the Proposed Solution on Shortening Task Durations

The timesheet presented in Table 6.2 shows the labour hours and workforce distribution for the manufacture and assembly of a single module in an OSC setting. The breakdown encompasses various components, each contributing to the comprehensive assembly process, providing the actual time spent manufacturing and assembling one module under the existing workflow (i.e., prior to implementation of the proposed workflow).

The total labour hours to complete this module under the existing workflow (i.e., prior to implementation of semi-automation) was found to be 1,464 h. However, 28% of the workers needed to work the night shift in order to achieve this completion time, which was still 41% behind the planned schedule.

The External Wall, Internal Wall, Roof Cassettes, and Floor Frame components were found to be particularly labour-intensive to fabricate, collectively demanding a significant portion of the overall labour hours. As such, these tasks represented critical areas where optimization efforts could yield substantial time savings. Moreover, windows and doors were found to contribute significantly to the overall labour hours, meaning that focused attention on these components could lead to targeted efficiency improvements.

It should also be noted that, given that windows are prefabricated, precision in aligning the window openings with the specified dimensions is critical. It was observed that inaccuracies in this regard led to a deceleration of the assembly process.

Table 6.2 Work breakdown-based timesheet for module fabrication and assembly prior to workflow setup

Items	Labour (h)	No. of Workers	Total Hours	
Wall				
Internal			152	
Stud 3 ½	16	3		48
Top and Bottom Track	Included			
Gyps Board 5/8	24	2		48
Wool Insulation	24	1		24
CLT finishes	16	2		32
External			320	
Stud 6	16	3		48
Top and Bottom Track	Included			
Gyps Board 5/8	16	2		32
Wool Insulation	16	2		32
Vapor Barrier	24	2		48
Wood furring	16	2		32
Air Barrier	24	2		48

Table 6.2 Work breakdown-based timesheet for module fabrication and assembly prior to workflow setup (continued)

Items	Labour (h)	No. of Workers	Total Hours	
Plywood ½	16	2		32
External wall finishes	24	2		48
Floor			176	
OSB 7/16	16	2		32
Plywood	16	2		32
Gyps Board	16	2		32
Air barrier	16	2		32
Vapor barrier	16	2		32
Wood Insulation	8	2		16
Roof			224	
Rafter 800S200-68 (Track)	16	4		64
Purlin 800S200-68 (Joist)	Included			
OSB (Top and bottom)	Included			
Steel Truss Wall Support	16	2		32
Side External	16	2		32
Plywood (Edge of roof)	16	2		32
Vapor barrier	16	2		32
Metal Flashing Finishes	16	2		32
Ceiling			128	
Plywood ¾	16	2		32
Insulation 2′	16	2		32
Joist 3 ½	16	2		32
Track	Included			
Vapor barrier	16	2		32
Suspended Ceiling			48	
Gyps board 1 ½	8	2		16

Table 6.2 Work breakdown-based timesheet for module fabrication and assembly prior to workflow setup (continued)

Items	Labour (h)	No. of Workers	Total Hours	
Acoustic Tile 24×96	8	2		16
Metal Hanger	8	2		16
Windows			96	
Fix L53″ × H50″	24	4		96
Door			96	
Single Door 36″ × 96″	24	4		96
Floor Frame			160	
Floor joist 800S200-68	16	2		32
Beam W 200×15	16	2		32
Secondary joist 300S200-24	24	2		48
Wood runner 2×10	8	2		16
Framing Lumber	16	2		32
Steel Column			64	
HSS 89×63×4.8	16	2		32
Top Plate	16	2		32
Total Hours to complete the module before Semi-Automation application				**1,464**

To assess the effectiveness of the proposed workflow as presented in Figure 6.2, a timesheet recorded three months after the implementation of the proposed workflow was evaluated. Table 6.3 presents the recorded hours and the corresponding labour requirements for the manufacturing and assembly of a module. This module was identical to the one completed prior to the introduction of the semi-automation workflow.

The overall analysis shows the total original labour hours required for the module construction was found to be 906 h. Following the implementation of the semi-automation workflow, a marked reduction in labour hours was achieved, resulting in a total of 558 h, a 38% reduction.

Table 6.3 Work breakdown-based timesheet for module fabrication and assembly after workflow setup

Items	Labour (h)	No. of Workers	Total Hours		Hours reduced	Hours Reduced %	Total Hours reduced	Total %
Wall								
Internal			76				76	50%
Stud 3 ½″	6	2		12	36	75%		
Top and Bottom Track	Included							
Gyps Board 5/8″	16	2		32	16	33%		
Wool Insulation	16	1		16	8	33%		
CLT finishes	8	2		16	16	50%		
External			176				144	45%
Stud 6″	8	2		16	32	67%		
Top and Bottom Track	Included							
Gyps Board 5/8″	8	2		16	16	50%		
Wool Insulation	8	2		16	16	50%		
Vapor Barrier	16	2		32	16	33%		
Wood furring	8	2		16	16	50%		
Air Barrier	16	2		32	16	33%		
Plywood ½	8	2		16	16	50%		
External wall finishes	16	2		32	16	33%		
Floor			152				24	14%
OSB 7/16	10	2		20	12	38%		
Plywood	16	2		32	0	0%		
Gyps Board	10	2		20	12	38%		
Air barrier	16	2		32	0	0%		
Vapor barrier	16	2		32	0	0%		
Wood Insulation	8	2		16	0	0%		

Table 6.3 Work breakdown-based timesheet for module fabrication and assembly after workflow setup (continued)

Items	Labour (h)	No. of Workers	Total Hours		Hours reduced	Hours Reduced %	Total Hours reduced	Total %
Roof			112				112	50%
Rafter 800S200-68	8	3		24	40	63%		
Purlin 800S200-68	Included							
OSB (Top and bottom)	Included							
Steel Truss Wall Support	8	2		16	16	50%		
Side External Finishes	12	1		12	20	63%		
Plywood (Edge of roof)	12	1		12	20	63%		
Vapor barrier	16	2		32	0	0%		
Metal Flashing Finishes	16	1		16	16	50%		
Ceiling			112				16	13%
Plywood ¾	16	2		32	0	0%		
Insulation 2′	16	2		32	0	0%		
Joist 3 ½	8	2		16	16	50%		
Track	Included							
Vapor barrier	16	2		32	0	0%		
Suspended Ceiling			42				6	13%
Gyps board 1 ½	7	2		14	2	13%		
Acoustic Tile 24×96	7	2		14	2	13%		
Metal Hanger	7	2		14	2	13%		

Table 6.3 Work breakdown-based timesheet for module fabrication and assembly after workflow setup (continued)

Items	Labour (h)	No. of Workers	Total Hours		Hours reduced	Hours Reduced %	Total Hours reduced	Total %
Windows			40				56	58%
Fix L53″ × H50″	20	2		40	56	58%		
Door			32				64	67%
Single Door 36″ × 96″	16	2		32	64	67%		
Floor Frame			112				48	30%
Floor joist 800S200-68	8	2		16	16	50%		
Beam W 200×15	16	2		32	0	0%		
Secondary joist 300S200-24	8	2		16	32	67%		
Wood runner 2×10	8	2		16	0	0%		
Framing Lumber	16	2		32	0	0%		
Steel Column			52				12	19%
HSS 89×63×4.8	10	2		20	12	38%		
Top Plate	16	2		32	0	0%		
Total Hours to complete Module with Semi-Automation application				**906**	**558**	**38%**	**Percentage reduced (Total)**	

The processing of light-gauge steel components, including studs, tracks, rafters, and purlins, saw significant reductions in labour hours, indicative of heightened efficiency. This heightened efficiency in the processing of these elements, primarily employed in the fabrication of wall panels, floors, and roof cassettes, was found to contribute significantly to time savings. Table 6.4 shows the comparison of task durations between processes before and after implementation of the proposed workflow, which introduced semi-automation to the manufacturing process.

Notably, substantial reductions of 58% and 67% were observed in the installation of windows and doors, respectively. This efficiency is attributable to increased accuracy in opening dimensions, facilitated by access to the 3D model and shop drawings with QR codes for component identification and positioning.

Conversely, for some components, such as plywood, vapor barrier, and insulation there was no reduction in the labour hours required for their installation. This may be attributable to the fact that these elements are not directly influenced by automation and digitalization in the proposed workflow.

Table 6.4 Task duration comparison before and after implementation of proposed workflow

Items	Duration before semi-automation (h)	Duration by semi-automation (h)	Coefficient of variation %
Internal Wall	152	76	50%
External Wall	320	176	45%
Floor	176	152	14%
Roof	224	112	50%
Ceiling	128	112	13%
Suspended Ceiling	48	42	13%
Windows	96	40	58%
Doors	96	32	67%
Floor Frame	160	112	30%
Steel Column	64	52	19%
Difference between processes			**38%**

6.5.2 Impact of the Proposed Solution on Enhancing Measurement Accuracy

The effect of the proposed workflow on the accuracy of takeoff and bill of quantities was also investigated. Estimators at the case production facility were asked to take off quantities by implementing the proposed workflow using DfMA 3D model and shop drawings. iTWO CostX was employed to automatically measure quantities from the BIM model prepared by the DfMA team. Table 6.5 illustrates the difference in quantities between the two processes (i.e., before and after implementation of the proposed workflow), where a positive percentage indicates a reduction in quantity measured through the digitalization of takeoff processes.

Table 6.5 Quantitative difference before and after implementing the workflow

Items	Unit	Difference
Internal Wall		
Stud 3 ½	m	25%
Top and Bottom Track	m	15%
Gyps Board 5/8	m^2	18%
Wool Insulation	m^2	10%
CLT finishes	m^2	35%
Painting	m^2	16%
External Wall		
Stud 6	m	20%
Top and Bottom Track	m	16%
Gyps Board 5/8	m^2	16%
Wool Insulation	m^2	10%
Vapor Barrier	m^2	5%
Wood furring	m	−2%
Air Barrier	m^2	4%
Plywood ½	m^2	8%
External wall finishes	m^2	10%
Floor		
OSB 7/16	m^2	4%
Plywood ¾	m^2	5%
Gyps Board 13 mm	m^2	13%
Air barrier	m^2	4%
Vapor barrier	m^2	5%
Wool Insulation 8′	m^2	9%
Latte 1×3	m^2	15%

Table 6.5 Quantitative difference before and after implementing the workflow (continued)

Items	Unit	Difference
Floor Finish Vinyl	m²	4%
Roof		
Rafter 800S200-68 (Track)	m	18%
Roof support 3 ½	m	45%
Purlin (Joist)	m	20%
Plywood (Top and bottom)	m²	5%
Side External Finishes (Plank Cedar)	m²	2%
Plywood (Edge of roof)	m²	3%
Vapor barrier	m²	9%
Metal Flashing Finishes	m²	12%
Insulation 3″	m²	11%
Sub-base membrane	m²	8%
Ceiling		
Plywood ¾	m²	9%
Joist 3 ½	m	15%
Track	m	8%
Vapor barrier	m²	4%
Suspended Ceiling		
Gyps board 1 ½	m²	14%
Acoustic Tile 24×96	m²	22%
Metal Hanger	L.S	0.00%
Windows		
Fix L53″ × H50″	ft^2	0.00%
Door		
Single Door 36″ × 96″	no	0.00%
Floor Frame		
Floor joist 800S200-68	m	18%
Beam W 200×15	m	4%
Secondary joist 300S200-24	m	−13%
Wood runner 2×10	m	3%

Table 6.5 Quantitative difference before and after implementing the workflow (continued)

Items	Unit	Difference
Steel Column		
HSS 89×63×4.8	m	2%
Top Plate	no	0.00%
Total Deviation (Average)		11%

The deviations observed in the takeoffs before and after implementation of the proposed workflow, averaging 11% and in some cases as significant as 45%, indicate that the existing (manual-based) workflow (i.e., prior to implementation of the proposed workflow) for performing takeoffs carried a high risk of errors and that the digitalized and automated approach is significantly more effective and accurate than the manual approach.

Previous studies, such as those by Barkokebas et al (2023). and Pratoom et al. (2016), have examined the impact of digital takeoffs, reporting improvements of 12% and 18%, respectively, in quantity takeoffs (Barkokebas *et al.*, 2023 ; Pratoom et Tangwiboonpanich, 2016). Our study expanded the investigation by applying automated framing design techniques, as illustrated in Figure 6.2, Phase 2 - Step 3.

Automated framing design techniques were found to have a significant and direct positive impact in improving the accuracy of DfMA-based BIM, leading to a reduction in errors in takeoffs and increased accuracy in the bill of quantities established after the implementation of the proposed workflow. The identification of substantial deviations between manual and automated process, ranging from 15% to 45%, in items designed through automated framing design techniques, (i.e., light-gauge steel studs, tracks, purlins, joists, and roof support components) underscores the benefit of integrating automated framing design techniques to increase the accuracy of takeoffs.

In essence, the considerable variation in automatically designed elements underscores the tangible benefits of employing automated framing design methods, thereby affirming the pivotal role of automation in enhancing precision and reliability.

6.5.3 Cost–Benefit Analysis and investment decision making

Given that digitalization and automation require a considerable amount of initial investment, we performed a CBA to analyze the economic value of the proposed workflow and the adoption of digitalization and automation. The monetary costs and benefits of investing in the proposed workflow were estimated in the context of the case study in order to determined the payback period (i.e., the estimated duration to attain return on investment) for the proposed workflow. Table 6.6 shows the CBA for the duration of the project (12 months).

The CBA provided in Table 6.6 offers a comprehensive overview of the costs and benefits associated with the proposed workflow and the adoption of digitalization and automation over a 12-month period.

The costs are categorized into seven main areas: the purchase of an Automated Manufacturing Machine, Maintenance, Off-site Facility Rental & Utilities, Labour Cost, Engineering Cost, Management and Coordination, and Training. Additionally, there are costs associated with Hardware & Software.

These costs are incurred at different points throughout the 12-month period. For instance, the purchase of the Automated Manufacturing Machine, Training, and Hardware & Software are one-time costs incurred in the first month. Maintenance costs are incurred in the first, seventh, and twelfth months. The remaining costs (Off-site Facility Rental & Utilities, Labour Cost, Engineering Cost, Management and Coordination) are recurring and incurred every month.

The benefits are divided into two categories: Time-related benefits and Quantity-related benefits. Time-related benefits, calculated as 38.11% of hourly expenses, and Quantity-related benefits, calculated as 10.77% of cost per area, are accrued every month.

Table 6.6 Cost–Benefit Analysis

Costs	Month 1	Month 2	Month 3	Month 4	Month 5	Month 6	Month 7	Month 8	Month 9	Month 10	Month 11	Month 12
Automated Manufacturing Machine (Purchase)	C1M1											
Maintenance	C2M1					C2M1						C2M12
Off-site Facility Rental & Utilities	C3M1	C3M2	C3M3	C3M4	C3M5	C3M6	C3M7	C3M8	C3M9	C3M10	C3M11	C3M12
Labour Cost	C4M1	C4M2	C4M3	C4M4	C4M5	C4M6	C4M7	C4M8	C4M9	C4M10	C4M11	C4M12
Engineering Cost	C5M1	C5M2	C5M3	C5M4	C5M5	C5M6	C5M7	C5M8	C5M9	C5M10	C5M11	C5M12
Management and Coordination	C6M1	C6M2	C6M3	C6M4	C6M5	C6M6	C6M7	C6M8	C6M9	C6M10	C6M11	C6M12
Training	C7M1											
Hardware & Software	C8M1											
Total Cost	TC1	TC2	TC3	TC4	TC5	TC6	TC7	TC8	TC9	TC10	TC11	TC12
Benefits												
Time related benefits (38.11% of hourly expenses)	B1M1	B1M2	B1M3	B1M4	B1M5	B1M6	B1M7	B1M8	B1M9	B1M10	B1M11	B1M12
Quantities related benefits (10.77% of cost per area)	B2M1	B2M2	B2M3	B2M4	B2M5	B2M6	B2M7	B2M8	B2M9	B2M10	B2M11	B2M12
Total benefits	TB1	TB2	TB3	TB4	TB5	TB6	TB7	TB8	TB9	TB10	TB11	TB12
Payback Period	I--10 Months and 26 days---I											

In the table, CiMi represents the cost associated with each item in the respective month. Similarly, BiMi represents the monetary value of the benefits associated with each item in the respective month. For instance, B1M1 is the time-related benefits of the implementation of the proposed future state during the first month of implementation.

The total costs and total benefits for each month are represented as TCi and TBi respectively, where i represents the month number.

The payback period, which is the time taken to recover the initial investment, is calculated by subtracting the total investment from the cumulative total benefits until the point where the total benefits equal the total investment. According to the table, the payback period for this project is approximately 10 months and 26 days.

The CBA analysis indicates that the proposed workflow and the adoption of digitalization and automation would be a financially viable decision, with the benefits outweighing the costs after approximately 11 months.

6.6 Conclusion

This study proposed and evaluated a workflow for enhancing the efficiency of manufacturing processes in LGS-OSC projects, presenting a digitalized and semi-automated approach. This included assessing the impact of the proposed workflow in terms of time savings and increased accuracy of quantity takeoffs.

This project focused on bridging the knowledge and practice gap by presenting a comprehensive workflow specifically tailored for LGS-OSC projects. The overarching objective was to reduce task durations, improve data flow, and enhance the accuracy of the bill of quantities. To implement and evaluate the effectiveness of the solution, a real OSC project case study was employed, with the results demonstrating the significant positive impact of the proposed workflow in terms of both time efficiency and measurement accuracy.

The effects of the proposed solution in terms of shortening task durations were particularly notable. The implementation of the semi-automation workflow led to a marked 38.11% reduction in overall time spent on manufacturing and assembling a single module in the project.

This reduction was not only substantial, but also resulted in a more streamlined workforce distribution, eliminating the need for night shifts. There were noteworthy reductions in labour hours for components such as LGS elements, windows, and doors.

Furthermore, the proposed workflow was found to have a significant impact in terms of its ability to enhance measurement accuracy. The use of automated framing design techniques within the proposed workflow led to a significant improvement in accuracy. On average, the application of the proposed workflow resulted in an 11% improvement in measurement accuracy and for single components enhancement with deviations ranging from 15% to 45%.

This surpassed the improvements reported in previous studies, highlighting the critical role of automated framing design methods in ensuring precision and reliability, particularly for components such as LGS studs, tracks, purlins, joists, and roof support components. Moreover, the CBA yielded a favourable outcome, with the payback period for the initial investment found to be 10 months and 26 days. This finding signifies a financially feasible investment, given that the payback period is shorter than the total duration of the project (i.e., 12 months).

This study underscores the importance of a systematic approach to mitigate process uncertainties and boost productivity in OSC, while acknowledging the current application of automation in LGS construction. It contributes valuable perspectives to the growing body of research on digitalization and automation in OSC, emphasizing the need for tailored workflows for unique construction contexts. The focus is on presenting a systematic method to tackle process uncertainties and enhance productivity in OSC, while recognizing the established role of automation in LGS construction.

By addressing the issue of process uncertainty and introducing a practical solution through the DSR-based approach, this research provides a flexible and implementable strategy for improving manufacturing processes in LGS-OSC projects.

The findings confirm the effectiveness of a digitalized and semi-automated workflow as a means to enhance productivity, and fine-tune cost assessment, within the OSC context. Despite the promising results, this study has several limitations that should be acknowledged.

The research was conducted within the context of the Canadian construction industry, so the findings may not be directly applicable to other regions with different regulatory environments, labour markets, and construction practices. Furthermore, the CBA did not account for potential additional costs related to technology upgrades, unexpected maintenance, or extended training requirements, all of which could influence the overall financial feasibility of the proposed workflow.

The success of this research highlights the tremendous potential of efforts to further explore and implement digitalization and automation technologies in OSC manufacturing processes to further improve the efficiency, accuracy, and cost-effectiveness of construction processes. Conducting multiple case studies across different jurisdictions and project types would also help to validate the generalizability of the proposed workflow and its potential impact on various construction contexts.

Moreover, a more detailed long-term financial analysis, taking into potential additional costs and savings over an extended period, would provide a clearer picture of the financial feasibility and sustainability of the proposed workflow. Finally, examining the impact of the digitalized and semi-automated workflow on the workforce, including training needs, job satisfaction, and potential resistance to change, would provide valuable insights for successful implementation.

DISCUSSION

The construction industry is known for its low productivity, cost overruns, and delays in building projects. To address these challenges, there is a need for innovative technologies and strategic decision-making frameworks. This thesis focused on improving construction efficiency by advancing OSC techniques and their integration with BIM through informed decision-making. The overall objective was to develop a two-stage BIM-Enabled Decision Support System for the selection of a suitable IBS in OSC.

The first stage of the BeDSS involves assessing the suitability and feasibility of OSC integration for a given building project. This assessment considers various dimensions such as project characteristics, supply chain, time, cost, quality procurement, and socio-cultural factors. By leveraging digitalization and BIM, stakeholders can make informed decisions regarding the adoption of OSC, taking into account benefits such as accelerated construction schedules and improved quality control. Building upon the OSC feasibility assessment, the second stage of the BeDSS focuses on the selection of a suitable IBS tailored to the project's requirements. This stage utilizes a digitalized workflow specifically designed for off-site construction building projects. The BeDSS integrates Fuzzy logic with the AHP in a multi-factor decision method incorporating BIM. This integration streamlines decision-making and ensures reliable and informed decisions that account for all pertinent considerations, contributing to the success of the project.

The novelties of research are as follows:

Integration of FAHP and BIM in BeDSS: The use of a Fuzzy Analytic Hierarchy Process within a BIM environment to handle subjective judgments and uncertainties in decision-making is a novel approach. This integration allows for more nuanced and accurate evaluations. FAHP enhances traditional AHP by incorporating fuzzy logic, which is particularly useful in dealing with the inherent uncertainties and subjective judgments in construction projects. This combination provides a more robust and flexible decision-making framework, enabling stakeholders to make more informed and reliable decisions.

Development of BeDSS: The development of a unique, systematic two-stage Decision Support System specifically designed for OSC and IBS selection, incorporating validated KDSFs and KPIs, is a significant contribution to the field. The BeDSS is tailored to address the specific needs and challenges of OSC projects, providing a structured approach to evaluate the feasibility of OSC and select the most suitable IBS. This systematic approach ensures that all relevant factors are considered, leading to more effective and efficient decision-making.

Automatic Data Extraction from BIM: The BeDSS is fully compatible with BIM platforms, facilitating the automatic extraction of data from BIM models. This automation has the potential to significantly enhance both the efficiency and accuracy of the decision-making process. By directly extracting critical information from BIM models, such as project size, the cost of various components, and material specifications, the system minimizes the potential for human error, ensuring that decisions are grounded in accurate and up-to-date data. This functionality substantially improves the speed and reliability of decision-making, rendering the process more efficient and consistent.

It is important to note that the BeDSS is not restricted to BIM-based projects. Instead, it is a BIM-enabled system, capable of functioning independently of BIM models. In other words, while BeDSS can operate in projects without a BIM model, the presence of a BIM model enhances its capabilities, particularly through the Automatic Data Extraction feature, which, as previously discussed, further supports decision-makers.

The application of various techniques of multi-factor decision-making has been widely explored in the field of construction management for decision-making purposes. MCDM methods are essential in construction management due to the complexity and multitude of factors involved in construction projects. These techniques help in evaluating and selecting the best options among various alternatives based on multiple factors. Moreover, the integration of a decision support system such as the BeDSS proposed in this research with BIM models offers a sophisticated tool for construction management professionals.

It allows them to make informed decisions regarding the construction methodologies, ensuring optimal outcomes for specific projects.

By leveraging the strengths of both MCDM techniques and BIM technology, BeDSS provides a robust framework for enhancing decision-making processes in construction management. Similar to this research, previous scholars, such as Kamari et al. (2018), have utilized these MCDM techniques integrated with BIM to select appropriate renovation scenarios. In their study, they integrated a proposed decision support system with BIM. This integration allowed for a more effective evaluation process by combining the visualization and data management capabilities of BIM with the analytical power of MCDM methods. The result was a comprehensive approach to selecting the best renovation scenarios based on multiple factors, enhancing the decision-making process in construction management.

In comparison to Kamari's research, the present study focuses on the development of a decision support system called BeDSS. This system is specifically designed for OSC and the identification of suitable IBSs. Kamari's research primarily focused on renovation scenarios, whereas BeDSS is tailored for new construction projects using OSC techniques. The selection process in BeDSS is based on key decision support factors that have been validated for their applicability in the Canadian construction context. Additionally, one notable feature of the proposed BeDSS is its ability to automatically extract data from BIM models.

This automation significantly enhances the efficiency and accuracy of the decision-making process. By extracting relevant data directly from BIM models, BeDSS can suggest recommended scores for pairwise comparisons of KDSFs. These scores are crucial for the MCDM process, as they facilitate the evaluation of different construction methodologies and IBS options based on the identified key factors. The system’s capability to automate data extraction and scoring ensures that the decision-making process is not only faster but also more reliable and consistent.

The study conducted by Attouri et al. (2022) examining the current utilization of industrialized construction techniques in France provides further context concerning the KDSFs introduced in this thesis. According to Attouri et al. (2022), the adoption of OSC techniques offers numerous advantages, including enhanced productivity, reduced construction time, improved quality, and minimized waste, and facilitates industrialization and automation.

Attouri's ranking, which identified improved productivity, minimized on-site construction time, and improved quality as key benefits of OSC, aligns with the outcomes presented in Chapter 4 of the present work. Specifically, the present research identifies Time factors (D3), Quality factors (D5), and Socio-Cultural factors (D7) as the top three KDSFs in the selection of OSC approaches.

Another study by Attouri et al. (2022) examining the current utilization of industrialized construction techniques in France provides further context concerning the KDSFs introduced in this thesis. According to Attouri et al. (2022), the adoption of OSC techniques offers numerous advantages, including enhanced productivity, reduced construction time, improved quality, and minimized waste, and facilitates industrialization and automation. Attouri's ranking, which identified improved productivity, minimized on-site construction time, and improved quality as key benefits of OSC, aligns with the outcomes presented in Chapter 4 of the present work. Specifically, the present research identifies Time factors (D3), Quality factors (D5), and Socio-Cultural factors (D7) as the top three KDSFs in the selection of OSC approaches.

Furthermore, Attouri's study identified specific challenges that impede the effective implementation of OSC techniques. These challenges include the need for extensive coordination between the design office and the pre-manufacturer prior to commencing production, the challenge of finalizing the design early enough in the process to initiate factory production, the exclusion of prefabrication as the construction approach of choice due to existing key decisions, and the requirement to prioritize the lowest cost option.

These obstacles are reflected in the ranking of the importance of OSC benefits, where cost-related benefits, including labour cost, congestion on the construction site, and project construction cost, are considered the least significant factors. Similarly, in line with Attouri's findings, this research introduces Cost-related factors (D4), encompassing the cost of design, materials, production and manufacturing, logistics, assembly and construction, management, and maintenance, as the least important KDSFs in the selection of OSC approaches.

Unlike Attouri's research, which primarily focused on the benefits and challenges of OSC, the present study goes a step further by developing a practical decision support system (BeDSS) that incorporates these factors into a structured decision-making process. This makes BeDSS not only a theoretical framework but also a practical tool that can be directly applied in real-world construction projects to enhance decision-making and project outcomes.

As mentioned earlier in Chapter 1 of this thesis, the integration of DfMA and IBS has the potential to maximize the benefits of IBS in OSC. To complement the identification and introduction of KDSFs in this research, as reported in Annex II, the challenges related to DfMA in OSC are categorized into nine categories: economic and financial, technological, legal and contractual, technical and cognitive, procedural, cultural, geographical, policy, and commercial (Montazeri et al, 2024). This classification is consistent with the study by Attouri, which identified specific challenges for OSC implementation, as well as with the KDSFs introduced in this research. However, there is a difference between Montazeri's findings regarding the most important challenge in DfMA and the outcomes of this research. Based on the evaluation of KDSFs by experts, as reported in Chapter Four of this thesis, the highest-ranked factors are the time-related factors (D3), such as the design period, production time, mobilization and transfer time, and assembly and construction period. This finding does not contradict Montazeri's findings, as the relevant challenges are addressed and discussed under the procedural and technical cognitive classifications, including project timeline, project planning, and scheduling.

As introduced earlier, the first paper in this thesis is a systematic literature review that focuses on the integration of digital fabrication, BIM, and OSC, particularly in decision-making within the construction domain. The main objective of this review is to identify areas where knowledge gaps exist and further research is needed. A bibliometric analysis is conducted to examine the relationship between these practices. The review identifies key trends and research gaps in OSC and suggests potential avenues for future research in this area.

The findings indicate that there has been insufficient research on the integration of off-site construction, BIM, and digital fabrication. Although the benefits of BIM and digital fabrication in off-site construction have been discussed by pioneering scholars and demonstrated in various studies, little research has been found linking BIM and digital fabrication in OSC. Overall, the article contributes to the existing body of knowledge by identifying research gaps and proposing a practical solution in the form of a two-stage BIM-enabled DSS, which has the potential to improve the efficiency and effectiveness of construction processes involving digital fabrication, BIM, and OSC.

The second paper builds upon the findings of the SLR (first paper) and further presents a detailed study of KDSFs in the Canadian OSC context. This study employs a mixed-methods approach, combining a systematic literature review, expert reviews and surveys to validate and analyze the KDSFs. Thirty-two KDSFs are validated and grouped into seven dimensions: project characteristics, supply chain, time, cost, quality, procurement, and socio-cultural factors. The most important dimension identified is project time, which encompasses the design period, production time, mobilization and transfer time, assembly, and construction period. The research highlights the significance of time-related factors in the decision-making process for OSC projects and emphasizes the need to consider a comprehensive set of KDSFs beyond merely cost savings. The findings provide KDSFs for OSC practitioners in selecting appropriate construction methods. These KDSFs are subsequently used in the development of the proposed BeDSS. The development of the BeDSS, as the core artifact of this thesis, is discussed in the following article.

The third paper presents the development of the BeDSS, in which MCDM and FAHP are integrated with BIM. The study's contribution extends to the development of a two-stage BIM-enabled DSS designed to enhance decision-making in OSC projects. This system uses validated KDSFs to recommend suitable construction methodologies.

During the development of the BeDSS, the factors were consolidated, resulting in a total of 21 factors. For instance, the factors of design flexibility and design complexity were merged into a single factor of project design. These factors were further validated through questionnaires and interviews with 15 experts, including both local and international professionals, as part of the overall BeDSS evaluation and validation process. To assess the generalizability of the research findings, experts from Germany and Malaysia also participated in this exercise. All experts had more than five years of professional experience in the construction industry and came from diverse backgrounds, including architecture, mechanical and electrical engineering, project management, construction management, cost management, BIM management, environmental and sustainability expertise, manufacturers, and contractors

As discussed earlier, the BeDSS is a two-stage solution. In the first stage, decision-makers evaluate the relevance of OSC for building projects based on KDSFs. The BeDSS uses multi-factor decision-making techniques, such as the fuzzy analytic hierarchy process, to provide recommendations. In the second stage, the focus shifts to selecting an appropriate IBS solution for the OSC project. The BeDSS plugin, integrated with BIM tools, checks the consistency of user inputs and extracts data from the BIM model to facilitate decision-making.

A real-world scenario in Canada tested the system, demonstrating that OSC was the more suitable methodology based on weighted evaluations of KDSFs, and the prefabricated wall panel system emerged as the most appropriate IBS. Following the BeDSS development and initial testing, industry experts evaluated the software through semi-structured interviews and questionnaires. The software's performance was assessed based on satisfaction ratings and rankings, with the decision-making aspect receiving the highest ranking.

However, usability aspects, such as a more user-friendly dashboard and simplified data entry methods for pairwise comparisons, were identified as areas needing improvement. Overall, the level of satisfaction with BeDSS was deemed satisfactory.

The fourth paper underscores the significance of the research findings by presenting a digitalized workflow designed specifically for light-gauge steel OSC projects. The paper discusses the identified KDSFs and their application in the development of the proposed workflow. Moreover, the Cost Benefit Analysis in this research assists decision-makers in making reliable decisions regarding the integration of BIM and automation technology in implementing IBS. The motivation for this research stems from the persistent productivity challenges faced by the construction industry. Building on the findings from Chapter 4, where time and quality-related factors were identified as the most critical, and cost-related factors as the least significant, a more in-depth investigation and discussion of these factors were conducted in this paper. Furthermore, the inclusion of the additional Key Decision Support Factor of finance, following the validation process, has led to a deeper analysis of the financial feasibility of initial investments, with the aim of facilitating more informed decision-making in OSC.

The article demonstrates the practical application of digitalization and semi-automation in OSC, which aligns with the thesis's objective of enhancing construction efficiency through informed decision-making in the selection of OSC and IBS. Moreover, the findings from the article validate several KDSFs identified in the thesis, such as time, cost, and quality-related KDSFs. These factors are critical in the decision-making process for selecting suitable IBS solutions, thereby reinforcing the relevance of the Decision Support System.
Moreover, the article provides empirical evidence of the effectiveness of digitalized workflows and semi-automation in improving productivity and accuracy in OSC projects.

Implementing this workflow in a real OSC project demonstrated significant time savings and improved measurement accuracy. The semi-automated workflow led to a 38% reduction in overall time spent on manufacturing and assembling a single module, streamlining workforce distribution and eliminating the need for night shifts. Additionally, the workflow improved measurement accuracy by an average of 11%, with deviations for single components ranging from 15% to 45%. The cost-benefit analysis showed a favourable outcome, with a payback period of 10 months and 26 days, indicating a financially feasible investment.

These findings underscore the importance of systematic approaches to mitigate process uncertainties and boost productivity in OSC. The study highlights the potential of digitalization and automation technologies to revolutionize traditional construction practices, making them more efficient, accurate, and cost-effective. The proposed digitalized workflow for light-gauge steel OSC projects reduces task durations, enhances data flow, and improves project cost assessment.

Building upon the identification and evaluation of KDSFs in Chapter 4 and the outcome of ranking the cost-related KDSFs as the least important factors, complementary research is done as presented in Annex VIII to address the challenges posed by inflation in the Canadian construction industry. It emphasizes the importance of adopting innovative strategies such as digitalized OSC and IBS to enhance the industry's resilience in the face of persistent inflation.

This paper involved a comprehensive analysis of construction project data, examining inflation trends using Spearman's correlation test and Sensitivity Coefficient analysis. The findings provide a robust foundation for effective material procurement, work execution, and overall project cash flow management. The analysis indicates that divisions with high SC, such as Metals and Special Construction, are most affected by inflation and are therefore best suited for completion using the OSC approach. OSC allows a significant portion of the work to be carried out in a controlled environment, resulting in shorter timelines and reduced material waste. By understanding the impact of inflation on various project aspects, this research highlights the importance of OSC techniques in mitigating the adverse effects of inflation, such as increased prices, material waste, and project delays. Minimizing these impacts helps safeguard the project budget against inflation.

Finally, It assists decision-makers in making reliable decisions regarding the selection of OSC for a given project. This approach can be applied not only to immediate project planning but also to long-term strategy, fostering a resilient and cost-effective approach in the face of inflationary pressures. By completing the above-mentioned articles, the research presented in this thesis has significant implications for both academia and industry. The research findings provide practical guidance for industry professionals, researchers, and policymakers navigating the evolving landscape of construction productivity and efficiency. The proposed BeDSS and digitalized workflow offer innovative solutions to enhance decision making, construction efficiency and address challenges in OSC. The research presented in this thesis makes significant contributions to both academia and industry. First, it provides an in-depth analysis of the main trends in OSC, identifies research gaps in selecting suitable construction methodology, and offers recommendations for future directions in the field. Furthermore, this research identifies KDSFs for improving construction efficiency through the selection of a suitable IBS in OSC. By assessing the importance of and relationships among KDSFs in the successful use of OSC techniques, this research enhances the understanding of the factors that influence project outcomes in OSC.

Moreover, the outcomes of this research have the potential to have a significant impact on the OSC industry in Canada. By identifying the KDSFs that can aid construction stakeholders, including project owners and designers, in making informed decisions regarding OSC and IBS implementation, this research will contribute to the advancement of OSC. The proposed BeDSS, a multi-criterion decision support system integrated within BIM tools, as a computerized framework, utilizes mathematical programming, decision analysis, and statistical procedures to assist users in selecting and implementing the most suitable IBS for OSC projects, thereby enhancing project efficiency. In conclusion, the comprehensive analysis of the research findings underscores the importance of a systematic approach to enhance productivity and efficiency in OSC. The integration of digitalization, BIM, and decision-making methodologies in the BeDSS streamlines the decision-making process and ensures reliable and informed decisions.

CONCLUSION

This thesis focused on improving construction efficiency by advancing OSC techniques and their integration with BIM through informed decision-making. This project developed a decision support system integrated into a BIM platform to assist decision-makers in selecting a suitable IBS for OSC, thereby overcoming the challenges identified in this research.

The first research question, "*What are the Key Decision-Support Factors (KDSFs) at play in the decision whether to select the OSC approach and how do they affect the decision?*" is answered in detail in the second paper (Chapter 4). In this paper, the 32 KDSFs were validated and grouped into 7 dimensions. By addressing the first research question, the scope described in Chapter 4 successfully fulfilled the first research objective of "*identifying and analyzing the KDSFs that significantly influence the feasibility and success of OSC*".

These KDSFs were then concolidated and categorized into a set of 21 factors for the development of the proposed decision support system in addressing the second research question, "*How can a DSS be developed to facilitate the decision-making process for OSC?*". The second question is answered in the third paper through the implementation of the MCDM method and FAHP technique, which are incorporated into the BIM platform as a plug-in for Revit. This integration assists decision-makers in conducting feasibility studies on OSC.

To meet the second objective of this research, "*Develop a comprehensive computerized BIM-enabled DSS for OSC*", BeDSS developed in two stages. Stage 1 assesses the feasibility of OSC based on KDSFs and KPIs, while Stage 2 specifically addresses the third research question: "*How can a suitable IBS be selected for a particular OSC project*?" This question is answered through the evaluation of alternative IBS options and the ranking of the most appropriate IBS for a given OSC project, utilizing the proposed BeDSS plug-in. By addressing the second and third research questions, the study presented in Chapter 5 (the third paper) successfully fulfills the third research objective: "*To propose a method for evaluating and selecting a suitable IBS using BeDSS for a particular OSC project*."

These objectives involve the development of a comprehensive, computerized decision support system for OSC building projects, which is BIM-enabled and based on a systematic approach that incorporates validated KDSFs and KPIs. This enhances the decision-making process, leading to more informed and reliable decisions, which is the primary aim of this research.

The research presented in this thesis makes significant contributions to both academia and industry. The findings provide valuable insights into the bodies of knowledge on OSC, IBS, and DSS. The research identifies comprehensive Key Decision Support Factors and KPIs for the selection of OSC and IBS in Canada.

The importance of time-related factors, such as design period, production time, mobilization and transfer time, and assembly and construction period, in the decision-making process for OSC projects is highlighted.

Moreover, the proposed BeDSS, integrated within BIM tools, assists stakeholders in selecting and implementing the most suitable IBS for a given OSC project, thereby enhancing project efficiency through informed decision-making.

In conclusion, the proposed BeDSS and digitalized workflow have the potential to enhance the traditional decision-making process in OSC, making it more reliable, efficient, accurate, and informed.

As this thesis concludes, it is essential to acknowledge the limitations of the research and propose recommendations for future work. While the development of the two-stage BIM-Enabled Decision Support System and the integration of digitalized workflows have demonstrated significant potential in enhancing construction efficiency and decision-making in OSC projects, certain constraints and areas for improvement remain.

The key limitations of the thesis are outlined, and recommendations for future research are provided to build upon the foundation laid by this work.

Limitations of the thesis are as follows:

Canadian Context Focus: The research findings and validation efforts are primarily focused on the Canadian construction industry. While the insights and tools developed are valuable, their applicability to other regions with different regulatory environments, market conditions, and construction practices may be limited. This regional focus may restrict the generalizability of the research findings.

Reliance on Accurate and Comprehensive BIM Data: When connected to BIM, the effectiveness of the BeDSS heavily relies on the availability and accuracy of BIM data. Inaccurate or incomplete BIM models can lead to suboptimal decision-making and project outcomes. This dependency on high-quality BIM data may limit the applicability of the BeDSS in projects where such data is not readily available or is of poor quality.

Automation in Data Extraction and Scoring: The automation of data extraction and scoring in the BeDSS, while enhancing efficiency and accuracy, may not cover all project nuances. Certain complex or unique project characteristics may require manual oversight and adjustments, which the current automated system may not fully accommodate. This limitation highlights the need for continuous improvement and customization of the system to address specific project requirements.

Validation and Expert Feedback: Although the BeDSS was validated through expert reviews and real-world case studies, the sample size of experts and projects was relatively small. A larger and more diverse sample could provide a more comprehensive validation of the system's effectiveness and reliability.

Recommendations for future research are as follows:

Integration of AI and Machine Learning: Future research should explore the integration of artificial intelligence (AI) and machine learning techniques to further enhance decision-making and optimize costs. AI can provide predictive analytics, identify patterns, and offer data-driven recommendations, making the decision support system more robust and adaptive to changing project conditions.

Long-Term Effects on Productivity and Efficiency: Longitudinal studies should be conducted to track the long-term effects of the BeDSS and digitalized workflows on construction productivity and efficiency. Such studies can provide valuable insights into the sustained impact of these innovations and identify areas for further improvement.

Global Application: The research findings should be expanded to other regions to assess their applicability and effectiveness in different contexts. This involves adapting the BeDSS to accommodate regional variations in construction practices, regulatory requirements, and market conditions. Collabourating with international experts and conducting case studies in diverse geographical locations can enhance the global relevance of the research. The findings and tools can be applied to other regions with appropriate adjustments for local regulatory environments and market conditions. Especially since the BeDSS was evaluated and validated by experts from Germany and Malaysia, it has the capacity to be generalized and applied in other regions.

Generalization: The findings and tools can be applied to other regions with appropriate adjustments for local regulatory environments and market conditions. Especially since the BeDSS was evaluated and validated by experts from Germany and Malaysia, it has the capacity to be generalized and applied in other regions. Moreover, the principles and methodologies developed in this research can be adapted for other construction methods beyond OSC, such as traditional on-site construction or hybrid approaches.

Customization and Flexibility: Customizable modules within the BeDSS should be developed to address specific project nuances and unique characteristics. This flexibility will allow the system to be tailored to different project types and requirements, ensuring more accurate and reliable decision-making.

Enhanced Validation and Expert Feedback: The sample size and diversity of experts involved in the validation process should be increased. Engaging a broader range of professionals from different regions and disciplines can provide more comprehensive feedback and validation, strengthening the credibility and reliability of the BeDSS.

Interoperability and Integration: The focus should be placed on improving the interoperability and integration of the BeDSS with various BIM platforms and other construction management tools. Ensuring seamless data exchange and compatibility will enhance the system's usability and effectiveness across different projects and organizations.

By addressing these limitations and pursuing the recommended future research directions, the BeDSS can be further refined and enhanced, making it a more powerful and versatile tool for improving construction efficiency and decision-making in OSC projects.

ANNEX I

APPLICATION OF FUZZY LOGIC FOR SELECTION OF OFF-SITE CONSTRUCTION APPROACH

A. Mehdipoor[1], I. Iordanova[1], M. Al-Hussein[2]

[1]Department of Construction Engineering, École de Technologie Supérieure,
1100 Notre-Dame Ouest, Montréal, Québec, Canada H3C 1K3
[2] Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Canada T6G 2R3

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I.1 Abstract

Compared to other industries, the construction sector has poor productivity performance. Many megaprojects in this industry incur cost overruns, and this is largely due to inefficiencies. Although there are several reasons for these inefficiencies, the most significant factor is the lack of efficiency. One effective solution to improve productivity in construction projects is to adopt Off-site construction (OSC) methodology, which enhances efficiency. The construction method selection is an important exercise toward the productivity and success of a building project. This exercise is particularly critical during the early stages of a building project, as it is important for decision makers to consider all factor and make a prompt decision. The use of off-site construction is gaining popularity in building projects. Therefore, assessing the most relevant and key success factors in this context is necessary. Multiple Factor Decision Making (MCDM) techniques have been widely used in the construction management domain. These are being applied as a medium for decision-making purposes in the construction sector. One of the most frequent methods is Fuzzy Logic to select an option among different alternatives based on a ranking system. In this paper, Fuzzy logic was applied to evaluate and rank the performance of two alternatives i.e. conventional method of on-site construction cast in situ

works and Off-site construction steel structure fully modular approach. This project forms part of a Ph.D. research program which aims to develop a Two-Stage BIM-Lean Decision Support System (DSS) for the selection of a suitable Industrial Building System (IBS). The proposed DSS development consists of two main steps: 1) Identification and evaluation of Key Decision Support Factors (KDSF) for the selection of the OSC approach and 2) Choosing an appropriate IBS for a building project. This paper focuses on the second step where fuzzy logic is applied to rank and select the appropriate alternative. A decision maker was provided with a list of Key Decision Support Factors, which had been validated by industry experts, to input data and measure the importance and performance of each alternative. Crisp scores calculated using a fuzzy model indicated the rank of each alternative. The highest score of alternatives indicates the best approach. The result shows that alternative B – Off-site construction Steel Structure Modular approach, is the better option.

I.2 Introduction

The construction industry is known for its subpar productivity when compared to other industries. It is common for large-scale construction projects to go over budget. The primary cause of these inefficiencies is a lack of productivity. While there are various reasons for this, adopting Off-site construction (OSC) methodology has proven to be an effective solution to improve efficiency in construction projects (Abdul Nabi et El-adaway, 2020). Using decision-making models in the Off-site construction domain has improved project productivity and sustainability in building projects. Therefore, it is necessary to advance the OSC approach by proposing a comprehensive decision-making model from the perspective of the Canadian construction industry.

While various forms of OSC systems are available in the market, there is a need for a comprehensive decision-making tool that can effectively aid decision-makers in swiftly and confidently selecting the appropriate method during the preliminary design phase (Daget et Zhang, 2019).

The process of selecting an appropriate construction method can be complex due to the many options available. Those responsible for making these decisions must take into account various factors and considerations to determine the most appropriate construction method. As a result, the process of selecting a suitable construction methodology is complex and involves multiple attributes and objectives (Attouri, Lafhaj, Ducoulombier et Lineatte, 2022). Moreover, the selection of the construction approach method includes multiple factors and factor which can turn it into a complex process. This paper is part of a more comprehensive project to develop a DSS.

The main focus of this project is to demonstrate and present the proposed methodology to assist a decision maker in the construction management domain. The authors employed a mixed method of qualitative and quantitative expert review in addition to a systematic literature review to identify and validate the Key Decision Support Factors utilized for data collection and implementation.

I.3 Research Background

Considering Off-site construction approach at the early design stage of the project would assist all the team members to "think offsite" which is very important for the success of the project (Attouri, Lafhaj, Ducoulombier et Lineatte, 2022). In the construction industry, decision-making is an important and relevant task which can be supported by the use of computer technology to improve quality and efficiency in building projects (Marcher, Giusti et Matt, 2020). Due to the complexity of the construction process and the variety of different techniques and methods in planning, manufacturing and constructing a building project, the significance of decision-making becomes prominent.

Earlier scholars have examined decision-making elements associated with Off-site construction. Wuni (2019) discerned the primary five factors involved in the selection of modular integrated construction (MiC) including the availability of skilled labour and management, project timelines, transportation, limitations in size, and equipment availability.

The process of decision-making in the construction management domain based on Multi-factor decision-making (MCDM) techniques has been reviewed by pioneer researchers such as Aboelmagd (2018), Alhumaidi (2015), An et al. (2020), Daget & Zhang (2019), and Ordoobadi (2009). Aboelmadg (2018) used Analytical Hierarchy Process as a tool in MCDM to select the best constriction bid price. In that research, the benefits of MCDM techniques were demonstrated. Specifically, in the OSC domain, Daget & Zhang (2019) developed a decision-making model for the assessment of Industrialised Building System using MCDM techniques. However, that research is limited to housing projects in Ethiopia.

There are different techniques in the MCDM approach. Ordoobadi (2009) applied fuzzy logic for the selection of a proper supplier capable of meeting the client's requirements and demands. Daget et al. (2019) preferred to use the analytical hierarchy process to develop a decision-making model in the OSC domain.

Wuni (2020) developed a decision-making framework by determining fuzzy modelling to evaluate the critical failure factors for OSC projects. Poor design and lack of proper supervision and management were considered the main key failure factors for modular projects (Wuni et Shen, 2020a). Ishuzaka (2014), compared the most widely used techniques in MCDM i.e. fuzzy logic, AHP, Fuzzy AHP and hybrid fuzzy AHP. Integration of Fuzzy logic with AHP is a new trend to overcome the challenges of uncertainties in the MCDM approach (Ishizaka, 2014).

This research is focused on applying fuzzy logic in the MCDM approach to evaluate and rank alternatives in a case study based on relevant factors that influence the decision making process in OSC building projects. The alternatives taken into consideration are Alternative A-Conventional method of onsite construction using cast in situ concrete works and Alternative B- Off-site construction steel structure fully modular approach.

I.4 Research Methodology

This section explains the methodology that will be applied in the case study, followed by an elabouration of the procedure for using Fuzzy Logic to rank each alternative. The data analysis calculation and results will be discussed in the next section. The selection of the proper construction method in this paper is part of a larger project that aims to develop a two-stage computerized decision support system (DSS) for selecting an appropriate Industrial Building System in OSC projects.

The process of developing the proposed Decision Support System (DSS) consists of two main aspects: 1) identification and evaluation of Key Decision Support Factors (KDSF) for the selection of the OSC approach, and 2) choosing an appropriate approach based on a ranking system for a building project.

This study mainly focuses on the second part, where fuzzy modeling is chosen to analyze and rank the alternatives. The list of KDSF validated in the first stage of the research project was used to collect data from a decision-maker to rank alternatives. The expert was asked to give a value to the importance and performance of each factor. A mixed method of quantitative and qualitative techniques was implemented to identify, validate, and assess Key Decision Support Factors (KDSF) for the selection of the OSC concept. The assessment of KDSF importance and relevancy resulted in generating a list of the system's suggestions of weighting based on the mean score ranking.

The list of the system's suggestions assists the decision-maker in proceeding with the application of the Multi-factor decision-making (MCDM) model using Fuzzy logic. The expert can refer to the values suggested by the system and adjust them according to the nature of a specific project to determine the best judgment in this process. Fuzzy logic evaluation and modeling determine the ranking of the alternatives.

Figure AI.1 shows the overall fuzzy modeling methodological framework applied in this project. However, this project is only focusing on Fuzzy logic analysis and system recommendations on the selection of the proper alternative.

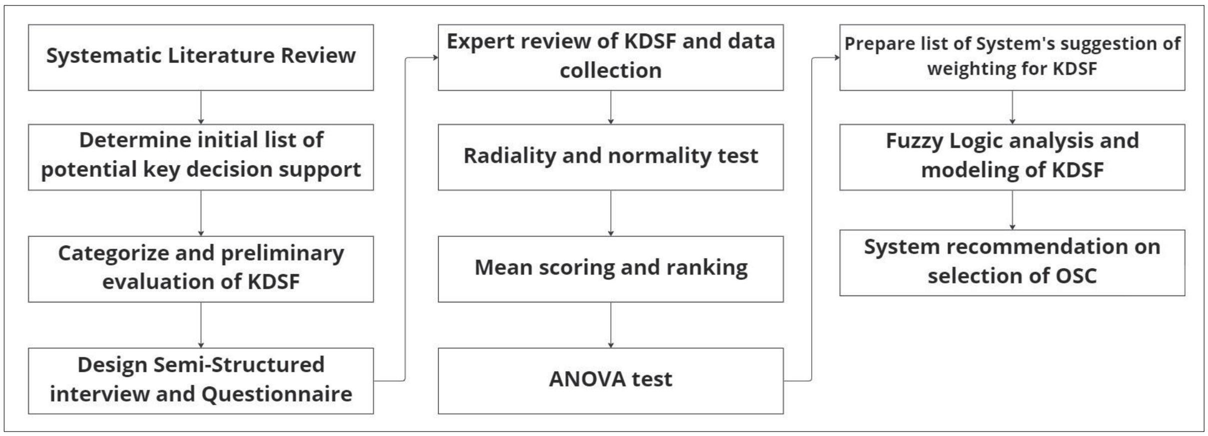

Figure A I.1 Fuzzy modelling methodological framework

The initial list of potential key decision support factors consisted of 32 factors that were categorized into seven dimensions. These were validated by 12 experts through semi-instructed interviews. A total number of 21 KDSFs were used to implement Fuzzy logic as per Table AI. 1. A real case study was selected to assess the functionality of the proposed method.

The selection process was based on the list of KDSF validated during the first stage and the expert's (decision maker's) weighting for each factor's importance and performance in stage two.

Table A I.1 Key Decision Support Factor (Main and sub-factor)

Main Factor	Key Decision Support Factor (KDSF)	Weights
Project characteristics (D1)	Project Location (F1)	w_1
	Project Design (Size, complexity and flexibility) (F2)	w_2
Supply chain (D2)	Financing (F3)	w_3
	Available Manufacturer (F4)	w_4
	Available Infrastructure (Hardware & Software) (F5)	w_5
	Available experts and skilled workers (F6)	w_6
Time (D3)	Design period (F7)	w_7
	Production time (F8)	w_8
	Mobilization & transfer time (F9)	w_9
	Assembly & construction period (F10)	w_{10}
Cost (D4)	Design (F11)	w_{11}
	Production & Manufacturing (F12)	w_{12}
	Logistics (F13)	w_{13}
	Assembly & Construction (F14)	w_{14}
	Maintenance (F15)	w_{15}
Quality (D5)	DfMA + Disassembly (F16)	w_{16}
	Standards and protocols (F17)	w_{17}
	Sustainability (Carbon emission, Energy consumption, waste) (F18)	w_{18}
Procurement (D6)	Type of procurement & delivery method (F19)	w_{19}
Socio-Cultural (D7)	Cultural resistance (F20)	w_{20}
	Local authority regulation (Workers Union-Syndicate) (F21)	w_{21}

The alternative weight given to each factor is based on the importance and performance scale given verbally by the decision-maker. For this case study, the value is assigned by an expert user with more than 10 years in OSC. Fuzzy logic is used to convert the 'linguistic' assessment into a numeric scale (Zadeh, 1965). The perception of the expert (decision maker) is based on 2 aspects, i.e. 1) the importance of each dimension (D_i) and 2) performance rating of DKSF (F_i). Ordoobadi (2009) applied membership functions consisting of two axes. The vertical axis represents the degree of membership and the horizontal axis represents the importance and performance scale (Ordoobadi, 2009). Table AI.2 and Table AI.3 respectively show the importance and performance of linguistic scale to fuzzy importance/performance.

The importance of each dimension for each alternative is assessed by assigning a linguistic importance set of “Low”, “Medium”, “High” and “Very High” which correspond to their relevant fuzzy value on a scale of 0-1 as per Table AI.2. The membership functions of the linguistic importance weight and performance rate are based on the linguistic importance and performance scale presented by Ordoobadi (2009). The performance of an alternative with respect to each factor is evaluated on the linguistic scale of “Poor”, “Good”, “Very Good” and “Excellent” which correspond to a fuzzy value of 0-10 as per Table AI.3.

Table A I.2 Linguistic Importance Scale

Linguistic Importance	Fuzzy importance value
Low (L)	(0.0, 0.0, 0.2, 0.4)
Medium (M)	(0.2, 0.4, 0.4, 0.6)
High (H)	(0.4, 0.6, 0.6, 0.8)
Very High (VH)	(0.6, 0.8, 1.0, 1.0)

Table A I.3 Linguistic Performance Scale

Linguistic Performance	Fuzzy Performance value
Poor (P)	(0, 0, 2, 4)
Good (G)	(2, 4, 4, 6)
Very Good (VG)	(4, 6, 6, 8)
Excellent (EX)	(6, 8, 10, 10)

Equation A I.1 shows the calculation of the Fuzzy weight of a KDSF, where I_{Di} is an importance fuzzy value of a dimension and I_{Fi} is an importance fuzzy value of a factor. For example, the Fuzzy weight w_1 is calculated by multiplying the importance of project characteristics D_1 by the importance of size F_1 as per equation A I.1.

$$w_i = I_{Di} \times I_{Fi} \qquad \text{(A I.1)}$$

The next step is to construct the fuzzy performance rate for each KDSF and to calculate the fuzzy score for each alternative. The fuzzy score of an alternative is calculated by multiplying the fuzzy performances by the fuzzy importance weights in a weighted sum according to equation A I.2, where fs_i is a fuzzy score, fp_i is a fuzzy performance and w_i is a fuzzy importance weight:

$$fs_i = \sum_{i=1}^{n} fp_i \times w_i \quad \text{; where } n = \textit{number of KSDF} \tag{A I.2}$$

The final step is to rank the alternatives based on crisp scores. Fuzzy scores are defuzzified using the centroid method according to equation A I.3 where *(l,* m_l*,* m_u*, u)* construct fuzzy score. The alternative with the higher crisp score ranks first:

$$\text{Crisp score } x = \frac{l+m_l+m_u+u}{4} \tag{A I.3}$$

Where l= first member, m_l= second member, m_u= third member, u= fourth member

The following shows an example calculation of fuzzy weight w_i, fuzzy score fs_i and fuzzy performance fp_i:

Importance input by the expert for D1 (Project characteristics): High (H)

Importance fuzzy value for D1: (0.4, 0.6, 0.6, 0.8) = I_{D1}

Importance input by the expert for F1 (Project Location): High (H)

Importance fuzzy value for F1: (0.4, 0.6, 0.6, 0.8) = I_{F1}

$w_1 = I_{D1} \times I_{F1}$= (0.16, 0.36, 0.36, 0.64)

Performance input by the expert for F1 in Alternative A: Poor (P)

Performance fuzzy value for F1 in Alternative A: (0, 0, 2, 4) = fp_1

Fuzzy score for F1 in Alternative A: $fs_1 = fp_1 \times w_1$ = (0, 0, 2, 4) × (0.16, 0.36, 0.36, 0.64) = (0, 0, 0.72, 2.56)

As discussed earlier, among various techniques in MCDM, Fuzzy logic was selected for this project since it was necessary to show the importance of decision making in the early design stage of a building project while the amount of information and data might be very limited. By using Fuzzy logic compare to other methods such as AHP or FAHP, the decision making process is faster (Ishizaka, 2014).

I.5 Results and discussion

Case study

A real case study is presented to evaluate the application of the proposed method. The case study is a building project located in Canada that had a unique characteristic in terms of location, accessibility, and delivery time. The weather condition of the case study is characterized by extremely cold winter and short summer duration. Accessibility is very difficult, and the client's priority is to have an efficient building that can overcome challenges in that area such as proper thermal insulation, fast delivery and minimum building energy consumption.

The decision maker was asked to provide input based on the list of KDSF to be considered for the selection of an appropriate construction method. The decision maker in this case was an expert with more than 40 years of professional experience in the construction industry. The list of KDSF factor as per Table AI.1, consisting of 7 Main factor and 21 sub-factor, was used to develop the fuzzy model. The first input set was the importance values for the main and sub-factor. Table AI.4 shows the importance rating for Project characteristics (D1), Project Location (F1) and Project Design - size, complexity and flexibility (F2) as an example.

Table A I.4 Importance rating for Project Characteristics (D1)

Main Factor rate	Sub-Factor rate	Weight
Project Characteristics (H)	Project Location (H)	w_1 = (0.16, 0.36, 0.36, 0.64)
	Project Design (VH)	w_2 = (0.24, 0.48, 0.60, 0.80)

The other weights are calculated in the same manner:

w_1 = (0.16, 0.36, 0.36, 0.64), w_2 = (0.24, 0.48, 0.60, 0.80), w_3 = (0.24, 0.48, 0.60, 0.80), w_4 = (0.16, 0.36, 0.36, 0.64), w_5 = (0.08, 0.24, 0.24, 0.48), w_6 = (0.24, 0.48, 0.60, 0.80), w_7 = (0.36, 0.64, 1.00, 1.00), w_8 = (0.24, 0.48, 0.60, 0.80), w_9 = (0.36, 0.64, 1.00, 1.00), w_{10} = (0.36, 0.64, 1.00, 1.00), w_{11} = (0.04, 0.16, 0.16, 0.36), w_{12} = (0.04, 0.16, 0.16, 0.36), w_{13} = (0.08, 0.24, 0.24, 0.48), w_{14} = (0.08, 0.24, 0.24, 0.48), w_{15} = (0.04, 0.16, 0.16, 0.36), w_{16} = (0.36, 0.64, 1.00, 1.00), w_{17} = (0.24, 0.48, 0.60, 0.80), w_{18} = (0.36, 0.64, 1.00, 1.00), w_{19} = (0.16, 0.36, 0.36, 0.64), w_{20} = (0.24, 0.48, 0.60, 0.80), w_{21} = (0.16, 0.36, 0.36, 0.64).

Table A I.5 shows alternative A - Traditional method and alternative B – Off-site construction (Modular) performance rating in the case study.

Table A I.5 Performance rating with respect to KDSF

Factor	Rating of Alternative A	Rating of Alternative B
Project characteristics(D1)		
Project Location (F1)	P	EX
Project Design (Size, Complexity and Flexibility) (F2)	VG	G
Supply chain (D2)		
Financing (F3)	VG	VG
Available Manufacturer (F4)	P	VG
Available Infrastructure (Hardware & Software) (F5)	G	EX
Available experts and skilled workers (F6)	P	VG
Time (D3)		
Design period (F7)	VG	VG
Production time (F8)	P	EX
Mobilization & transfer time (F9)	VG	G
Assembly & construction period (F10)	P	EX
Cost (D4)		
Design (F11)	VG	VG
Production & Manufacturing (F12)	VG	VG
Logistic (F13)	VG	G
Assembly & construction (F14)	VG	EX
Maintenance (F15)	G	VG
Quality (D5)		
DfMA + Disassembly (F16)	P	EX
Standards and protocols (F17)	VG	VG
Sustainability (Carbon emission, Energy, waste) (F18)	G	EX
Procurement (D6)		
Type of procurement & delivery method (F19)	VG	VG
Socio-Cultural (D7)		
Cultural resistance (F20)	VG	G
Local authority regulation (Workers Union-Syndicat) (F21)	G	EX

Fuzzy score was constructed by using performance rating for each alternative with respect to the sub-factor. Fuzzy scores of the alternatives were calculated by applying equation A I.2 with respect to the expert's rating. The fuzzy scores were defuzzified by the centroid method determined in equation A I.3. Finally, Alternatives were ranked according to their crisp score. The highest ranking was considered the most appropriate construction method for this project's specific case study.

Table A I.6 summarizes the result. Alternative B- Off-site steel structure fully modular building, has a higher crisp score compared to alternative A- conventional method cast in situ concrete building. Therefore, the proposed fuzzy model ranked alternative A first. It is also supporting the critical success factors for this particular case study.

As mentioned earlier, due to the case study's location, weather conditions, accessibility, and specific client's quality requirement the factors of project location (F1), available infrastructure (F5), Production time (F8), assembly and production period (F10), assembly and construction cost (F14), DfMA + Disassembly (F16) and local authority regulation (F21) are major factors with higher performance value.

Table A I.6 Fuzzy score, crisp scores and ranking

Alternatives	Fuzzy Score	Crisp scores	Rank
Alternative A	(9.60, 31.76, 48.24, 94.56)	46.04	2
Alternative B	(18.72, 55.84, 81.76,124.96)	70.32	1

The finding of this research is also in line with discussions by previous scholars in this domain such as the study by Wuni (2019) on the five primary factors involved in the selection of modular methodology since skilled labour, project timeline, transportation, limitation in size and equipment availability have a similar perception to this study's factors with higher performance value. The significance of this study is the validation of the suggested alternative for the specific case study which is an ongoing project. The real scenario shows the reliability of the proposed system as well as its adaptability to other cases with different characteristics.

I.6 Conclusion

The decision-making process for selecting a suitable construction method is complex and influenced by many factors. It is an important process since a rapid and proper decision needs to be made at the early stages of a project. The initial selection of the most suitable approach will assist all stakeholders, such as engineers and architects, to develop their detailed designs in compliance with the specificities of the selected method (in the case study, the Off-site concept).

This project studied the application of fuzzy logic in the MCDM concept to select an appropriate offsite construction approach. The decision maker was asked to rank their preferences in a linguistic manner using a given scale to address subjectivity during data collection. These data were used to measure the importance and performance of Key Decision Support Factors. For the specific case study used in this project, Alternative A is the conventional method of cast-in-situ concrete works on site, while Alternative B is the Off-site steel structure fully modular building. The results show that Alternative B, with a crisp score of 70.32, ranks first, while Alternative A scored 46.04 and ranked second. Since the case study of this project was an ongoing modular project, the decision maker could validate the suggestion of the proposed Decision Support System (DSS) and its functionality.

The outcome of this research provides a useful and applicable framework to support the management process to reduce failure risk and improve the decision-making process. The proposed framework can be relevant and applied to any similar context, such as the comparison between various types of Industrial Building Systems. The importance and performance of relevant KDSF may differ in other countries and different types of construction projects, such as infrastructure, which are excluded from this study. Therefore, a future comparative study is suggested to investigate these differences. This project is limited to the use of data input by one expert. Furthermore, future research aims to collect more data to cover a larger context.

ANNEX II

IDENTIFYING CHALLENGES FOR EXTENDED DESIGN FOR MANUFACTURING AND ASSEMBLY (DfMA) IN ALL PHASES OF A CONSTRUCTION PROJECT

Sadaf Montazeri[1], Amirhossein Mehdipoor [1], Sara Rankohi[2], Ivanka Iordanova[1]

[1]Department of Construction Engineering, École de Technologie Supérieure, 1100 Notre-Dame Ouest, Montréal, Québec, Canada H3C 1K3
[2]Department of Management, Université du Québec à Montréal, Case postale 8888, succursale Centre-ville, Montréal, Québec, Canada H3C 3P8

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II.1 Abstract

Design for Manufacturing and Assembly (DfMA) has emerged as a promising approach to enhance productivity in the construction industry. In recent studies, the most widespread DfMA adoption is foreseen in off-site construction (OSC). This creates a misconception that DfMA serves OSC only, while not all projects are suitable for full OSC, but they can still benefit from DfMA design principles. In this context, "on-site construction (OnSC)" refers to work completed on-site as part of an OSC project, as well as OnSC using specific realization methods. Since the adoption of DfMA as a systematic procedure is anticipated to be widespread within the construction sector, it is crucial to identify challenges associated with its implementation in the different stages of the construction process. This article aims to identify, verify, and analyze the challenges to the adoption of DfMA with a focus on the on-site parts of the construction. The study utilized a mixed-method approach, comprising of an extensive review of the literature and industry expert interviews. The information gathered was analyzed and synthesized using NVivo 14 Pro and prioritized using the mean score (MS) analysis and weighting function. Based on the research methodology, 42 DfMA challenges were validated and grouped into 9 Main categories. Further analysis concluded that the three

most important challenges in implementing DfMA in on-site parts of the construction are economic and financial, technological, and legal contractual challenges. They formed the basis for developing a conceptual framework representing DfMA-related challenges. By identifying and understanding the challenges for DfMA adoption in both OSC and OnSC, this article aims to contribute to the body of knowledge in construction management and provide valuable insights for industry professionals, researchers, and policymakers. Ultimately, the findings of this study can guide organizations in effectively implementing DfMA strategies in all stages of a project, leading to enhanced construction productivity, sustainability, and competitiveness in the built environment.

Keywords: design for manufacturing and assembly (DfMA), off-site construction (OSC), on-site construction (OnSC), challenges, construction productivity

II.2 Introduction

For decades, the construction industry has suffered from remarkably low productivity. Global productivity growth in the construction sector has averaged just one percent a year for the past two decades compared with world economic growth of 2.8 percent and manufacturing growth of 3.6 percent, this clearly indicates that the construction industry is underperforming (McKinsey Global Institute., 2017).

In the past few decades, OSC has grown in popularity in the construction sector, and various studies have recommended it as a way to boost productivity (Alazzaz & Whyte, 2014) (Li et al., 2022) (Barlow et al., 2004). In a 2016 report by KPMG, it was highlighted that OSC could not address all the challenges of the construction industry; hence, an integrated approach like Design for Manufacture and Assembly (DfMA) was considered essential. DfMA, initially developed in the manufacturing industry, has now become a significant approach in construction, enhancing the process through the standardization of components and the reduction of variables. It offers the potential to enhance productivity, efficiency, and quality (Goulding et al., 2015).

Different studies have been conducted on the use of DfMA methods in OSC projects leading to the misconception that DfMA only serves OSC. However, according to (Lu et al., 2021) the use of DfMA is expected to have a wide range of applications, ranging from one-off small-scale to large-scale construction projects, benefitting both OnSC and OSC methods.

This study was partly inspired by a real-world industrial application, introduced through a Mitacs project in collabouration with GBE innovation company, a manufacturer and supplier based in France. GBE is known for producing cast-in-place concrete walls with integrated insulation, a process they believe to be a novel and updated approach in the construction industry which is an excellent alternative to insulated double walls (prefabricated sandwich panels) or external thermal insulation. The implementation of the GBE® process necessitates exacting accuracy, especially during the simultaneous continuous pouring of self-compacting concrete on both sides. It was observed that the vast majority of this process was executed on-site, emphasizing the critical nature of onsite operations in its success. This insight into GBE's practices underscores the relevance of examining the importance of OnSC, particularly those processes that are thought to be innovative yet remain heavily reliant on traditional on-site methods.

In the broader context of construction, even the highest degree of prefabrication, as classified by Gibb's (2001) taxonomy (level 4, indicating a fully modular building), involves elements that require on-site completion. It is a fundamental aspect of construction that some processes, adaptations, or integrations are more effectively managed directly at the project site. This reality brings into focus the significance and applicability of the DfMA principles beyond the OSC, reveals opportunities to streamline even those on-site components and activities. This approach aims to enhance efficiency and coherence throughout the entire building process, merging innovative methods like those of GBE with on-site techniques.

There have been numerous challenges identified and documented with regard to DfMA methods in OSC projects in previous studies. In addition, some strategies were suggested to facilitate DfMA's application in OSC, However, based on the literature review, none of these studies conducted a comprehensive study to identify the existing challenges, focusing on all phases of construction projects to consist of both OSC and OnSC parts. Even in the literature with a focus on the DfMA challenges in OSC the impact and the importance of the identified challenges are not investigated.

This article begins by defining DfMA, as a methodology that simplifies and optimizes the manufacturing and assembly processes of various components used in construction. The study then aims to identify the challenges hindering the adoption of DfMA methodology beyond the boundaries of OSC, focusing on OnSC parts. By integrating insights from a comprehensive literature review and interviews with industry experts, the article delves into the current state of knowledge surrounding DfMA. It focuses on uncovering and discussing the key barriers and difficulties that currently impede its widespread implementation in the construction sector. By shedding light on the challenges related to DfMA adoption, the article contributes to construction management knowledge. It provides valuable guidance for researchers and practitioners, facilitating quicker investigation of the root causes of barriers in implementing DfMA strategies across various construction projects. Additionally, it assists in addressing these hindrance factors by suggesting appropriate remedial measures.

This paper is structured in a way that facilitates a comprehensive understanding of the subject matter. It begins with the 'Research Background' section, offering an in-depth overview of DfMA in construction. Following this is the 'Methodology' section, detailing the research approach and the techniques employed for data collection and analysis. The 'Discussion and Research Findings' section comes next, where the analysis of the data is explored, highlighting key results and their implications. An additional section, 'Compare DfMA in OSC and On-site,' is included to specifically focus on the comparative analysis of DfMA in OSC versus traditional on-site methods. The paper concludes with the 'Conclusion' section, summarizing the study's main insights and contributions, and emphasizing significant findings from the data analysis.

II.3 Research Background

DfMA as a methodology, emphasizing simplicity and minimizing the use of materials, labour, and manufacturing-related activities (Wasim et al., 2020). It was in the late 1960s and early 1970s that formal approaches to design for manufacture (DfM) and design for assembly (DfA) were developed, which were reflected in 1975 British standards on managing design for economic production. With Boothroyd and Dewhurs' practice and research, DfMA also became an academic field in the 1970s. Since the 1980s, it has been extensively used to streamline product design and cut down on manufacturing time and costs (Langston & Zhang, 2021).

DfMA is a tool that is used to illustrate how an approach that was previously sequential and conventional is now taking a non-linear and iterative approach (Tuvayanond & Prasittisopin, 2023). Various researchers (Bogue, 2012; Boothroyd, 1994; Vaz-Serra et al., 2021) mentioned that DfMA, as a methodology, is based on certain guidelines, standards, and rules; and diverse policies have been introduced to enable efficient implementation of DfMA. In general, common guidelines for DfMA encompass minimization, standardization, and modularization (Song et al., 2022).

According to (Gao et al., 2018), for the construction industry in particular, there are three views on the adoption of DfMA: DfMA as a systematic process combining design, manufacture, and assembly to enhance value of the overall process; DfMA as an evaluation system that can assess the efficiency in manufacturing and assembly, integrating with virtual design and construction; and DfMA as a technology which is a revolutionary approach linked with evolving prefabrication and modular construction techniques.

Numerous studies have emphasized the benefits of DfMA such as; reduce cost and time (Lu et al., 2021; Tan et al., 2020; Wasim et al., 2020), enhance quality (Bao et al., 2022a; Favi et al., 2017), reduced construction labour (Bakhshi et al., 2022; Machado et al., 2016), enhanced sustainability and circular economy during asset’s lifecycle (Favi et al., 2017; Gao et al., 2018), and enhancing waste management (Roxas et al., 2023). According to (Lu et al., 2021), if we take a closer look at DfMA and its similar concepts, such as buildability, value management, and lean construction, we can see that the DfMA philosophy is reflected in various construction practices throughout the industry.

As reported in the literature by (Bao et al., 2022a; Wasim et al., 2020), DfMA applications are still limited, and not much information is available on DfMA adoption in the construction industry. However, in different research there are several challenges associated with the adoption of DfMA in the construction industry including resistance to change and a preference for traditional methods (Langston & Zhang, 2021; Montali et al., 2018), lack of government support and incentives (Chen et al., 2017), lack of planning and building codes alignment (Bao et al., 2022), higher costs, government regulations, risk aversion (Langston & Zhang, 2021), lack of suitable technical requirements (Bakhshi et al., 2022). It is important to recognize that each of these challenges has a complex environment for the widespread adoption of DfMA in the construction industry. This underscores the need for coordinated efforts from industry stakeholders, government agencies, as well as the construction industry to ensure that these issues are addressed and DfMA's benefits are promoted positively.

While the existing literature provides insights into the use of DfMA in OSC, a significant gap remains in understanding its challenges and opportunities in OnSC contexts. As outlined earlier in this study, “on-site construction (OnSC)” is defined as the work carried out on the actual project site, both as a part of OSC projects and those involving unique OnSC methodologies. This gap is particularly notable given the construction industry's chronic underperformance in productivity compared to other sectors. Moreover, while DfMA's potential in enhancing productivity, efficiency, and quality in OSC is acknowledged, its broader application in OnSC – where processes and integrations often require direct management on project sites – is less explored. This paper aims to bridge this gap by specifically focusing on the challenges of implementing DfMA beyond the OSC environments.

The objectives of this study are: to begin with, conducting a comprehensive investigation into the current challenges hindering DfMA's adoption in OnSc, a facet less emphasized in existing studies. This involves analyzing both the challenges documented in the context of OSC and identifying unique challenges pertinent to OnSc. Next, the paper seeks to evaluate the impact and significance of these challenges, providing insights into their relative importance and potential implications for the construction industry. By addressing these objectives, this study endeavors to extend the existing body of knowledge on DfMA and its applicability, offering practical recommendations for overcoming barriers and promoting the wider adoption of DfMA principles in both OnSc and OSC projects.

II.4 Methodology

This study was conducted using a mixed method research approach consisting of quantitative and qualitative research design as the methodological framework in the pursuit of creating a comprehensive understanding of the studied phenomenon. According to (Boswell & Cannon, 2022), due to the complexity of today's problems, the rise of qualitative research, and the need for diverse audiences to be served by various forms of data, mixed methods research is becoming increasingly important; so, in order to provide a complete analysis of problems, quantitative and qualitative data must be combined. Figure AII.1 shows the multistage methodological approach flowchart for this research.

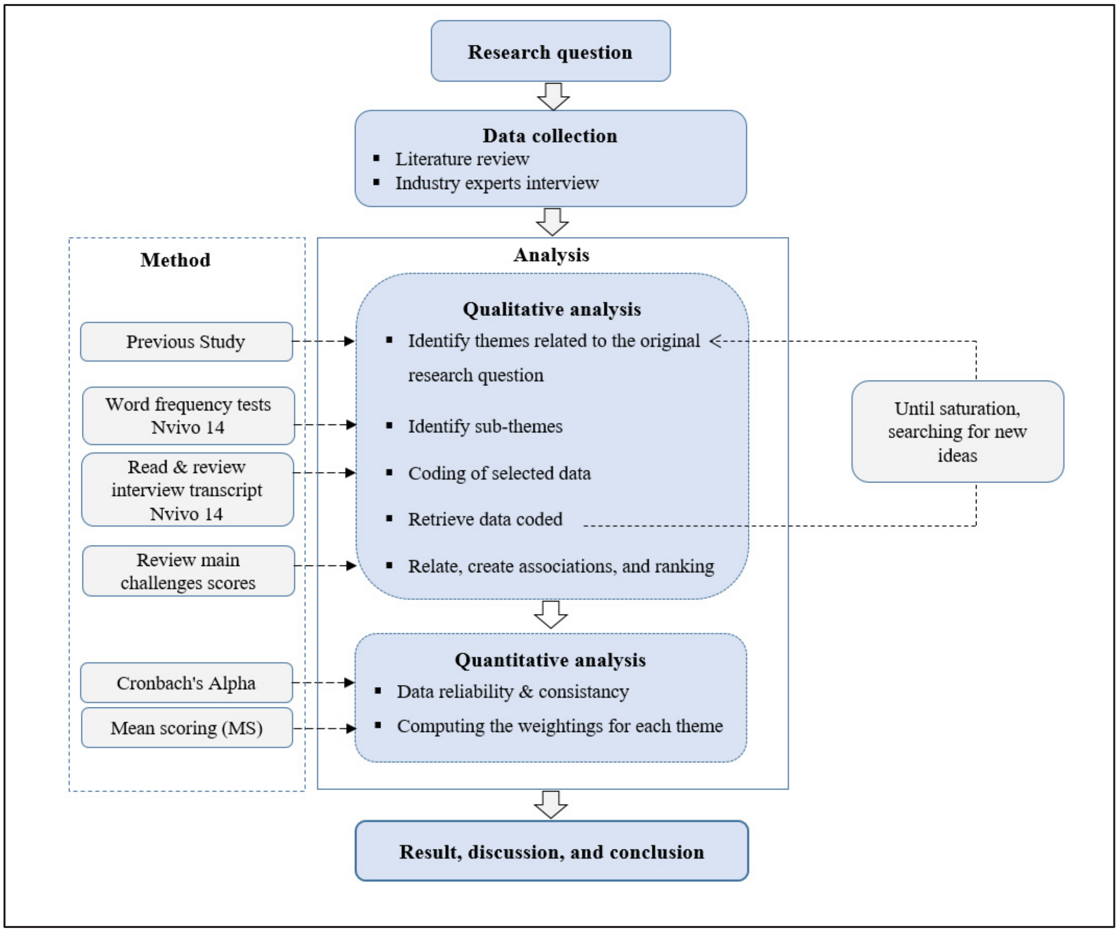

Figure A II.1 Multistage methodological approach flowchart

II.4.1 Data collection

First, a review of the previous literature was conducted in section 2, as part of the overall multistage methodology in order to assess the current state of the DfMA in construction and its adoption in OSC and OnSC. The literature review shed light on the fact that the literature on DfMA is limited in OSC and there has been insufficient research on the application of DfMA in OnSC (Lu et al., 2021).

To identify DfMA challenges in OnSC, we used the opinion and experience of industry experts. It is very common to conduct interviews in order to gather data (Taylor 2005), and semi- structured interviews are the most commonly used interview technique in qualitative research (DiCicco-Bloom & Crabtree, 2006). A semi-structured interview approach was applied, where we asked open-ended questions within a specific theme as described by (Denzin & Lincoln, 2011). This method, as mentioned by (Kallio et al., 2016), helped us gathered reliable and comparable data; It also gave us flexibility to ask more questions on the spot and plan out the main topics in advance. The study employed a comprehensive questionnaire, it was designed to cover a broad spectrum of potential challenges in DfMA implementation, derived from both literature review and preliminary expert feedback. This iterative design process ensured the questionnaire's relevance and comprehensiveness. The questionnaire comprised of four sections.

The first section, titled 'Expert's Profile and Professional Experience,' requested participants to share their occupational background and their experience in construction. The second section, served as an introduction to the questionnaire, setting the context for the subsequent queries. The third section delved into “OnSC Project Description” which included detailed examples of some of these specific OnSC projects like GBE process. Finally, the fourth section, “DfMA Challenges Interview Questions” encompassed a series of questions categorized into nine different sections according to previous study. The questionnaire probed into various aspects of DfMA implementation in OnSC.

Questions covered legal and contractual considerations, such as contract drafting and negotiation factors. Technological inquiries focused on tools and bottlenecks in DfMA application, including automation and robotics. Procedural barriers, including scheduling and workforce coordination. Cultural factors, like stakeholder communication and social attitudes. Commercial challenges, geographical influences, and economic and financial impacts, such as cost and Return of Investment (ROI), were also discussed. The questionnaire delved into technical cognitive aspects like project planning and labour requirements.

Finally, policy and regulatory barriers, alongside unforeseen challenges like weather and site constraints, were also addressed. Additionally, this section concluded with an open-ended query inviting respondents to share any further insights or points not covered in the interview, emphasizing the value of their unique perspectives. The questionnaire is attached in Appendix 1 for reference.

Noble and Smith (2015) emphasized the importance of truth value in qualitative studies, such as semi-structured interviews, for ensuring the credibility of results and the representation of samples. This study conducted ten interviews, using the purposive sampling technique and thematic analysis, until reaching saturation. Saturation is achieved when new data no longer provides significant new insights, as outlined by Saunders et al. (2018).

II.4.2 Semi-structured interviews

We conducted interviews with a diverse group of ten industry experts from various professional backgrounds, each possessing varying years of experience within the construction industry. All interviews were conducted online for maximum accessibility and convenience for the participants, with interview durations ranging from 30 minutes to one hour. Table AII .1 indicates the profile of respondents in the interview. In order to prevent ethical issues, the interviewees were informed that their names and companies were kept anonymous. As well, interviewees were free to quit at any time. All interviews were audio-recorded and transcribed accurately in Microsoft Word documents. The transcripts of each single-person interview were imported as single documents into the NVivo 14 project. This computer-assisted qualitative data analysis software (CAQDAS) was developed by QSR International (Melbourne, Australia), the world's largest qualitative research software developer. By using this software, one can perform qualitative inquiry beyond mere coding, sorting, and retrieval of data. A key feature of the software is its ability to integrate coding with qualitative linking, shaping, and modeling (Wong, 2008).

Table A II.1 Interviewees' profile

Interviewee	professional role	Type of company	Industry experience (years)	Interview duration
Int-1	Project manager	Manufacturer	10	55 min
Int-2	Project manager	Structural engineering	8	32 min
Int-3	Director	General contractor	10	38 min
Int-4	Design director	General contractor	20	40 min
Int-5	Project manager	Structural engineering	13	30 min
Int-6	Architect	Manufacturer	20	35 min
Int-7	Director	Architecture	10	45 min
Int-8	Digital construction director	General contractor	15	30 min
Int-9	Director	General contractor	10	30 min
Int-10	Architect	Architecture	4	50 min

II.4.3 Data analysis

According to (Wong, 2008) in the qualitative data analysis process, the process of coding or categorizing the data is the most important part of the procedure; which involves subdividing a huge amount of raw information or data and subsequently assigning the collected information or data to different categories. NVivo enhances research quality by simplifying the data analysis process that would typically be done manually. It saves time, facilitates the identification of trends and themes, and makes qualitative data analysis more systematic (Wong, 2008).

As proposed by Lewins and Silver. (2007), qualitative studies should reflect on how the coding themes were chosen in analyzing interview transcripts. The coding process for this research followed the approach used by Dransfield et al. (2004) involving two steps:
Initially, NVivo codes were established by conducting a thorough review of the existing literature, particularly focusing on the research that served as the theoretical foundation for this study. This included an in-depth analysis of challenges to the implementation of DfMA in OSC, as outlined by Rankohi et al. (2023). These challenges were categorized into eight groups: legal contractual, technological, procedural, cultural, commercial, geographical, economic and financial, technical cognitive. The codes were further classified into nine categories. These categories are directly related to the challenges associated with DfMA in the OnSC process. The identified categories, considered as parent codes, include: (1) legal contractual, (2) technological, (3) procedural, (4) cultural, (5) commercial, (6) geographical, (7) economic and financial, (8) technical cognitive, and (9) policy. Employing such a technique ensures a clear link between the research questions and the data. It also facilitates the generation of new insights, as highlighted by Bazeley.(2013).

Secondly, after importing interview transcripts into NVivo 14 using the code functions, we looked for repetitions and regularities by running word frequency tests. According to Ryan & Bernard, (2003), discovering concepts and themes in texts can be done most efficiently by analyzing the frequency of words or the number of repetitions. Similarly, Bazeley. (2019) mentions people repeating ideas of significance to them, and identifying these repetitions can provide insight into the context in which they are used. So, Sub-themes were meticulously defined by conducting separate word frequency queries in NVivo for each main theme. This process involved analyzing the query results, which included the frequency of each word's occurrence in the text, its weighted percentage, and its synonymous terms Figure A II.2 is a screenshot of word frequency queries. Based on these comprehensive data, we systematically delineated sub-themes for each main theme.

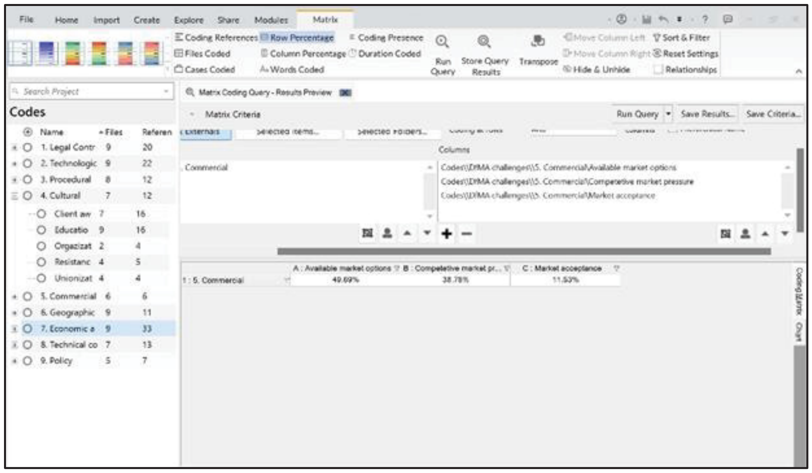

Figure A II.2 Matrix coding query for one of the main DfMA challenges and the sub- categories by NVivo 14

Finally, a total of 42 challenges were reviewed and discussed by 10 interviewees across 9 categories of the DfMA implementation with a focus in OnSC, who agree that these challenges have adversely affected the implementation of the DfMA in construction projects. Table AII.2 shows the DfMA challenges for the on-site part of the constructions identified through industry expert interviews.

Table A II.2 On-site construction (OnSC) DfMA challenges

N	Categories	Code	Challenges
1	Legal Contractual (L)	L1	Accurate cost estimation
		L2	Agility and flexibility
		L3	Clear performance metric
		L4	Clear role and responsibilities
		L5	Collabourative contracting
		L6	Competitive BID pricing
		L7	Dispute resolution method
		L8	Guarantee and insurance clarity
		L9	Risk and reward sharing

Table A II.2 On-site construction (OnSC) DfMA challenges (continued)

N	Categories	Code	Challenges
2	Technological (T)	T1	Cost of technology adoption
		T2	Identifying appropriate tools and techniques
		T3	Interoperability and digital integration
3	Procedural (P)	P1	Additional project planning
		P2	Interdisciplinary communication and collabouration
		P3	Owner expectation management
		P4	Quality control at every stage
		P5	Supply chain management
4	Cultural (C)	C1	Client awareness
		C2	Education and training
		C3	Organizational culture
		C4	Resistance to change
		C5	Unionization and corporate policies
5	Commercial (CO)	CO1	Available market options
		CO2	Competitive market pressure
		CO3	Market acceptance
6	Geographical (G)	G1	Infrastructure and utilities
		G2	Local climate and weather conditions
		G3	Local regulations and permitting
		G4	Local workforce and skills
		G5	Logistics and transportation considerations
		G6	Manufacturing facilities availability
		G7	Material availability
		G8	Specific site factors and limitations

Table A II.2 On-site construction (OnSC) DfMA challenges (continued)

N	Categories	Code	Challenges
7	Economic and financial (E)	E1	Cost overruns and contingencies
		E2	Financial options and funding
		E3	Initial capital cost and automation
		E4	Insurance and liability considerations
8	Technical cognitive (TG)	T1	Design detail and complexity
		T2	Project planning and scheduling
		T3	Technical expertise and skills
9	Policy (P)	P1	Incentives and investments
		P2	Permitting and approval process

After conducting a qualitative analysis using NVivo on the interview transcripts, and identifying the primary challenges, each main challenge was ranked on a scale of 1 to 5 based on its significance through the reviewing the interview transcripts.

Various methods were employed to assign scales based on expert opinions gathered during interviews and through the analysis of transcripts. The first approach involved direct inquiry into factors commonly identified in the list and sought the opinions of experts. These experts were requested to assess the significance of challenges in implementing DFMA. These factors could include aspects such as Accurate cost estimation (L1), Initial capital cost (E3), Permitting and approval process (P2), or the Local regulations and permitting (G3). The experts were then asked to assess the significance of these challenges on a scale ranging from 1 to 5.

The subsequent method involved evaluating the frequency of the topic and the degree of emphasis placed on specific factors in terms of repetition and the time experts dedicated to discussing each factor. In this method, the researchers analyzed the transcripts of interviews to evaluate the frequency of certain topics and the degree of emphasis placed on specific factors by the experts. This involved identifying how often certain challenges were discussed, and the amount of time dedicated to each factor during the interviews.

The goal is to assign a numerical value on the scale of 1 to 5, where 1 indicates "Not at all important" and 5 indicates "Very important." Table A II.3 used to assign the degree of importance based on transcription:

Table A II.3 Degree of importance

Scale	1	2	3	4	5
Frequency	Never mentioned during the interview.	The category was discussed, but the specific factor was indirectly mentioned.	The category and factor were discussed directly once	The category and factor were discussed directly more than once.	Experts directly emphasized the importance and elabourated on it further

The scale is interpreted as follows: 1 = Not at all important, 2 = Slightly important, 3 = Important, 4 = Fairly important, and 5 = Very important. We continued by analyzing the data set using Statistical Package for the Social Science (IBM SPSS v.25), and Cronbach's Alpha was used to evaluate both the data reliability as well as the reliability of the survey instrument. According to Tavakol & Dennick. (2011) for evaluating the internal consistency of the answers, Cronbach's alpha was employed, a scale from 0 to 1. A Cronbach's alpha of 0.7 signifies an acceptable level of reliability, with 0 denoting no reliability and 1 signifying absolute reliability (Tavakol & Dennick, 2011). The assessment resulted in a Cronbach's alpha score of 0.804, surpassing the acceptable limit and indicating a dataset of high reliability. Table 4.4 illustrates the variable and internal consistency values based on Cronbach's alpha.

$$\alpha = \frac{K}{K-1}\left[1 - \frac{\sum S^2 y}{S^2 x}\right] \tag{A II.1}$$

Taken from Tavakol & Dennick (2011)

Table A II.4. Internal consistency

Variable	Description	Value	Internal consistency
K	Number of DfMA challenges	9	0.804
$\sum s^2 y$	Sum of each DfMA challenges variance	4.87	
$s^2 x$	The variance of a sum of DfMA challenges value	17.09	

We computed the mean scores (MS) for the identified DfMA challenges on a 5-point grading scale. This approach can be applied as a result of the work of researchers (Attouri, Lafhaj, Ducoulombier et Linéatte, 2022 ; Wuni et Shen, 2020), that they all used the MS in order to form the basis for evaluating the ranking and prioritizing different factors in their research. We used the following formula to compute MS (mi).

$$MS = \frac{\sum(E \times F)}{N}, \ (1 \leq MS \leq 5) \tag{A II.2}$$

Taken from Tavakol & Dennick (2011)

Where E is a score given to each challenge based on the analysis with NVivo, ranging from 1 to 5; F is the frequency of each rating (1–5) for each challenge; and N represents the total number of industry experts. Among challenges, those with the highest score were regarded as the major challenges that influenced the adoption of DfMA in on-site part of the constructions. Table A II.5 displays the mean scores (MS) analysis results.

Table A II.5 DfMA challenges ranking

Categories	MS	Rank
Economic and financial (E)	4.6	1
Technological (T)	4.4	2
Legal Contractual (L)	4.3	3
Technical cognitive (T)	4.2	4
Procedural (P)	4.1	5
Cultural (C)	3.6	6
Geographical (G)	3.1	7
Policy (P)	2.6	8
Commercial (CO)	2.2	9

In the process of ranking the sub-categories pertinent to DfMA challenges, our methodology employed a matrix coding query. As delineated by (Bazeley, 2018), this technique enables the creation of a matrix or table, providing a visual intersection of various codes or themes. Such an approach is instrumental in unveiling underlying patterns and relationships within the dataset. Specifically, this method facilitates the observation of recurring themes across different data sources, such as interviews, or the frequent co-occurrence of certain themes. To enhance our analysis, we utilized the row percentage feature, which displays the proportion of words coded in each category as a percentage of the total words in that row. This was complemented by a thorough screening of the text to verify the accuracy of these percentages. The culmination of this meticulous process is reflected in the sub-category rankings presented in Table A II.6.

Table A II.6 DfMA Sub-category challenges ranking for on-site construction

	Categories	Code	Sub-categories	Row percentage (%)	Rank
1	Economic and financial (E)	E1	Cost overruns and contingencies	25.92	2
		E2	Financial options and funding	18.69	4
		E3	Initial capital cost	33.54	1
		E4	Insurance and liability considerations	21.85	3
2	Technological (T)	T1	Cost of technology adoption	31.4	2
		T2	Identifying appropriate tools and techniques	45.89	1
		T3	Interoperability and digital integration	22.71	3
3	Legal contractual (L)	L1	Accurate cost estimation	9.66	6
		L2	Agility and flexibility	13.51	4
		L3	Clear performance metric	6	7
		L4	Clear role and responsibilities	20.3	1
		L5	Collabourative contracting	15.24	3
		L6	Competitive BID pricing	2.27	9
		L7	Dispute resolution method	4.43	8
		L8	Guarantee and insurance clarity	11.76	5
		L9	Risk and reward sharing	16.83	2
4	Technical cognitive (TG)	T1	Design detail and complexity	23.15	2
		T2	Project planning and scheduling	18.97	3
		T3	Technical expertise and skills	57.88	1

Table A II.6 DfMA Sub-category challenges ranking for on-site construction (continued)

	Categories	Code	Sub-categories	Row percentage (%)	Rank
5	Procedural (P)	P1	Additional project planning	16.2	4
		P2	Interdisciplinary communication and collabouration	35.87	1
		P3	Owner expectation management	25.11	2
		P4	Quality control	19.51	3
		P5	Supply chain management	5.11	5
6	Cultural (C)	C1	Client awareness	25.51	2
		C2	Education and training	32.46	1
		C3	Organizational culture	10.76	5
		C4	Resistance to change	13.36	3
		C5	Unionization and corporate policies	17.91	4
7	Geographical (G)	G1	Infrastructure and utilities	3.72	7
		G2	Local climate and weather conditions	6.42	4
		G3	Local regulations and permitting	20.15	2
		G4	Local workforce and skills	0.26	8
		G5	Logistics and transportation considerations	52.12	1
		G6	Manufacturing facilities availability	3.47	6
		G7	Material availability	4.36	5
		G8	Specific site factors and limitations	9.5	3
8	Policy (P)	P1	Incentives, Investments	82.74	1
		P2	Permitting and approval process	17.26	2
9	Commercial (CO)	CO1	Available market options	49.69	1
		CO2	Competitive market	38.78	2
		CO3	Market acceptance	11.53	3

II.5 Discussion and research findings

The nine challenges categories and their sub-categories were used to create a conceptual framework for DfMA challenges in the field of OnSC. The framework is illustrated in figure AII.3. The importance and ranking of the DfMA challenges have the potential to guide industry experts to have an ideal implementation scheme for DfMA in their construction projects.

Overall, economic and financial-related challenges, such as initial capital costs, cost overruns and contingencies, insurance and liability considerations, and financing options and funding are considered the most important and relevant challenges for implementing DfMA in OnSC for building projects. In contrast, commercial-related factors, such as available market options, competitive market pressure, and market acceptance have the least influence on the implementation of DfMA in OnSC projects. Figure A II.3 shows the conceptual framework of DfMA challenges in OnSC projects based on MS with the sub-challenges that differ between OSC and OnSC highlighted in a red dashed format for easy identification and comparison. In the following sections, more details will be provided about the first three most significant challenges associated with DfMA in OnSc, along with a comparison of these challenges to those in OSC.

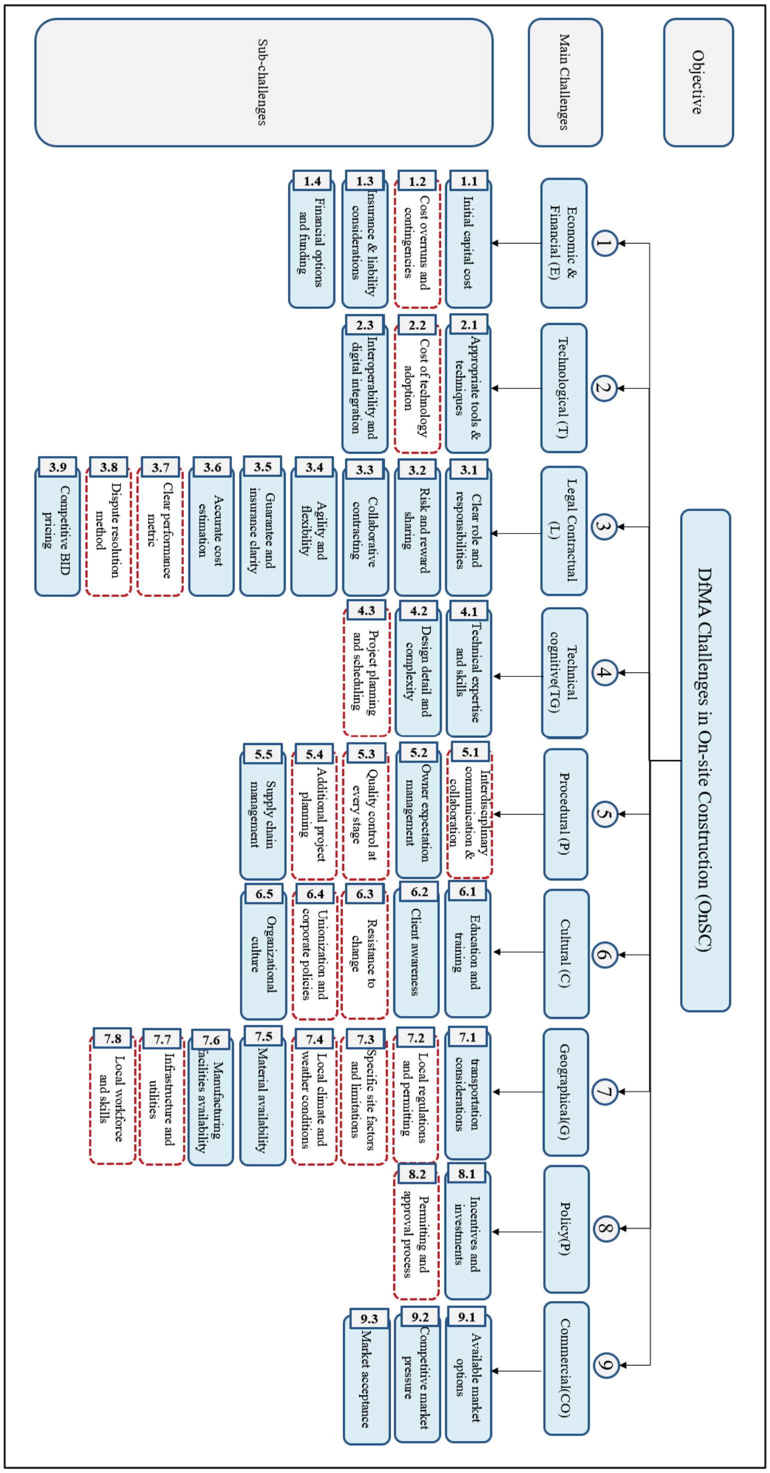

Figure A II.3 The proposed conceptual framework of DfMA challenges in OnSC projects
(The sub-challenges marked with a red dashed format indicate ones that are different between OnSC and OSC)

<u>Economic and financial</u>

The economic and financial aspects of DfMA in OnSC are identified as the most important challenges by scoring a total mean of 4.6 (Table A II.5). The discussion highlights various factors that contribute to the economic and financial considerations in implementing DfMA such as initial capital cost, cost overruns and contingencies, insurance and liability considerations, and financing options and funding.

An expert opinion suggests that "*Initial capital costs are a critical factor in DfMA implementation in OnSC. Acquiring technology and equipment for design, fabrication, and installation involves significant upfront expenses. This can pose a challenge, especially for smaller firms or projects with limited budgets. The accuracy of initial budget estimation is crucial to avoid financial setbacks*" *(Int-2)*. This emphasizes the significance of estimating the budget accurately at the project's outset, and considering all capital costs. The interviewees also noted that "*cost overruns are often underestimated, especially by those new to DfMA" (Int-2).* This observation is particularly significant in light of the NVivo analysis, which ranks cost overruns and contingencies as the second most prominent economic and financial challenges in DfMA implementation in OnSC. The focus on contingencies echoes the literature's recognition of the need for risk management in the initial phases. According to an expert opinion, "*Stakeholders often perform a thorough return of investment (ROI) analysis to assess whether the long-term benefits of DfMA, such as reduced construction time and operational efficiency, outweigh the initial capital costs" (Int-8).*

As a general summery of the conducted interviews, the economic and financial challenges of adopting DfMA primarily involve the trade-off between initial capital investments in technology and equipment and the potential for long-term labour cost savings. This balance between upfront expenditures and future efficiencies is crucial in decision-making for DfMA projects. Stakeholders must carefully consider these trade-offs, as the shift towards DfMA requires reallocating funds from traditional labour to capital investments, impacting the project's financial strategy and necessitating a thorough analysis to fully understand the economic implications of DfMA in OnSC.

The availability of financing options and funding sources plays a pivotal role in DfMA adoption from the industry experts' viewpoint as one mentioned "*Access to favorable financing or funding mechanisms can influence the decision to invest in DfMA. Government projects or those aligned with societal needs may attract more funding which makes them more likely to implement new methodologies like DfMA" (Int-4).*

In General, these findings are aligning with the findings of other scholars who have identified "higher design costs" compared to traditional methods as a barrier to the proper implementation of DfMA methods in OSC projects (Boothroyd, 1994). This comparison underscores the consistency of challenges faced across different construction methods and emphasizes the universal nature of economic and financial hurdles in the implementation of DfMA methodologies.

<u>Technological</u>

The technological challenges in DfMA implementation in OnSC can be categorized into three main areas: identification of appropriate tools and techniques, the cost of adopting new technologies, and issues related to interoperability and digital integration. Our data analysis reveals that these technological challenges are the second highest among the nine challenges faced in DfMA implementation in OnSC.

A significant challenge identified through NVivo analysis is the selection of the right tools and technologies for each project phase. Experts particularly emphasize "the *importance of specific software for different tasks like precise estimation and quality control. However, the unfamiliarity with these software tools necessitates training, highlighting a knowledge gap in the industry*" *(Int-5).*

Through qualitative analysis, it was revealed that the cost of technology adoption ranked second among the technological challenges in OnSC. The expert specifically mentions, "*high initial investment required for advanced technologies could be considered as a challenge, particularly for smaller construction firms. Implementing cutting-edge technology directly at the construction site can be both costly and complex. This involves not just the financial aspect of having and integrating different equipment, but also encompasses the challenges of training personnel, adapting existing processes, and ensuring compatibility with site-specific conditions. Additionally, maintaining advanced technology in a dynamic on-site environment adds to the complexity, requiring robust support systems and contingency planning to mitigate potential disruptions. "(Int-9)*. This acknowledges that financial constraints may hinder the adoption of technologies, potentially impacting efficiency and project outcomes. The interoperability issue, ranked third in technological challenges, industry expert interview emphasizes "the *complexity of integrating diverse technologies and the critical need for streamlined digital communication for the successful implementation of DfMA in different stages of OnSC projects" (Int-7)*.

The common thread between the expert's insights and existing literature such as (Gao, Low et Nair, 2018 ; Lu *et al.*, 2021b) discussed about not having the right tools and affordable technology hindering the adoption of DfMA in OSC projects. This underscores the global nature of technological challenges and the necessity for innovative solutions to enhance DfMA practices adoption in the construction industry.

Legal contractual

Legal contractual challenges have been ranked as the third most significant barrier in implementing DfMA in OnSC with a total MS of 4.3, which shows that integrating DfMA principles into OnSC projects requires careful consideration of various legal and contractual factors. These challenges encompass several sub-categories, including: Clear role and responsibilities, Risk and reward sharing, Collabourative contracting, Agility and flexibility, Guarantee and insurance clarity, Accurate cost estimation, Clear performance metrics, Dispute resolution methods, and Competitive bidding prices. In our analysis, we have selected the first three sub-categories for their significant comprehensiveness and relevance, as indicated by the interviewees. These sub-categories are: clear role and responsibilities, risk and reward sharing, and collabourative contracting.

Based on the direct interviews, it is evident that clarity in roles and responsibilities is a priority in implementing DfMA. One interviewee emphasizes the necessity of "*clear requirements, Role and responsibilities mentioned in the contract"(Int-4)*, highlighting the question: "*Who's going to do what?"(Int-4)*. This correlates with the prevailing literature that identifies clarity in roles as essential for successful project execution when implementing DfMA in OSC (Rankohi *et al.*, 2023). Such clarity ensures that there is no ambiguity about each party's duties, which can lead to confusion and disputes.

Risk and reward sharing is about defining how the different parties (owners, designers, contractors) share the risks and potential rewards associated with DfMA (Scott, Flood et Towey, 2013). One interviewee discussed the subject of "*risk allocation"(Int-8)* and queried, *"if [DfMA] failed… Who's gonna take care of this? Who's gonna pay for it?"*(Int-8). According to the industry expert interviews, it can be concluded that such queries reflect concerns in the industry about unforeseen issues and the subsequent financial implications.

Collabourative contracting is essential for implementing DfMA in construction projects, promoting cooperation among all project stakeholders from the very beginning (Langston et Zhang, 2021). One interviewee emphasized "*The early involvement of all parties, including suppliers and subcontractors, is crucial. This initial collabouration is a key for ensuring optimal design and precise product specifications are achieved efficiently" (Int-10)*. However, according to *(Int-1)* there is an inherent challenge here: "*OnSC procurement rules, especially in government-funded projects, sometimes hinder this early, integrated collabouration due to rigid tendering processes and strict compliance requirements that limit flexibility and hinder the adoption of more collabourative, innovative approaches. These regulations often emphasize competitive bidding and cost minimization over the potential long-term benefits of* *early stakeholder integration, thereby restricting opportunities for open communication and joint planning in the initial stages of the project*" *(Int-1).* Finally , the collabourative contracting section can be completed by the *(Int-2)* opinion "*for DfMA projects to truly flourish, stakeholders must prioritize collabouration over competition, ensuring that the best ideas, materials, and methods are utilized to their fullest potential"(Int-2).*

As supported by the literature, for DfMA to be effectively applied in OSC, early stakeholder involvement, open communication, and comprehensive information sharing are necessary (Abueisheh *et al.*, 2020 ; Gao, Jin et Lu, 2020 ; Wuni et Shen, 2020c). Traditional project delivery methods that exclude stakeholders during design stages hinder DfMA application, in line with opinions from interviewees who emphasized the significance of collabourative contracting and early engagement.

II.6 Compare DfMA challenges in OSC and OnSC

In this section, we will conduct a comparative analysis of DfMA challenges identified in OnSC with challenges identified in previous studies for OSC. By examining these challenges, we aim to gain a comprehensive understanding of the similarities and differences of DfMA adoption for OSC and its implementation when we are extending it to all the phases of a construction project - also considering the on-site parts. This comparative assessment will shed light on how DfMA practices are evolving and adapting in response to the unique demands and characteristics of both OSC and OnSC, contributing valuable insights to the field of construction management and innovation.

<u>Economic and financial</u>

The implementation of DfMA in OSC and OnSC presents distinct economic and financial challenges. As outlined in Section 4.1 (Int-2), and also according to different literature (Lu et al., 2021; O'Rourke, 2013) DfMA necessitates a considerable initial investment in design, leading to higher upfront costs for both construction methodologies OSC and OnSC. Even though both methods share this initial cost factor, the nature of the economic challenges varies between the two. For considering DfMA in OnSC, the challenges are predominantly centered around the unpredictability of site conditions. Unforeseen issues such as adverse weather or unexpected site constraints can lead to cost overruns and require extensive contingency planning. These factors introduce significant financial uncertainties and can escalate overall project costs beyond initial projections. In contrast, OSC DfMA's primary challenge lies in its high initial capital requirements. This involves substantial investment in facilities, technology, and processes before the construction phase even begins. Despite these differing points, both OSC and OnSC underscore the need for innovative and flexible financial strategies. This includes preparing for higher initial expenditures and emphasizes the importance of adaptable financial management among stakeholders to accommodate the unique demands and uncertainties inherent in each construction approach. Figure A II.4 graphically shows the economic and financial challenges associated with the OSC and OnSC.

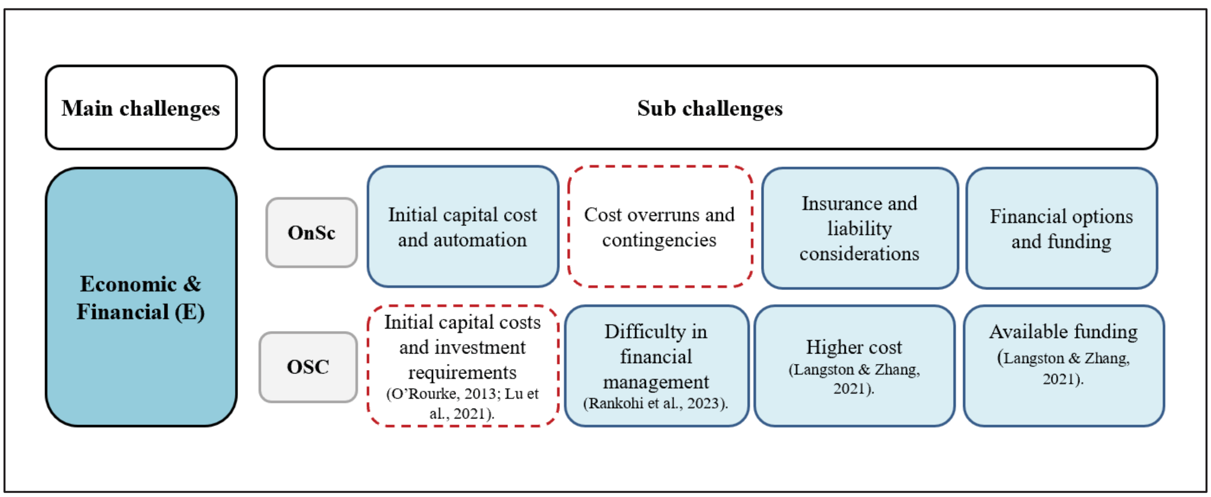

Figure A II.4 Comparative analysis of economic and financial challenges in implementing DfMA in OnSC and OSC (Sub-challenges in blue are specific to each construction method, and red dashes marking differences between OnSC and OSC)

Technological

In terms of technological challenges for DfMA adoption, as stated in the research of (Gao et al., 2018) and as mentioned by (Int-5), both OSC and OnSC face the challenge of identifying appropriate DfMA tools and techniques. This highlights the importance of selecting the right technology and methodologies to enhance construction processes. According to (Rankohi et al., 2023) OSC-specific challenges include managing the module configuration process, and coordinating between phases and contractors. These challenges arise due to the off-site nature of construction in OSC, where modules are manufactured separately and assembled on-site, while according to the expert overviews (Int-9), what is important from the technological perspective in OnSC is that this construction method specifically faces the challenge of the cost of technology adoption. This is because implementing advanced technology directly on the site location can be expensive and challenging. Both contexts encounter interoperability and digital integration challenges. Ensuring that various digital tools and systems work seamlessly together is essential in modern construction practices. Figure A II.5 provides a visual representation of the comparative analysis outlined in this section.

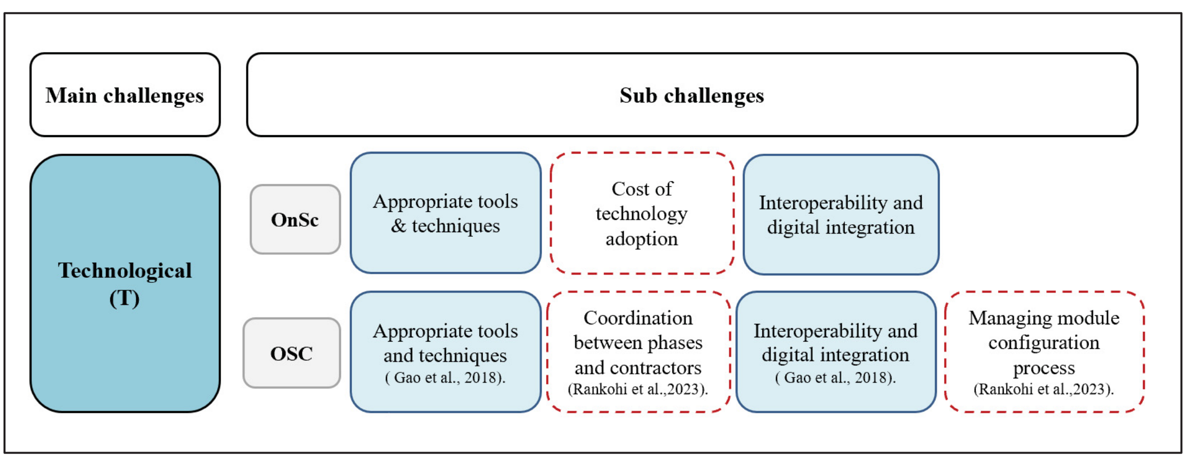

Figure A II.5 Comparative analysis of technological challenges in implementing DfMA in OnSC and OSC (Sub-challenges in blue are specific to each construction method, and red dashes marking differences between OnSC and OSC)

Legal contractual

There are several common challenges in the contractual category between implementation of DfMA in OSC and OnSC, such as accurate cost estimation, clarity in terms of guarantees and insurance, contract agility, and supply chain integration. However, as indicated by (Langston & Zhang, 2021; Lu et al., 2021) OSC-specific legal contractual challenges primarily are related to the integration of prefabrication and industrialized construction methods, and different stakeholders' collabouration. While, the insights from industry expert interviews suggest that OnSC may place more emphasis on performance metrics and dispute resolution within the construction site context (Int-3). It is also important to mention the emphasis on supply chain integration, which underscores its significance in ensuring that the coordination and flow of resources align with the specific needs and challenges of both OSC and OnSC (Gao et al., 2018). This is especially true for the mentioned specific OnSC projects, which typically involve numerous variables, such as varying weather conditions, site-specific challenges, coordination of multiple trades, and unforeseen issues that may arise during construction. These complexities make supply chain integration more challenging compared to the controlled environments found in OSC facilities (Int-2). Figure A II.6 depicts a comparative analysis of the main and sub challenges associated with implementing DfMA across the two construction methods.

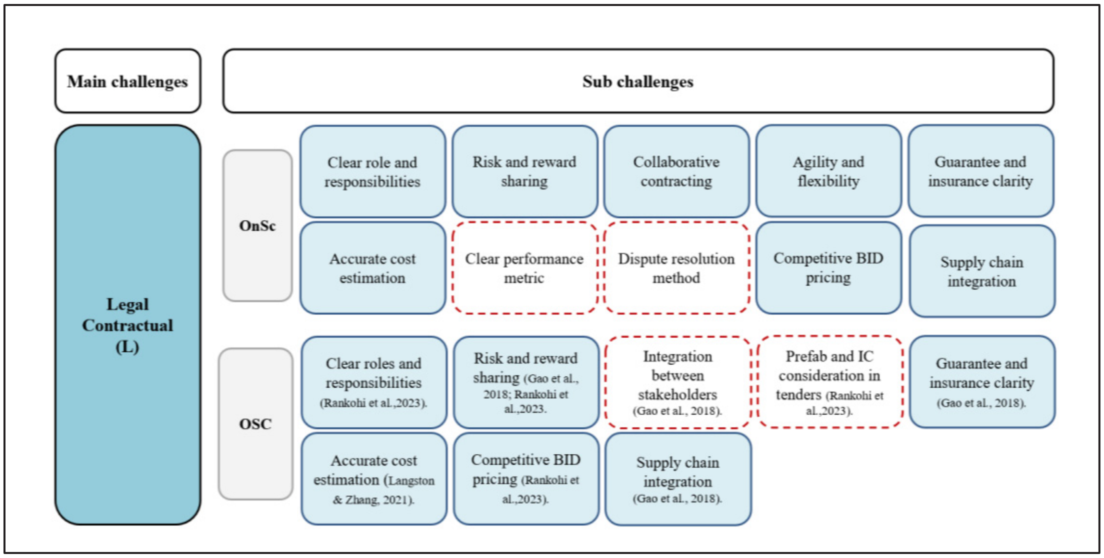

Figure A II.6 Comparative analysis of legal contractual challenges in implementing DfMA in OnSC and OSC (Sub-challenges in blue are specific to each construction method, and red dashes marking differences between OnSC and OSC)

<u>Technical cognitive</u>

Although DfMA in both OSC and OnSC within the technical cognitive category exhibit common concerns such as the need for specialized expertise, the complexity of design, and stakeholder awareness, industry expert interviews and a review of various literatures reveal distinct challenges in each approach. OSC heavily relies on the standardization of details, as pointed out by Jin et al. (2018), emphasizing uniformity and predictability. In contrast, OnSC DfMA demands a higher degree of flexibility, necessitating adaptability to unique site-specific challenges, as noted in interview Int-8. Both Jin et al. (2018) and the insights from Int-8 converge on the conclusion that technical proficiency and increased awareness among stakeholders are essential for both OSC and OnSC, despite their differing approaches and specific challenges. Figure A II.7 provides a visual comparison of the technical cognitive challenges encountered in implementing DfMA in both OSC and OnSC, delineating the specific sub-challenges unique to each construction approach.

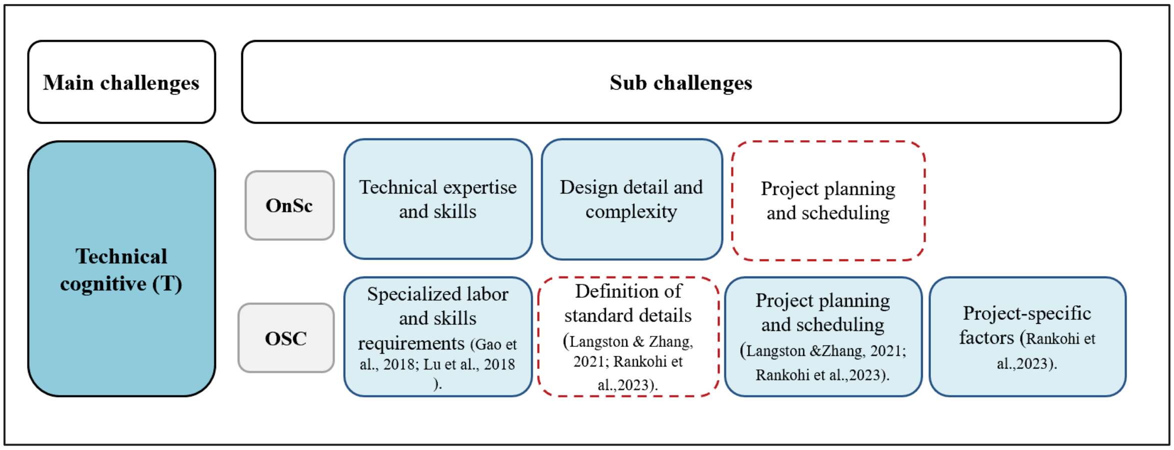

Figure A II.7 Comparative analysis of technical cognitive challenges in implementing DfMA in OnSC and OSC (Sub-challenges in blue are specific to each construction method, and red dashes marking differences between OnSC and OSC)

Procedural

According to the interview analysis and reviewing the literature both OSC and OnSc share some common procedural challenges related to DfMA implementation, such as additional project planning and interdisciplinary communication and collaboration, and they differ in their specific areas of emphasis. For example, in OSC the additional project planning is required to ensure smooth transportation and assembly of prefabricated components (Jin *et al.*, 2018b; Rankohi *et al.*, 2023). OnSC also necessitates additional project planning, but its primary focus may revolve around scheduling and coordinating various on-site activities (Int-8).

Furthermore, in terms of communication and collaboration, OSC places a high premium on effective coordination between design, manufacturing, and construction teams to guarantee the seamless fit of prefabricated components on-site (Gao, Low et Nair, 2018). On the other hand, OnSC may involve a broader spectrum of on-site trades and subcontractors, making interdisciplinary communication and collaboration more critical (Int-7). In terms of quality control, it is essential for OSC to ensure that factory-produced components meet the required standards before transportation to the construction site (Alazzaz et Whyte, 2014), as stated by Int-8 the quality control for OnSC would be more rigorous and the focus may shift towards the quality of installation and workmanship. Figure A II.8 presents a comparative analysis, illustrating the divergent aspects between OSC and OnSC.

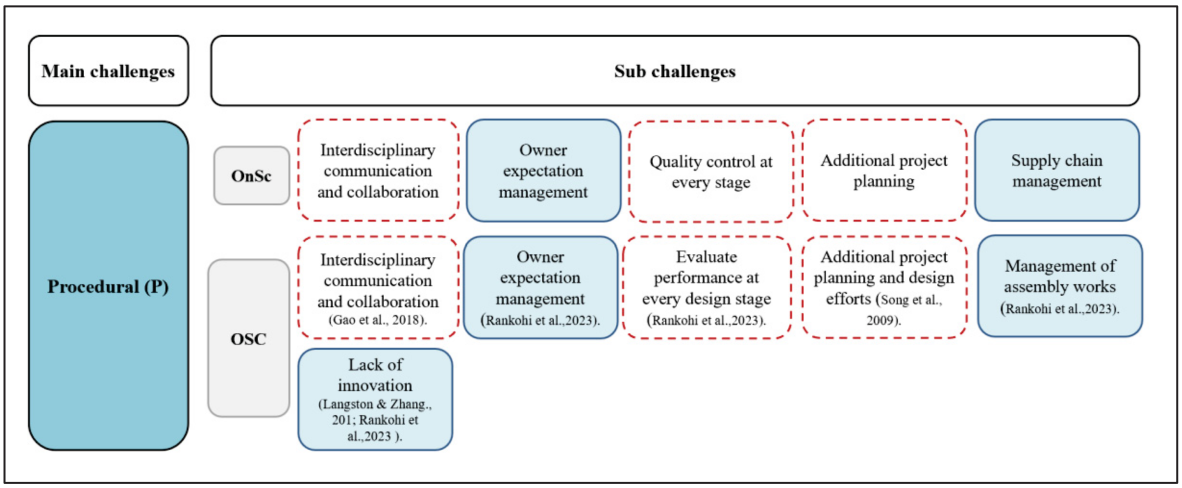

Figure A II.8 Comparative analysis of procedural challenges in implementing DfMA in OnSC and OSC (Sub-challenges in blue are specific to each construction method, and red dashes marking differences between OnSC and OSC)

Cultural

Both OSC and OnSC face cultural challenges in DfMA adoption, but the nature and emphasis of these challenges differ due to the distinct characteristics of each construction approach. Clients may be more familiar with OnSC practices and may need more education on the benefits of DfMA, while OSC may face skepticism or resistance from clients familiar to OnSC in its own nature.

OSC's challenges often center around aligning stakeholders communication, supply chain collaboration (Abd Razak et al., 2022), and transforming perceptions of industrialized construction (Rankohi *et al.*, 2023). OnSC's challenges are more focused on internal cultural shifts, adapting to new practices, and addressing resistance within existing teams (Int-10). Figure A II.9 displays the comparative analysis, highlighting the distinct areas of OSC and OnSC.

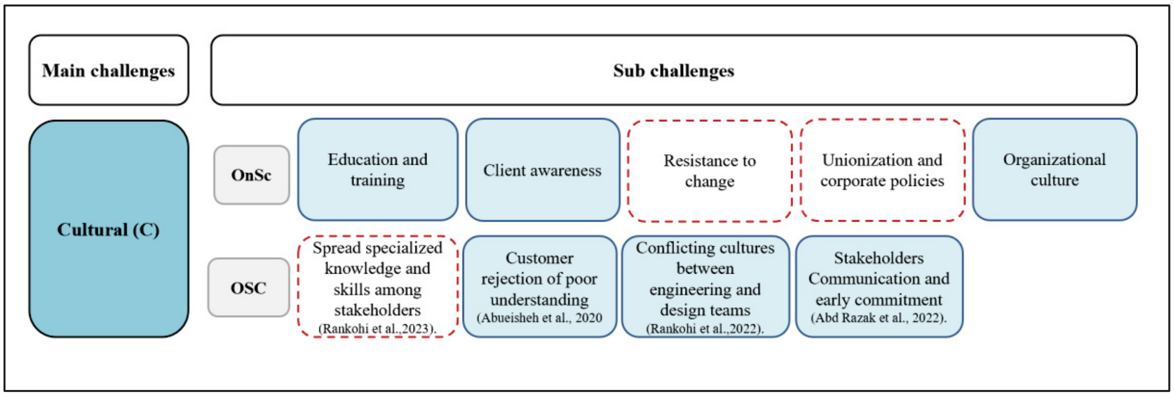

Figure A II.9 Comparative analysis of cultural challenges in implementing DfMA in OnSC and OSC (Sub-challenges in blue are specific to each construction method, and red dashes marking differences between OnSC and OSC)

Geographical

While both OSC and OnSC share some common challenges in DfMA implementation, the differences primarily stem from the distinct nature of each approach. OSC encounters challenges associated with centralized manufacturing in a controlled factory environment, the transportation of various components (Gao, Low et Nair, 2018; Rankohi *et al.*, 2023), and the need to ensure code compliance across regions (Rankohi *et al.*, 2023). Conversely, OnSC deals with site-specific factors (Int-4), local workforce (Int-2) and regulatory considerations (Int-4; Int-8), and the necessity to adapt to existing infrastructure (Int-1). It is important to note that OnSC also requires navigating local regulations and permitting (Int-4), which can exhibit significant variations across different geographic locations.

The Figure A II.10 underscores that while some challenges are shared—such as material availability and the necessity to navigate local regulations—there are distinct differences.

OSC's challenges are largely logistic and regulatory due to the nature of prefabrication and transportation, while OnSC's challenges are more focused on the immediate physical and regulatory environment of the construction site.

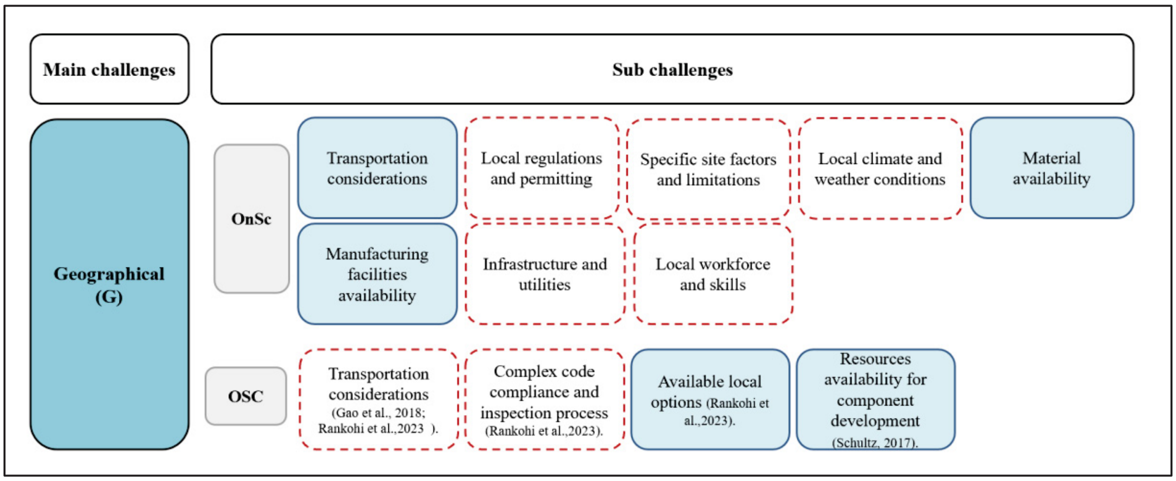

Figure A II.10 Comparative analysis of geographical challenges in implementing DfMA in OnSC and OSC (Sub-challenges in blue are specific to each construction method, and red dashes marking differences between OnSC and OSC)

Policy

Both OSC and OnSC face DfMA policy-related challenges, but the details differ. OSC's challenges revolve around the complexities of prefabrication, transportation, and assembly (Gao, Low et Nair, 2018 ; Langston et Zhang, 2021), while on-site DfMA's challenges are more about integrating DfMA techniques into construction environments in a manner compliant with existing on-site regulations (Int-4). For instance, Gao et al. (2018) provide insights from the OSC perspective, while Interviewee 8 (Int-8) offers a viewpoint from OnSC, indicating that in the realm of DfMA, there is an expectation for government involvement that extends beyond mere policy support. Both sources underscore the necessity for proactive government incentives aimed at facilitating growth within the sector. This highlights a shared understanding across both OSC and OnSC that government engagement should not be limited to policy formulation but should also include tangible incentives to catalyze the advancement of DfMA practices.

While OSC is looking for legislation support that accommodates the unique needs of factory-made components and their transport (Gao, Low et Nair, 2018), the on-site DfMA focuses on the facilitation of designs and methods specific to the technique and coordinating the actual site issues (Int-3). Both, however, need governmental incentives. Figure AII.11 provides a clear visual comparison of DfMA in OSC and OnSC, focusing on the specific sub-challenges that differentiate these two construction methods. This illustration simplifies the understanding of how DfMA challenges vary between OSC and OnSC, making it easier to grasp the unique aspects of each approach.

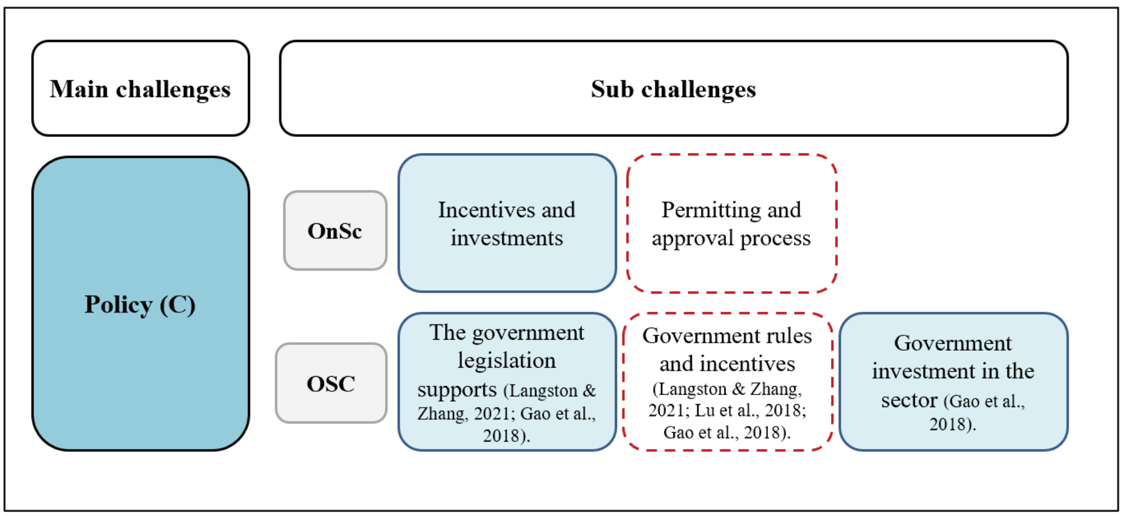

Figure A II.11 Comparative analysis of policy challenges in implementing DfMA in OnSC and OSC (Sub-challenges in blue are specific to each construction method, and red dashes marking differences between OnSC and OSC)

<u>Commercial</u>

Drawing from the scholarly discussion on DfMA implementation in OSC (Hall, Algiers et Levitt, 2018 ; Lu *et al.*, 2018 ; Rankohi, Bourgault et Iordanova, 2022), as well as the outcomes of our interview analysis, it is evident that both OSC and OnSC encounter parallel challenges in the commercial sphere when applying DfMA methodologies. These challenges predominantly center around the dynamics of available market options, the intensity of competition, and the degree of market acceptance. It can be concluded that this convergence in commercial obstacles highlights a shared area of focus and concern in the broader context of DfMA application across different construction modalities.

Regardless of whether the focus is on OSC solutions or OnSC methods. This alignment is primarily driven by the introduction of DfMA as a new and innovative methodology in both sectors, leading to a shared need to educate the market and address any resistance or uncertainty surrounding this modern approach to construction (Int-7). Figure AII.12 presents a detailed comparative analysis, underscoring the earlier discussion that the sub-challenges within the commercial category of OSC and OnSC exhibit minimal differences. This illustration serves to visually encapsulate the nuanced similarities in commercial challenges faced by both OSC and OnSC in the realm of DfMA, providing a clearer understanding of the shared obstacles in these construction approaches

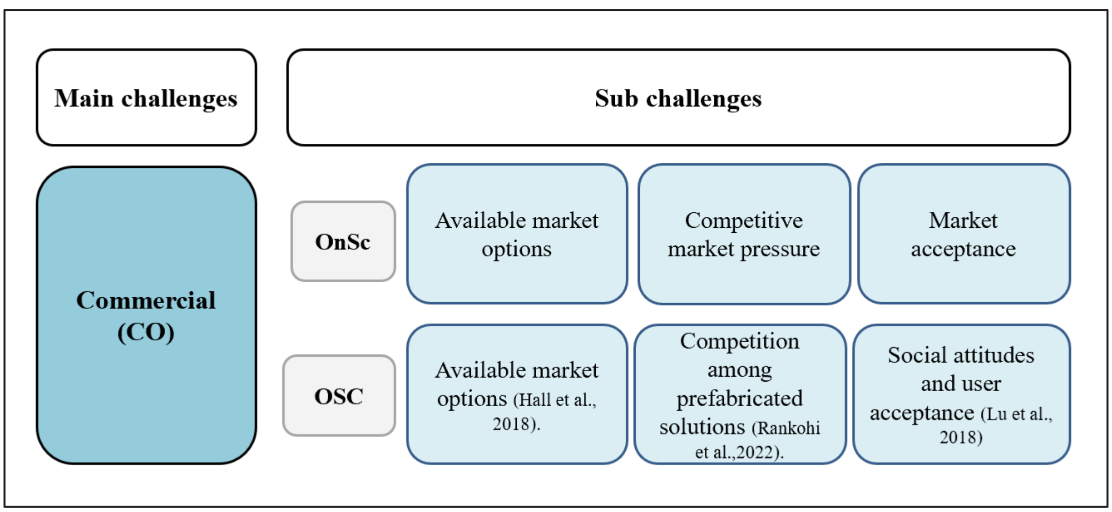

Figure A II.12 Comparative analysis of commercial challenges in implementing DfMA in OnSC and OSC (Sub-challenges in blue are specific to each construction method, and red dashes marking differences between OnSC and OSC)

The comparative analysis between DfMA challenges in OnSC and OSC underscores the inherent complexities and multifaceted nature of implementing DfMA techniques. When focusing on the on-site component of construction, it becomes evident that DfMA's scope expands beyond OSC, taking on broader meanings and contexts. This expansion necessitates a deeper consideration of specific site conditions, such as accessibility, existing infrastructure, and environmental factors. These factors influence construction outcomes. Moreover, this extended focus on the on-site aspects of DfMA implies that while the principles and guidelines established for OSC offer a foundation, they are insufficient by themselves. To ensure the holistic and effective application of DfMA in OnSC scenarios, the formulation of revised guidelines applicable to its broader context becomes critical. Embracing this detailed approach ensures DfMA's potential is maximized across the entire construction lifecycle. This allows for more streamlined, efficient, and adaptable construction practices in the future.

II.7 Conclusion

In conclusion, this paper focuses on DfMA within the construction industry, shedding light on its potential to enhance productivity and efficiency. While DfMA has often been associated with OSC, this study challenges the misconception that it focuses exclusively on OSC projects. Instead, it highlights the applicability of DfMA principles across a wide spectrum of construction projects, including on-site components and activities.

Through an in-depth mixed-methods research approach, combining a comprehensive literature review with interviews with industry experts, this study has identified, verified, and analyzed 42 DfMA challenges, categorizing them into nine main challenge categories. Furthermore, this research has extended beyond the prevailing focus on OSC and delved into the challenges specific to OnSC, contributing to a deeper understanding of the obstacles faced in the field.

The findings of this study have identified economic and financial challenges as the most critical barriers to DfMA implementation in OnSC, emphasizing the importance of budget accuracy, cost overruns, and funding availability. Technological challenges, including tool selection, technology adoption costs, and interoperability, have emerged as the second most significant hurdles. Furthermore, legal contractual challenges, encompassing role clarity, risk and reward sharing, and collaborative contracting, emphasizing the importance of clear contractual frameworks and early stakeholder engagement. As DfMA's relevance stretches beyond just OSC, the study underscores the need for a deeper understanding of on-site-specific factors like accessibility, infrastructure, and environmental considerations. While The existing DfMA-OSC guidelines provide a foundation, they alone do not suffice for the broader OnSC scenarios. This research aims to serve as a roadmap for the construction industry, guiding towards improved productivity and sustainability while laying groundwork for future studies. The conceptual framework developed in this study serves as a valuable guide for researchers, practitioners, and policymakers in understanding and addressing the challenges associated with DfMA adoption in OnSC. By recognizing and mitigating these challenges, the construction industry can move closer to achieving enhanced productivity, sustainability, and competitiveness in the built environment.

In summary, this research contributes to the construction management field by providing insights into the DfMA challenges specific to OnSC and lays the foundation for future studies and strategies aimed at overcoming these obstacles. Ultimately, it is hoped that the knowledge generated through this study will facilitate the widespread adoption of DfMA principles, leading to a more efficient and productive construction industry.

ANNEX III

TABLE OF KEY DECISION SUPPORT FACTOR'S DEFINITION AND KPI

Table A III.1 Key Decision Support Factor's Definition and KPI

Main Factor	Sub Factor	Description	Data Needed		Format/ Measuring Unit	KPI 1 : Least score to OCS - 5: Most score to OSC	Reference
Project characteristics (D1)	F1: Location	Proximity of the offsite construction facility to the project site is crucial for minimizing transportation costs and ensuring timely deliveries. However, limitation in accessibility is important to select offsite construction.	Distance from the offsite facility to the project site.	Geographic information system (GIS), project management tools.	Kilometers.	Distance from the offsite facility or available manufacturer. • 1: More than 200 km. • 3: 125-150 km.	(Salama, 2018)
	F2: Project Design	Size: Offsite construction is advantageous for projects with substantial building size, as it allows for efficient manufacturing of large components and faster assembly on-site.	Project size in terms of square meter	Project BIM, plans, specifications, or architectural drawings	Square meters.	Total building area. • 1: Below 5,000 sq m. • 3: 5,000 - 20,000 sq m. • 5: Above 20,000 sq m.	Canada Green Building Council (CaGBC) project size categorization. – Decarbonizing
		Design complexity: Simplified and standardized designs are more suitable for industrial building systems, reducing potential challenges during construction.	Evaluation of design complexity based on architectural and engineering documentation.	Design plans and complexity analysis.	Scale of complexity (e.g., low, medium, high)	Number of design elements. • 1: Highly complex, with intricate details. • 3: Moderate complexity. • 5: Simplified and standardized.	Expert
		Design flexibility: Projects that can accommodate modular or prefabricated components while maintaining design flexibility can benefit from the efficiency and customization options of offsite construction.	Assessment of how well the design accommodates OSC components.	Design plans and flexibility analysis.	Scale of flexibility (e.g., low, medium, high).	Percentage of modular design elements. • 1: Less than 20% OSC. • 3: 20-50% OSC. • 5: More than 50%	Expert

Table A III.1 Key Decision Support Factor's Definition and KPI (continued)

Main Factor	Sub Factor	Description	Data Needed		Format/ Measuring Unit	KPI 1 : Least score to OCS - 5: Most score to OSC	Reference
Supply chain (D2)	F3: Financing	Adequate funding and a clear financial plan are essential for supporting the procurement of offsite construction components and the industrial building system.	Financial plan and available funding.	Project budget and financial documents.	Currency	Budget adequacy. • 1: Funding covers less than 75% of the project. • 3: Funding covers 75-90% of the project.	CMHC Construction Financing
	F4: Available manufacturer	The presence of reliable and experienced manufacturers specializing in industrial building systems is critical for ensuring quality and timely production.	List of potential manufacturers and their capabilities.	Industry databases, manufacturer profiles.	List of manufacturers and their qualifications.	Number of years in business, knowledge of market and reputation • 1: Less than 5 years, minor knowledge and low reputation • 3: 5-10 years, good knowledge, acceptable reputation	Prequalification factor for selection of tenderer
	F5: Available Infrastructure	Equipment: Well-equipped manufacturing facilities with modern machinery and technology are necessary for efficient production of offsite components.	Information on the manufacturing facility's equipment.	Inventory	List of equipment and their capabilities.	Machinery age and capability. • 1: Mostly outdated machinery not capable of running VDC software. • 3: Most of hardware is capable of running basic VDC software.	Building Smart – BIM Competency Assessment (https://www.buildingsmart.org/bim-competency-assessment/)
		Software: Utilization of advanced software tools for design, planning, and project management can enhance the precision and coordination of offsite construction processes.	Information on software tools used.	IT department, software documentation.	List of software tools.	Software functionality. • 1: Basic design and planning system. • 3: Advanced design and planning system. • 5: Integrated,	Building Smart – BIM Competency Assessment (https://www.buildingsmart.org/bim-
	F6: Experts and skilled workers	A skilled workforce with expertise in offsite construction techniques is crucial to ensure proper assembly and installation, reducing errors and delays in the construction process.	Number and expertise of skilled workers.	HR records, qualifications of workers.	Number of workers, skill levels.	Workforce experience level.• 1: Expert identified but limited time commitment• 3: Expert with adequate time commitment• 5: Executive Level expert working closely with workers	Building Smart – BIM Competency Assessment (https://www.buildingsmart.org/bim-competency-assessment/)

Table A III.1 Key Decision Support Factor’s Definition and KPI (continued)

Main Factor	Sub Factor	Description	Data Needed		Format/ Measuring Unit	KPI 1 : Least score to OCS - 5: Most score to OSC	Reference
Time (D3)	F7: Design period	Efficient planning and design phases are crucial for offsite construction, as a shorter design period can accelerate project initiation and fabrication.	Duration of the design phase.	Project schedule, design plans.	Days or months.	Design phase duration.• 1: More than 6 months.• 3: 4-6 months.• 5: Less than 4 months.	Expert
	F8: Production time	Minimizing the time required for manufacturing offsite components is a key success factor, as it directly impacts the overall project schedule.	Time required for manufacturing components.	Production schedules, manufacturing plans.	Days or weeks.	Average component production time. • 1: More than 15% of project duration.	Expert
	F9: Mobilization and transfer time	Streamlining the logistics and transportation processes for offsite components reduces mobilization and transfer time, ensuring on-time delivery to the	Time for logistics and transportation.	Logistics plans, transportation schedules.	Days or hours.	Transportation time efficiency. • 1: More than 10% of project duration. • 3: 5%-10% hours.	Expert
	F10: Assembly and construction period	Offsite construction methods often allow for faster assembly and construction, making it essential to optimize this phase to achieve project completion within the desired timeframe.	Time required for on-site assembly and construction.	Construction schedules, assembly plans.	Days or weeks.	On-site construction speed. • 1: More than 6 months. • 3: 3-6 months. • 5: Less than 3 months.	Expert
Cost (D4)	F11: Design	Efficient and cost-effective design practices are critical to minimize design-related expenses when utilizing offsite construction methods. In addition, professional fees for designers specialized in offsite construction should be considered as well.	Design-related expenses.	Design contracts, cost estimates.	Currency	Design cost as a percentage of the overall budget. • 1: More than 15%. • 3: 7-15%. • 5: Less than 7%.	Royal Architectural Institute of Canada – A Guide Determining Appropriate Fees (2020)
	F12: Production and manufacturing	Reducing production and manufacturing costs through economies of scale and efficient processes is a key factor in cost-effective offsite construction.	Production and manufacturing costs.	Production cost analysis, manufacturing contracts.	Currency	Production cost per component. • 1: More than 15% of total cost • 3: 10%-15% of total cost	Expert - ECA benchmarks
	F13: Logistics	Effective logistics planning and optimization can help control transportation and handling costs associated with delivering offsite components to the	Transportation and handling costs.	Logistics contracts, transportation quotes.	Currency	Transportation cost per mile. • 1: More 5%of total cost • 3: 3-5% of total cost • 5: Less than	Expert - ECA benchmarks
	F14: Assembly and construction	Efficient assembly and construction techniques, often facilitated by offsite construction, can lead to cost savings in labour and site-related expenses.	Labour and site-related expenses.	Construction contracts, labour cost estimates.	Currency	Cost of assembly and installation including labour and equipment • 1: More than 35% of total cost • 3: 25%-35% of	Expert - ECA benchmarks

Table A III.1 Key Decision Support Factor's Definition and KPI (continued)

Main Factor	Sub Factor	Description	Data Needed		Format/ Measuring Unit	KPI 1 : Least score to OCS - 5: Most score to OSC	Reference
	F15: Maintenance	Consideration of long-term maintenance costs and the durability of offsite components is crucial for evaluating the overall cost-effectiveness of the project.	Long-term maintenance costs.	Maintenance contracts, durability assessments.	Currency	Annual maintenance cost as a percentage of the building present value • 1: More than 3%. • 3: 1.5-3%. • 5: Less than 1.5%.	Expenditures for the operation and maintenance of buildings (NRC Archive Publication)
Quality (D5)	F16: DfMA + disassembly	Incorporating Design for Manufacture and Assembly (DfMA) principles, as well as considering ease of disassembly, promotes higher quality by ensuring components are well-constructed and can be efficiently manufactured, assembled, and disassembled when needed.	Assessment of adherence to DfMA principles.	Design documentation, DfMA analysis reports.	Scale of adherence (e.g., low, medium, high).	DfMA adherence score. • 1: Less than 25% adherence. • 3: 25-60% adherence. • 5: More than 60% adherence.	Author's proposal
	F17: Standards and protocols	Adherence to industry standards and protocols for offsite construction and industrial building systems is fundamental to maintaining quality and consistency throughout the project. For example CSA A277 Certification of Prefabricated Buildings, Modules and Panels in Canada	Adherence to industry standards.	Quality control reports, industry guidelines.	Compliance status.	Compliance with industry standards.• 1: Completely new system and no certification obtained.• 3: Other recognized guidelines followed but no certification obtained.• 5: All components are already	Author's proposal
	F18: Sustainability (carbon emission, energy consumption, waste)	Incorporating sustainable practices in offsite construction, such as reducing carbon emissions, minimizing energy consumption, and managing waste responsibly, contributes to higher quality outcomes and aligns with environmental goals. Portfolio Manager ENERGY STAR: https://portfoliomanager.energystar.gov/pm/login?testEnv=false	Sustainability metrics (carbon emissions, energy consumption, waste).	Environmental impact assessments, sustainability reports.	Compliance status.	ENERGY STAR or LEED Certification • 1: No previous record of building with certification using this IBS • 3: No Certification but high chance of obtaining certification • 5: Strong record of building with certification using this IBS	Author's proposal
Procurement (D6)	F19: Type of procurement and delivery method	The choice of procurement method, such as design-bid-build, design-build, or integrated project delivery, can significantly impact project success. Selecting the most suitable method for the specific project requirements is crucial for efficient procurement.	Procurement method selected.	Procurement documents, contracts.	Type of procurement (e.g., design-bid-build, design-build).	Common procurement methods in Canada. • 1: Traditional procurement: Design-Bid-Build • 3: Interactive methods: Besign-Build, Construction Management or similar	Expert

Table A III.1 Key Decision Support Factor's Definition and KPI (continued)

Main Factor	Sub Factor	Description	Data Needed		Format/ Measuring Unit	KPI 1 : Least score to OCS - 5: Most score to OSC	Reference
Socio-cultural (D7)	F20: Cultural resistance	Recognizing and addressing cultural resistance to change within an organization or project team is crucial for fostering a positive socio-cultural environment that promotes the adoption of offsite construction practices.	Assessment of stakeholder awareness.	Surveys, stakeholder interviews.	Scale of awareness (e.g., low, medium, high).	Stakeholder awareness survey results. • 1: Not interested to adopt. • 3: Aware of benefit and they are in transition stage but not fully implementing • 5: Moving forward to full	Various literatures
	F21: Local authority regulation (workers' union syndicate)	Ensuring compliance with local authority regulations, including those related to workers' unions and syndicates, is vital for maintaining a harmonious relationship with the workforce and preventing disruptions that can impact the project's socio-cultural dynamics.	Compliance with local regulations.	Regulatory documentation, legal compliance reports	Compliance status.	Compliance with local regulations. • 1: Below 70% compliance. • 3: 70-90% compliance. • 5: Above 90% compliance.	Expert

ANNEX IV

EXAMPLE OF CODE FOR BeDSS SOFTWARE DEVELOPMENT

Code for Automatic Calculation of Gross Floor Area of BIM Model

```
# Load the Python Standard and DesignScript Libraries
import sys
import clr
clr.AddReference('ProtoGeometry')
clr.AddReference('System.Windows.Forms')
clr.AddReference('System.Drawing')
from Autodesk.DesignScript.Geometry import *
from System.Windows.Forms import Form, Label, Button, TextBox, ComboBox, TreeNode, TreeView,PictureBox,PictureBoxSizeMode
from System.Drawing import Point, Size,Image
# The inputs to this node will be stored as a list in the IN variables.
dataEnteringNode = IN
# Place your code below this line
clr.AddReference('RevitAPI')
clr.AddReference('RevitServices')
from Autodesk.Revit.DB import FilteredElementCollector, BuiltInCategory, FamilySymbol
from RevitServices.Persistence import DocumentManager
# Get the active document
doc = DocumentManager.Instance.CurrentDBDocument
# Define the Floor category
floor_category = BuiltInCategory.OST_Floors
# Retrieve all elements of the Floor category
floor_collector = FilteredElementCollector(doc).OfCategory(floor_category).WhereElementIsElementType()
# Get unique family types of the floors
familyList = [floor for floor in floor_collector]
familyName = [floor.LookupParameter("Type Name").AsString() for floor in floor_collector]
```

```
#familyList=IN[0]
#familyName=[str(x) for x in familyList]
familyDict=dict(zip(familyName,familyList))
class MyForm(Form):
    def __init__(self):
        # Initialize the form
        self.Text = "BeDss"
        self.ClientSize = Size(400, 550)
        # Create a label for the text input
        self.label = Label()
        self.label.Text = "Enter Zipcode 1:\n(Project site location, or point of assembly)"
        self.label.Location = Point(20, 20)
        self.label.AutoSize = True
        self.Controls.Add(self.label)
        # Create a textbox for the user input
        self.textbox = TextBox()
        self.textbox.Location = Point(20, 60)
        self.textbox.Size = Size(200, 20)
        self.Controls.Add(self.textbox)
                # Create a label for the text input
        self.label_2 = Label()
        self.label_2.Text = "Enter Zipcode 2:\n(Offsite facility, manufacturer or supplier)"
        self.label_2.Location = Point(20, 100)
        self.label_2.AutoSize = True
        self.Controls.Add(self.label_2)
        # Create a textbox for the user input 2
        self.textbox_2 = TextBox()
        self.textbox_2.Location = Point(20, 140)
        self.textbox_2.Size = Size(200, 20)
        self.Controls.Add(self.textbox_2)
        # Create a label for the dropdown
        #self.dropdown_label = Label()
        #self.dropdown_label.Text = "Select an option:"
```

```
#self.dropdown_label.Location = Point(20, 80)
#self.dropdown_label.AutoSize = True
#self.Controls.Add(self.dropdown_label)
# Create a dropdown (combobox) for the user input
#self.dropdown = ComboBox()
#self.dropdown.Location = Point(20, 110)
#self.dropdown.Size = Size(200, 20)
#self.dropdown.Items.AddRange(["Option 1", "Option 2", "Option 3"])  # Predefined options
#self.Controls.Add(self.dropdown)
# Create a label for the treeview
self.tree_label = Label()
self.tree_label.Text = "Select Main floors families: \n(This will be used to calculate Gross Floor
Area of the building)"
self.tree_label.Location = Point(20, 180)
self.tree_label.Size = Size(400,40)
self.Controls.Add(self.tree_label)
# Create a treeview for the user input
self.treeview = TreeView()
self.treeview.Location = Point(20, 220)
self.treeview.Size = Size(300, 200)
self.treeview.CheckBoxes = True  # Enable checkboxes for multiple selections
for family in familyName:
  self.treeview.Nodes.Add(family)  # Add a root node
self.Controls.Add(self.treeview)
# Create a button to submit the input
self.submit_button = Button()
self.submit_button.Text = "Submit"
self.submit_button.Location = Point(20, 480)
self.submit_button.Click += self.submit_button_click
self.Controls.Add(self.submit_button)
#Create Logo box
path=r"C:\dss\Logo.png
photo_path = path
```

```
        photo_image = Image.FromFile(photo_path)
        # Create a picture box to display the photo
        self.logo_box = PictureBox()
        self.logo_box.Location = Point(220,420)
        self.logo_box.Size=Size(120,120)
        self.logo_box.Image = photo_image
        self.logo_box.SizeMode = PictureBoxSizeMode.Zoom
        self.Controls.Add(self.logo_box)
    def submit_button_click(self, sender, args):
        # Event handler for submit button click
        global selected_items,zipCode
        selected_items=[]
        # Clear the list before adding new items
        selected_items.clear()
        # Get selected nodes from the treeview recursively
        self.get_selected_nodes(self.treeview.Nodes)
        zipCode = self.textbox.Text
        self.Close()
    def get_selected_nodes(self, nodes):
        # Recursively iterate through all nodes and their children
        for node in nodes:
            if node.Checked:
                selected_items.append(familyDict[node.Text])
            self.get_selected_nodes(node.Nodes)
# Create an instance of the form
form = MyForm()
form.ShowDialog()
# Assign your output to the OUT variable
```

ANNEX V

SOFTWARE DEVELOPMENT IN DYNAMO REVIT

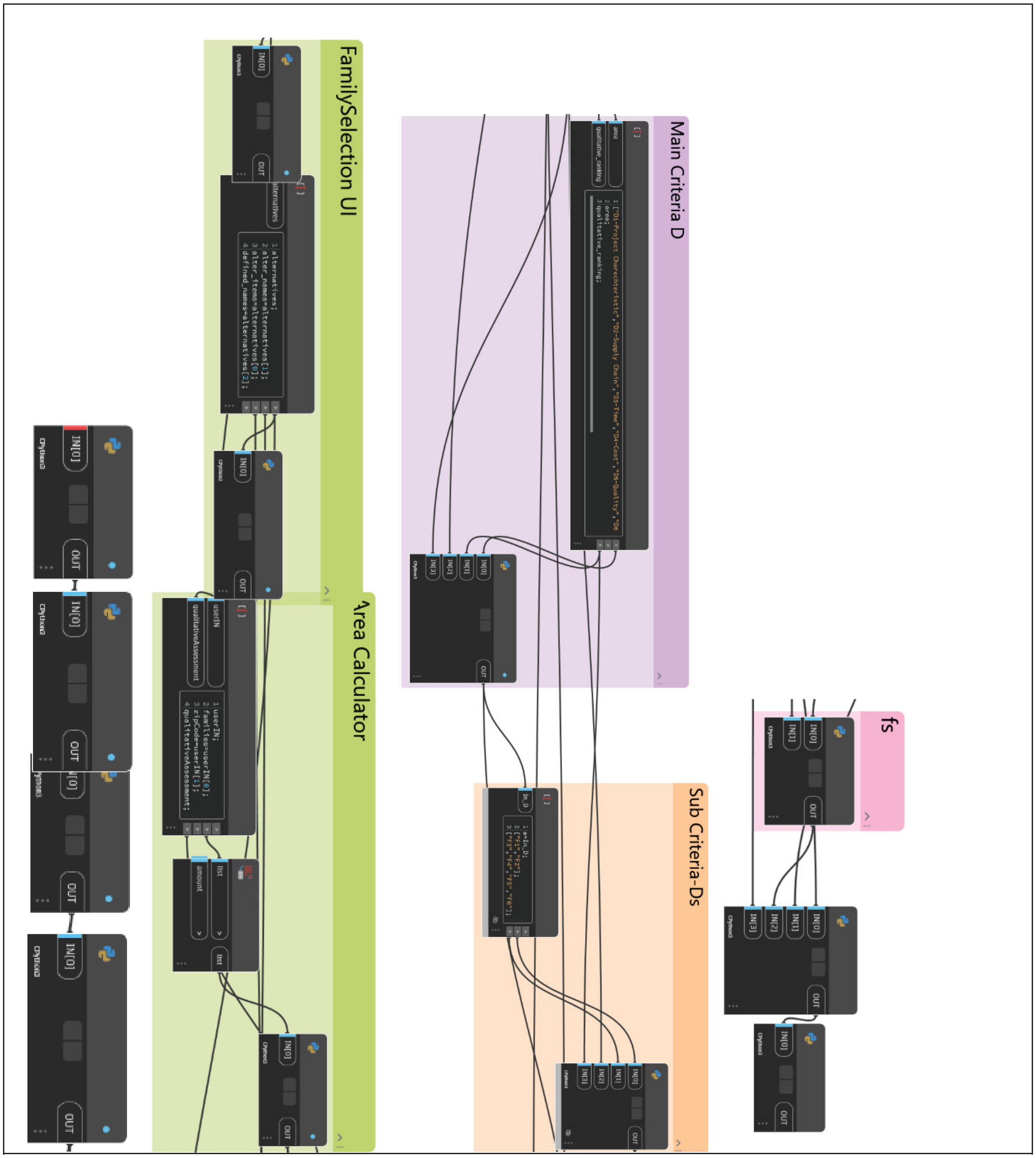

Figure A V.1 Dynamo Code for BeDSS in Revit

ANNEX VI

DECISION SUPPORT FACTOR VALIDATION AND EVALUATION

INTERVIEW AND QUESTIONAIRE

Invitation email:

Dear Sir/Madam

I am a PhD student at the ETS under the supervision of Dr. Ivanka Iordanova (ETS) and Dr. Mohamed Al-Hussein (University of Alberta). As a part of my research project I am conducting interviews to investigate and validate key decision-making factors in selection of an appropriate construction methodology i.e. conventional or offsite construction. During the interview we will discuss about different types of Industrial Building Systems (IBS) and factors which lead to choose a particular system for a given project.

As an expert with considerable experience in this domain, I would like to invite you, to participate in our interview (of 30-40 minutes). I would appreciate it if you could advise on your availabilities in the upcoming weeks by replying to this email so that I can schedule an interview at your convenience.

The interview will be conducted in English online, however kindly let us know if this poses a problem and we will make sure to proceed in French.

Your participation is valuable and much appreciated.

Interview questions:

Q1: How many years of experience do you have specially in offsite construction?

Q2: Can you please describe your organization in terms of the operational activities of the company i.e. client, consultant, contractor, manufacturer?

Q3: What is the status of offsite construction implementation in your organization and how long have you been using this method?

Q4: From your point of view, which dimension i.e. project characteristics, supply chain, time, cost, quality, procurement and socio-cultural plays an important role to select offsite construction methodology? If there is any other dimension rather than those mentioned please describe.

Q5: Literature claims "Industrialized Building System (IBS) is an effective solution that is based on Off-site Construction (OSC) to overcome poor productivity in the construction industry. However, many construction players including designers and developers are facing problems selecting suitable IBS for application in construction development projects". To what extend the statement is valid and what are the factors influence the successful selection of proper IBS system?

Q6: The following table of relevant factors shows identified main dimension discussed earlier and factors in selection of offsite construction and choose a particular system for a given project. It is highly appreciated if you could rate relevancy of each factor in scale of 1 to 5 (1 Not relevant, 2 Not very relevant 3 Neutral 4 Relevant 5 Very Relevant).

Table A VI.1 Key Decision Support Factors

Dimension			Factor	Factor
1	Project characteristics	F1	Size	Number of stories,Project GFA
		F2	Material	Framing, Exterior,Interior, ID and Furniture
		F3	Location	Site accessibility, Availability of manufacturing plants/facilities within economical transport distance, Onsite connections
		F4	Design complexity	Presence of repetitive layout in design
		F5	Design flexibility	Open design concept, adaptability, customisation
2	Supply chain	F6	Financing	Available Credit, capital and financing arrangement with client
		F7	Manufacturer	Availability of manufacturing plants/facilities within economical transport distance
		F8	Raw material	Available Material for production and manufactruing locally
		F9	Equipment	Transportation equipment availability and capability, Construction equipment availability and capability, Module Fabricator Capability,
		F10	Software	Use of digital, automation, information, communication and collabouration technology e.g., BIM, Automated production lines
		F11	Experts and skilled worker	On-site labour availability, skilled workforce and experienced team onsite and in factory environment, team management and collabouration
3	Time	F12	Design period	Overall project timescale, Certainty of project completion date, Timely Design Freeze, Preliminary Module Definition, Owner Delay Avoidance, tender duration
		F13	Production time	Limit of production time
		F14	Mobilization & transfer time	logistics optimization, Transport Delay Avoidance
		F15	Assembly & construction period	Need for expediting the schedule, Reduce time on site, Early Completion Recognition
4	Cost	F16	Design	Cost of design and produce drawings and models
		F17	Material	Cost of Material
		F18	Production & Manufacturing	Purchase or rent of production and manufacturing machines, labour and expert cost in factory environment
		F19	Logistic	logistics optimization, crane cost
		F20	Assembly & construction	Labour and expert cost on site
		F21	Management	Inspection , Quality Control and Management cost

Table A VI.1 Key Decision Support Factors (continued)

Dimension			Factor	Factor
4	Cost	F22	Maintenance	Maintenance and operation provisions
5	Quality	F23	DfMA + Disassembly	Design for Manufacture and Assembly + Disassembly
		F24	Defect liability period	Reduction in defects of product/facility
		F25	Standards and protocols	High standard quality of both internal and external finishes of a building. Local frameworks and policies. Industry standards and quality assurance. Quality management system
		F26	Sustainability(Carbon emission,Waste)	Reducing environmental impact through the reduction of site activities, Reducing neighborhood disruption and noise, Reducing traffic movement, reduce waste.
		F27	Construction safety	Improved construction safety. Reduced manual handling and work at height
6	Procurement	F28	Type of procurement & delivery method	Contractual basis. Collabourative contracts with reduced adversity
		F29	Number of tenderers	Efficient contractors pre-qualification, Continuity through Project Phases
7	Socio-Cultural	F30	Lack of awareness among all stakeholders	Organization's familiarity with Prefab, Early involvement of top management
		F31	Cultural resistance	Whole life-cycle approach, Contractor Leadership
		F32	Local Authority regulation	Workers union - Syndicat

ANNEX VII

BEDSS SOFTWARE EVALUATION - QUESTIONNAIRE

BIM-enabled Decision Support System Plugin for Revit Evaluation Questionnaire

This questionnaire is an integral component of the expert evaluation process for the artifact developed as part of a PhD thesis entitled " TWO STAGE BIM-ENABLED DECISION SUPPORT SYSTEM FOR THE SELECTION OF A SUITABLE INDUSTIALIZED BUILDING SYSTEM IN OFF-SITE CONSTRUCTION." The feedback collected through this questionnaire will directly contribute to assessing the practicality, efficiency, and user satisfaction of the development. The insights gained from this evaluation will be instrumental in the iterative development process, guiding enhancements and demonstrating the artifact's contribution to the domain of Off-site Construction.

Please answer the following questions to help us understand your experience with the BIM-enabled decision support system (BeDSS) plugin for Revit. Your feedback is invaluable in improving the functionality and user experience of our development.

Section 1: General Information

1.1 User information (Optional):

- Name:
- Email:
- Position:
- Profession:

1.2 What is your level of experience in AEC industry?

- Less than 1 year
- Between 1 year and 3 years
- Between 3 years and 10 years
- More than 10 years

1.3 What is your level of expertise with Revit?

- Beginner
- Intermediate
- Advanced
- Expert

1.4 What is the primary sector of activity for your company?

- Contractor
- Manufacturer
- R&D
- Educational
- Association
- Other

Section 2: Usability

2.1 How would you rate the ease of installation for the plugin?

- Very easy
- Somewhat easy
- Neutral
- Somewhat difficult
- Very difficult

2.2 How intuitive is the user interface of the plugin?

- Very intuitive
- Somewhat intuitive
- Neutral
- Somewhat unintuitive
- Very unintuitive

2.3 Did you encounter any issues while integrating the plugin with Revit?

- No issues
- Minor issues, easily resolved
- Moderate issues, required some effort to resolve
- Major issues, difficult to resolve
- Not able to setup

2.4 How would you rate the overall user experience of the plugin?

- Excellent
- Good
- Fair
- Poor
- Very poor

Section 3: Functionality

3.1 How effectively does the plugin extract data from BIM within the Revit file parameters?

- Very effectively
- Effectively
- Neutral
- Ineffectively
- Very ineffectively

3.2 How well does the plugin assist you in the first phase of selecting between offsite construction and conventional methods?

- Very well
- Well
- Neutral
- Poorly
- Very poorly

3.3 How satisfied are you with the pairwise comparison feature for selecting the appropriate Industrial Building System?

- Very satisfied
- Satisfied
- Neutral
- Dissatisfied
- Very dissatisfied

Section 4: Decision-Making Process

4.1 How clear is the explanation of the decision-making factors used in the comparisons?

- Very clear
- Clear
- Neutral
- Unclear
- Very unclear

4.2 How confident do you feel in the results provided by the ranking system?

- Very confident
- Confident
- Neutral
- Unconfident
- Very unconfident

4.3 How would you rate the relevance of the decision-making factors included in the software?

- Very relevant
- Relevant
- Neutral
- Not very relevant
- Not relevant at all

4.4 Did the software help you make a more informed decision between the two alternatives?

- Definitely
- To some extent
- Neutral
- Not really
- Not at all

Section 5: Overall Satisfaction

5.1 How likely are you to recommend this plugin to a colleague?

- Very likely
- Likely
- Neutral
- Unlikely
- Very unlikely

5.2 What features do you like the most about the plugin?

Please provide your comments here:

5.3 What improvements would you suggest for the plugin?

Please provide your comments here:

5.4 Overall, how satisfied are you with the decision support system plugin for Revit?

- Very satisfied
- Satisfied
- Neutral
- Dissatisfied
- Very dissatisfied

Thank you for completing this questionnaire!

ANNEX VIII

OFFSITE CONSTRUCTION RESILIENCE: A STRATEGIC RESPONSE TO INFLATION CHALLENGES IN CONSTRUCTION IN POST-PANDEMIC CANADA

A. Mehdipoor[1], I. Iordanova[1], M. Al-Hussein[2]

[1]Department of Construction Engineering, École de Technologie Supérieure,
1100 Notre-Dame Ouest, Montréal, Québec, Canada H3C 1K3
[2] Department of Civil and Environmental Engineering, University of Alberta, Edmonton,
Canada T6G 2R3

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VIII.1 Abstract

The COVID-19 pandemic triggered a period of inflation in Canada that has proven to be far from "transitory", with the Consumer Price Index (CPI) increasing by an average of 3.4% in 2021, followed by 6.8 % in 2022, and 3.9% in 2023, and this trend of high inflation expected to continue for the foreseeable future. This rising inflation presents significant challenges for various sectors, particularly the construction industry, which accounts for over 1.5 million jobs and more than 7% of the country's economic activity. Two years after the pandemic, the inflationary environment was characterised by high, persistent, and volatile rates and influenced by factors beyond the industry's control, such as supply constraints. To address these issues, a collabourative approach among all stakeholders involved in construction projects is necessary. One effective approach is to identify high-risk inflationary materials, such as steel, copper, aluminum, and wood, and create a price index based on historical market prices. Such a strategy allows project teams to track fluctuations in material prices and adjust project cost estimate, while also implementing risk mitigation strategies accordingly. Embracing innovative strategies digitalized Off-site Construction and Industrial Building System (IBS) can enhance the construction industry's resilience in the face of persistent inflation, delivering value-driven outcomes for clients and stakeholders. This paper examines the impact of inflation on construction project budgets and project costs in Canada. Correlation coefficient tests are utilised to analyse the relationship between inflation rates and building construction prices during the period, 2018 to 2023. The results indicate a 14% increase in the contract sum attributable to inflation, a factor that may result in cost overruns. The findings point to the benefits of adopting offsite construction techniques as a strategic solution aimed at specifically countering the detrimental effects of cost overruns resulting from material waste and project delays, factors that not only escalate project costs but also significantly amplify the adverse impact of inflation on the project budget.

Keywords: inflation, offsite construction, construction cost

VIII.2 Introduction

For the purpose of the present work, "inflation" is defined as an increase in price sustained over the course of one or more price index reporting quarters (Alaloul et al., 2021; Jordà & Nechio, 2023; Musarat et al., 2021). To assess and monitor the economic impact of inflation, factors such as interest rates, potential output, exchange rates, money supply, wage rates, and trade openness must be considered (Musarat et al., 2021).

Inflation is a critical factor affecting cost overruns in construction projects, and it can cause significant issues for project owners (Musarat et al., 2020). During the period following the Global Financial Crisis of 2007–2008 but prior to the COVID-19 pandemic, inflation was generally low worldwide. However, with the onset of the COVID-19 pandemic, governments worldwide implemented health measures to control the spread of the virus, resulting in a sudden slowdown in economic activity. To offset this, governments introduced various economic support measures, ranging from direct cash transfers (in the United States and Canada) to job preservation programs (in Germany). As economies reopened after the pandemic, some countries experienced a surge in inflation (Jordà & Nechio, 2023).

According to its 2023 annual review, the Consumer Price Index (CPI) in Canada increased by 3.9% in 2023, having increased by 6.8% in 2022 and by 3.4% in 2021. The years 2022 (5.7%) and 2023 (4.5%) saw the largest year-over-year increases in since 1991(Statistics Canada, 2024).

Meanwhile, Canada's construction industry has experienced particularly marked increases in both labour and material costs since the beginning of the COVID-19 pandemic in 2020. In the current scenario, inflation is not only high and persistent, but also highly volatile, with these conditions driven by various factors largely beyond the control of contractors (Chen & Tombe, 2023; Gower, 2022). Other contributing factors to high inflation include supply disruptions affecting international trade, and geopolitical events such as the conflict in Ukraine, which has caused spikes in oil and energy prices, in turn influencing building material prices (Jordà & Nechio, 2023).

Cost overruns pose significant challenges in construction, affecting project cost estimation, project timelines, and cash flow. These overruns can be attributed to fluctuations in the prices of project resources or changes in project orders (Alaloul et al., 2021; Musarat et al., 2020). Closely related to this, budget estimation plays a pivotal role in construction project performance, particularly in the initial phases, when decision-makers rely on the available cost data. Ensuring the feasibility of the project budget and monitoring the project cost during the construction phase are thus critical tasks.

One effective strategy to address these challenges is the adoption of offsite construction (OSC). OSC involves the prefabrication of building components in a factory setting before transporting them to the construction site for assembly (Smith & Quale, 2017). By centralizing production, OSC allows for better control over material usage and quality, thereby minimizing the risk of cost overruns due to material waste and project delays (Goulding & Rahimian, 2019).

Additionally, OSC addresses the critical issue of workforce shortages by reducing the dependency on on-site labour, which has become increasingly scarce and expensive (Alazzaz & Whyte, 2014; Assaad et al., 2023). The controlled factory environment in OSC enables the use of a more stable and skilled workforce, further enhancing the efficiency and reliability of construction projects (de Laubier et al., 2019). Moreover, OSC can substantially enhance workforce productivity by streamlining processes through prefabrication and assembly (Bertram et al., 2019). This method promotes a higher learning rate and safer working conditions, which can lead to an improved quality of work and increased safety.

The aim of the research presented in this paper was to address and mitigate the adverse effects of cost overruns in construction projects, particularly those stemming from material waste and project delays. Rather than drawing a comparison between on-site (traditional) and OSC, the aim of the present study is to identify the high-sensitivity divisions most affected by inflation and emphasize the benefits of using the OSC approach to manage these impacts effectively.

By streamlining the construction process and reducing the dependency on fluctuating on-site labour and material costs, OSC provides a more predictable and stable cost structure. This is particularly crucial in times of high and volatile inflation, where traditional construction methods may struggle to maintain budget control. According to Bertam et al. (2019), the efficiency gains from OSC not only help in keeping costs down but also enable faster project completion, which can be crucial in reducing exposure to inflationary pressures over extended project timelines.

Simultaneously, we explored ways to minimize the adverse impacts of inflation, many of which contribute to elevated project costs, and to safeguard project budgets against the detrimental effects of inflation. The objective underlying this work was to provide stakeholders with insights into inflation rates linked to elemental cost analysis, enabling strategic material procurement planning and facilitating the development of accurate project cash flow models by identifying the concentrated financial impacts across different aspects of the project.

VIII.3 Literature Review

Canada’s construction industry contributes over 1.5 million jobs and constitutes 7.5% of the nation's economic activity (Gower, 2022), yet the threats that inflation poses to Canada's construction industry warrant further examination. Numerous studies have underscored the role of inflation in causing project cost overruns (Musarat et al., 2021; Ribeirinho et al., 2020). Fluctuations attributed to inflation, such as variations in building material prices, labour wages, and machinery hire rates, lead to deviations between a project's initial and final budgets (Musarat et al., 2020). Due to the multifaceted impact of inflation on this crucial industry, timely and strategic interventions focused on alleviating its adverse effects are critical.

The New Housing Price Index (NHPI) is a monthly dataset designed to track variations over time in the selling prices of new residential houses constructed by builders. This index specifically considers houses with consistent specifications that remain unchanged between two consecutive periods (Statistics Canada, 2023b). In this regard, the literature underscores that increases in housing prices are influenced by inflation, especially prices for transportation, construction material, wages, and services (Alaloul et al., 2021; Anari & Kolari, 2002; Jordà & Nechio, 2023; Statistics Canada, 2023b, 2024).

Figure A VIII.1 depicts the NHPI (excluding land) in Canada for the period, 2020 to 2023. Notably, there is a substantial increase from 2020 until the middle of 2022, followed by a subtle decrease.

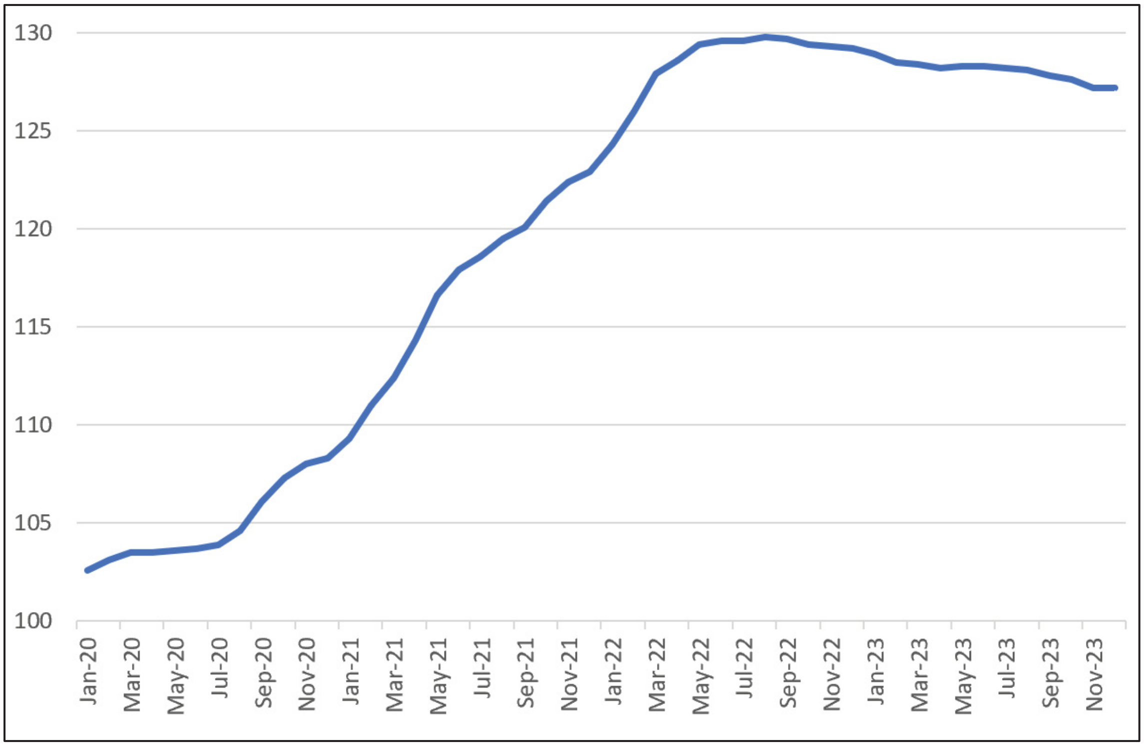

Figure A VIII.1 NHPI from 2020 to 2023 (Statistics Canada)

The critical resources affecting construction projects include finances, workforce, materials, and machinery. Thus, evaluating the impact of resource price changes on the budget is crucial in construction projects.

In the initial stages of a construction project, accurate cost estimation is crucial due to its significant financial implications, underscoring the criticality of giving early attention to this matter. Efficient budget estimation plays a vital role in this regard, as it has a significant effect on the financial outcome of the project (Alaloul et al., 2021).

According to the literature, most construction projects are subject to cost overruns (Ribeirinho et al., 2020). These cost overruns, in turn, affect project schedules, financial liquidity, and decision-making. These overruns can be attributed to variations in the costs of project resources or changes in project directives, both of which can affect decision-making and influence the success of a construction project (Strange et al., 2023). One significant aspect contributing to these overruns is productivity-related issues, which can lead to inefficiencies and additional costs (Changali et al., 2015). In this regard, OSC is a promising method for increasing productivity and addressing the problem of cost overruns (Jin et al., 2018).

The literature employs various terms to describe OSC, such as off-site manufacturing in construction, modern methods of construction (MMC), off-site production (OSP), and off-site prefabrication (Hammad et al., 2019; Rahman, 2014; Smith & Quale, 2017). Industrialization of the construction industry can be defined using the term “off-site”, which is a widely used term that refers to the preparation, design, fabrication, and assembly of building elements at a location separate from their final installation site (Kamar et al., 2011). The aim of OSC is to expedite and the improve efficiency of the construction process by shifting it to an industrial manufacturing environment (Hairstans, 2014).

A number of studies have advocated for the adoption of OSC techniques as a holistic solution to mitigating the risk of cost overruns resulting from increased price and project delays (de Laubier et al., 2019; Goulding & Rahimian, 2019; McKinsey Global Institute, 2017).

Recent studies set out to emphasis on the potential efficiency and costs savings benefits of adopting OSC, which helps to reduce project timelines, transportation requirements, and material waste (Bertram et al., 2019; Goulding & Rahimian, 2019). The primary focus has been on minimizing the adverse impacts of factors that frequently contribute to elevated project costs.

Moreover, by implementing OSC methods, construction projects aim to improve productivity, enhance cost predictability, reduce schedule delays, and maintain budgetary control. Therefore, OSC techniques not only addresses immediate challenges but also serves as a proactive measure, fortifying project budgets against the compounding impacts of inflation.

VIII.4 Methodology

The methodology followed in this research consisted of four phases. The first phase involved collecting historical data on the building construction price index and building material prices for Montréal, Canada. Also in this phase, the quarter-over-quarter percentage of deviation of the Building Construction Price Index (BCPI) was computed in order to identify trends in the BCPI during the period, 2021 to 2023.

In the second phase, Elemental Cost Analysis (ECA) was carried out on a case project, and data validation was then conducted. In the third phase, the effect on project cost of change orders triggered by inflation of building material cost was assessed. The last phase was a statistical analysis to examine the relationship between the inflation rate and the quarter-over-quarter deviations of building construction prices.

The data analysis results, which calculated the increased contract amount due to inflation, were intended for securing approval for the new contract amount from both the client and financial institutions. Consequently, a third-party consultant, the client's representative, and the project's financing agencies performed verification of the data analysis.
The flowchart underlying the research is provided in Figure A VIII.2.

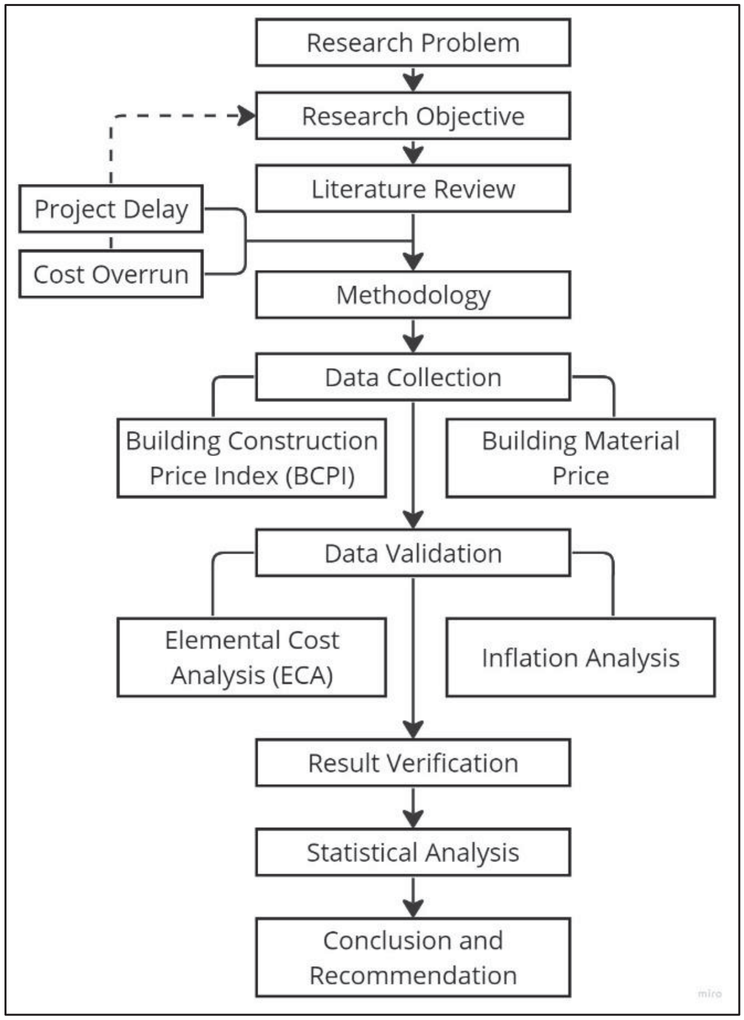

Figure A VIII.2 Research process flowchart

VIII.4.1 Data Collection

The BCPI data for Montréal, Canada, was obtained from Statistics Canada (Statistics Canada, 2023a). The building material price data, meanwhile, was collected from purchase orders, invoices by sub-trades, and internal data from the design-build company responsible for the case project. The price data was validated using RSMeans Construction Cost Data (RSmeans, 2023) in addition to consultations with an external cost consultant professional who has more than 20 years of experience in providing cost management for construction projects in Canada, including OSC projects.

VIII.4.2 Data Validation

Data validation is crucial for ensuring the accuracy and reliability of research data. In this study, the project owner, a key stakeholder, plays a central role in carefully reviewing and endorsing claimed amounts, drawing upon their understanding of project details and financial complexities. Their approval not only signifies a thorough evaluation of how inflation affects project costs, but also reinforces the credibility of the underlying data of this study.

Moreover, in this project, in collabouration with project owners, banking institutions also contribute to the data validation process. These institutions carefully examined claims, considering the influence of inflation on a project's overall financial aspects. Their validation, supported by financial expertise and adherence to regulatory standards, not only improves the accuracy of approved claim amounts but also increases confidence in the financial data associated with the project. Consequently, in this study, the combined efforts of project owners and banking institutions in validating data represent a sophisticated and comprehensive approach to ensuring the reliability of financial information in the dynamic context of project management.

Furthermore, the approval of the project's contract revised amount influenced by inflation, provided by both the client and the banking institution, solidifies the validation process and underscores its reliability. The joint endorsement from the client and the banking institution not only confirms the accuracy of the claimed amounts, but also heightens the overall dependability of the project's associated data.

VIII.4.3 Data Analysis

ECA is a fundamental process in building project cost management, and it plays a critical role in ensuring the successful planning and execution of construction projects (Soutos et Lowe, 2011). To conduct ECA effectively, the National Master Specification (NMS 2022-10 update) was used as the framework to determine a comprehensive work breakdown of the case project.

Table VIII.1 shows the ECA for the case study based on the NMS breakdown, showing each division's budget allocation as a percentage of the total construction cost. To capture the impact of inflation on the construction cost, soft costs (e.g., management, consultation, permits, etc.) were excluded from this ECA.

Table A VIII.1 Elemental Cost Analysis for the case study

Division	Description	Cost percentage
Division 01	General Requirement	1%
Division 02	Existing Condition	1%
Division 05	Metals	27%
Division 06	Wood	9%
Division 07	Thermal and Moisture Protection	3%
Division 08	Openings	6%
Division 09	Finishes	8%
Division 10	Specialties	1%
Division 13	Special Construction	14%
Division 22	Plumbing	6%
Division 23	HVAC	12%
Division 26	Electrical	6%
Division 31	Earthwork and Sitework	6%

Both Table A VIII.1 and Figure A VIII.3 show that the highest proportion of the project budget was allocated to Metals division, followed by the Special Construction, HVAC, and Wood divisions. In the case project, it should be noted, “Special construction refers to prefabricated components, such as roof cassette and wall supports. The cost percentage is in line with the project OSC concept, which consists of fully modularized light gauge steel components. Since the case project is a building featuring a heated floor, the HVAC system cost is high compared to what would be typical of a building with a conventional (non-heated) floor.

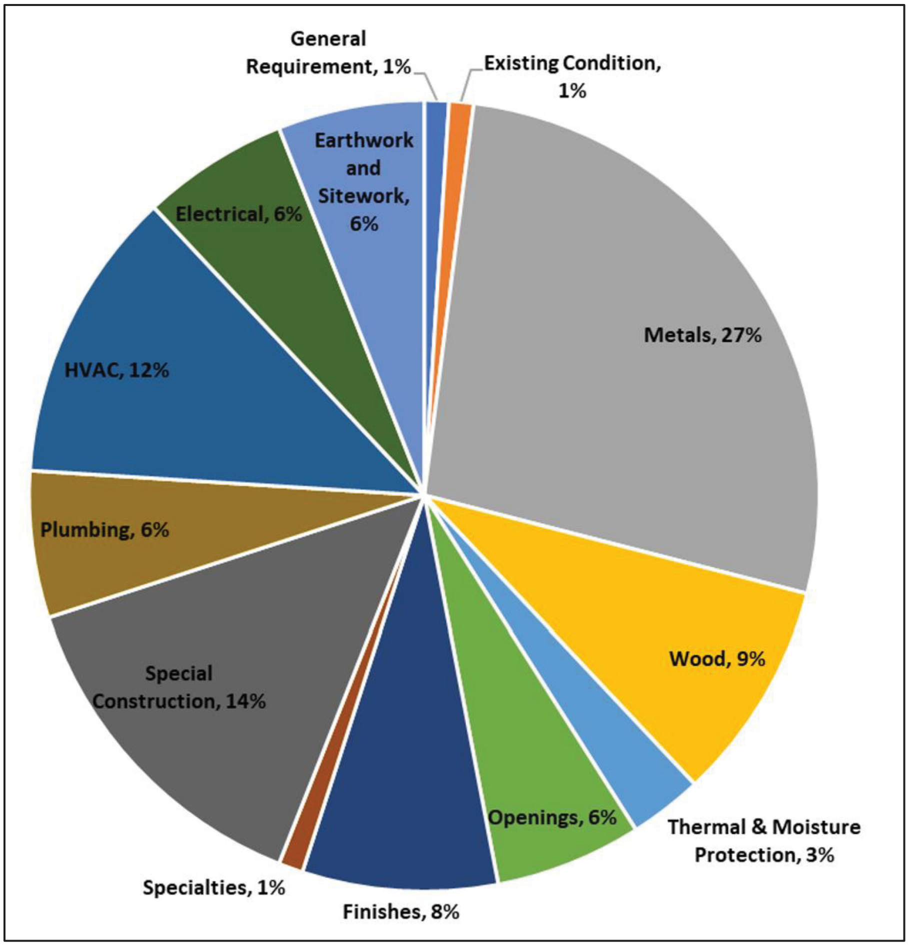

Figure A VIII.3 ECA pie chart

Figure A VIII.4 shows the building construction price index by city in major Canadian cities for the period spanning from the third quarter of 2021 to the third quarter of 2023. The trendlines reflect the price index by city for non-residential buildings and are based on Statistics Canada data. The price indices associated with this chart are provided in Table A VIII.2.

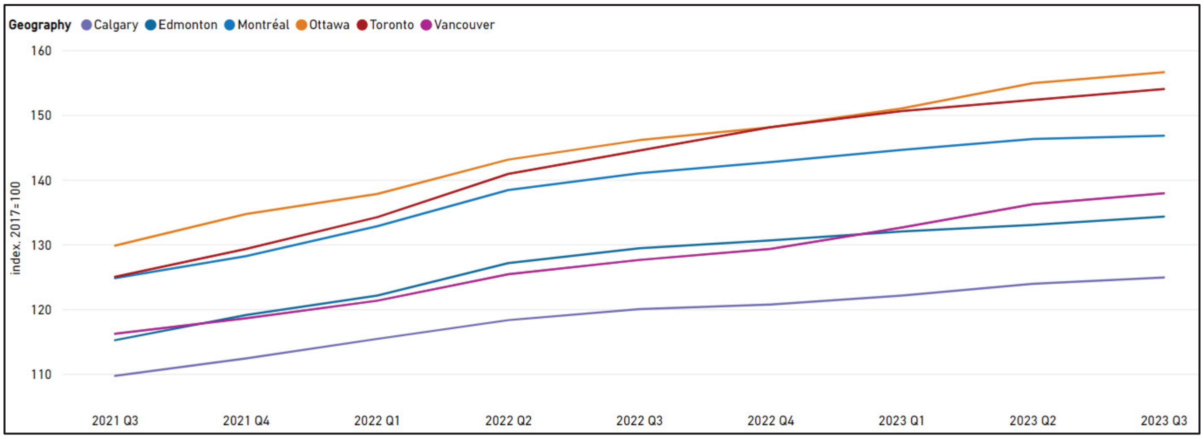

Figure A VIII.4 BCPI by city

Table A VIII.2 BCPI by city for non-residential buildings

Year	2021		2022				2023			Mean	S
quarter	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3		
Calgary	109.7	112.4	115.4	118.3	120.0	120.7	122.1	123.9	124.9	118.60	5.17
Edmonton	115.2	119.1	122.1	127.1	129.4	130.6	132.0	133.0	134.3	126.98	6.69
Montréal	124.8	128.2	132.8	138.4	141.0	142.7	144.6	146.3	146.8	138.40	8.03
Ottawa	129.8	134.7	137.8	143.1	146.1	148.1	151.0	154.9	156.6	144.68	9.15
Toronto	125.0	129.3	134.2	140.9	144.5	148.1	150.6	152.3	154.0	142.10	10.48
Vancouver	116.2	118.6	121.3	125.4	127.6	129.3	132.6	136.2	137.9	127.23	7.60

As can be seen, each of the cities for which data is available saw a steady increase in BCPI from 2021 Q3 to 2023 Q3. Our study focused on data for the Montréal region, since this is the location of the case project. The arithmetic mean and the standard deviation (presented in the table) were calculated in order to observe the variability of BCPI in different regions. The standard deviation values provide insights into the variability or dispersion of the quarterly indices around the mean. Higher standard deviation values (such as in Toronto) suggest more significant fluctuations, while lower values (such as in Calgary) are indicative of greater stability. The standard deviation was calculated using equation A VIII.1.

$$\sqrt{\frac{\sum_{i=1}^{N}(x_i - \bar{x})^2}{N-1}} : \text{Standard Deviation} \qquad \text{(A VIII.1)}$$

where:

s = sample standard deviation

N = number of observations

x_i = observed values of a sample item

$\bar{x}$ = mean value of the observations

Table A VIII.3 shows the percentage of deviation for the overall Building Construction Price in Montréal for each quarter in the study period, shedding light on the BCPI's behaviour in this region over the study period.

Table A VIII.3 Quarter-over-quarter percentage deviation for the overall building construction price, Montréal

Year	2021		2022				2023		
Quarter	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3
Montréal	124.8	128.2	132.8	138.4	141	142.7	144.6	146.3	146.8
% Deviation		2.72%	3.59%	4.22%	1.88%	1.21%	1.33%	1.18%	0.34%

Figure A VIII.5 presents a linear plot of BPCI in Montréal over the study period.

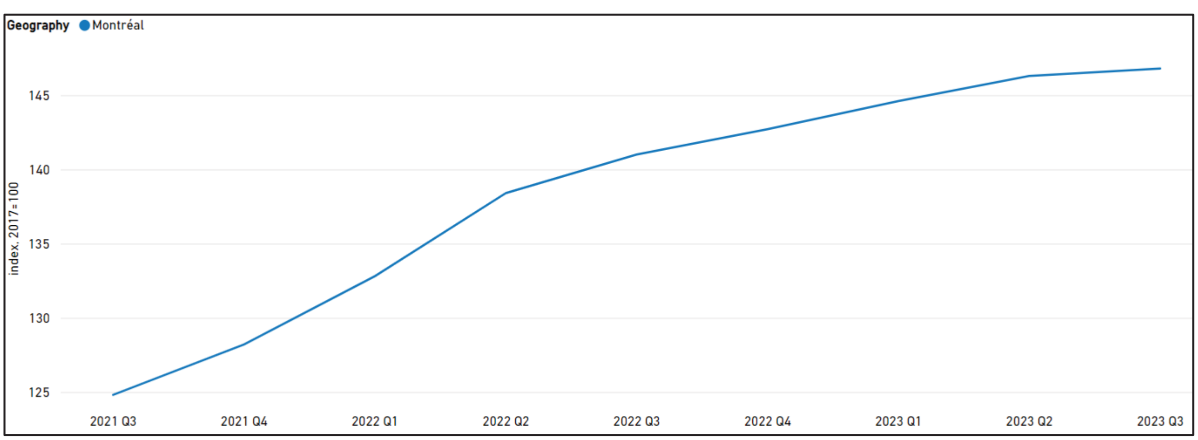

Figure A VIII.5 BCPI, Montréal

After examining the percentage of deviation, the inflation rate was then calculated for the project case study in accordance with the NMS breakdown. The inflation rate was calculated using equation A VIII.2.

$$\frac{BCPI_2 - BCPI_1}{BCPI_1} \times 100 \qquad \text{(A VIII.2)}$$

where:

$BCPI_2$ = Building Construction Price Index in the second period.

$BCPI_1$ = Building Construction Price Index in the previous period.

When there was an intermediate BCPI (due to purchase of material between the start and end of the project), $BCPI_1$ was the mean of the initial and intermediate BCPIs.

Table A VIII.4 shows the analysis of BCPI for the period 2021 Q3 to 2023 Q2. The case project was awarded to a design–build company in 2021. A Design–Build Stipulated Price Contract (CCDC-14) was applied to the project, meaning that the contract price was not to be increased due to inflation. As such, the design–build company made allowances for inflation in its bid based on the benchmark of the inflation rate from 2018 to 2019.

The allowances are the reason for the difference between the “actual inflation” and the “inflation approved for claim” in Table A VIII.5. The price indices utilised pertain to the period during which the design–build company allocated funds for purchasing material in accordance with the project plan.

Table A VIII.4 BCPIs building type, division, and Inflation Index

Description	Price index (Statistics Canada)								Inflation Index
	2021		2022				2023		
	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	
General Requirement	114.7							128.4	13.7
Existing Condition	105.5						112.3		6.8
Metals	179.4			215.7				227.7	42.3
Wood	135.4			145.9				153.0	14.1
Thermal and Moisture Protection	122.2			134.1				142.2	16.0
Openings	129.8				147.6			152.3	20.2
Finishes	131.5				147.9			152.5	18.7
Specialties	160.4							197.0	36.6
Special Construction	157.4			180.8				190.4	28.2
Plumbing	118.1			131.1				135.9	15.4
HVAC	104.7			115.7				119.8	13.1
Electrical	106.5			113.0				118.1	9.1
Earthwork and Sitework	117.0							134.1	17.1

Table A VIII.5 shows the results of the inflation analysis based on building divisions. The percentage of inflation served as the basis for computing the claim amount attributable to inflation for each building division. This methodology, approved by the key stakeholders, provided insights into the impact of inflation on individual components of the project.

Table A VIII.5 Inflation rate analysis for the case study

Description	Inflation Index	Actual Inflation %	Included Inflation Index (Benchmark Q4 2018 to Q4 2019) to the contract	Inflation Index approved for Claim	Inflation for Claim %
General Requirement	13.7	12%	3.6	10.10	9%
Existing Condition	6.8	6%	1.3	5.50	5%
Metals	42.3	24%	5.4	36.90	21%
Wood	14.1	10%	3.3	10.75	8%
Thermal and Moisture Protection	16.0	13%	3.6	12.35	10%
Openings	20.2	16%	3.3	16.85	13%
Finishes	18.7	14%	4.2	14.50	11%
Specialties	36.6	23%	5.3	31.30	20%
Special Construction	28.2	18%	4.4	23.83	15%
Plumbing	15.4	13%	2.6	12.80	11%
HVAC	13.1	12%	2.0	11.05	11%
Electrical	9.1	8%	1.8	7.25	7%
Earthwork and Sitework	17.1	15%	3.1	14.00	12%

Table A VIII.6 provides a detailed breakdown of the inflation rates associated with various Building Works, categorized in accordance with the NMS and aligned with the overall project budget. This comprehensive analysis shed light on the impact of inflation on each construction division, offering a nuanced perspective on cost variations within the project's scope.

Table A VIII.6 Inflation of Building Works based on NMS breakdown and project budget

Division	Description	Project Budget (%)	Inflation (%)
01	General Requirement	1%	9%
02	Existing Condition	1%	5%
05	Metals	27%	21%
06	Wood	9%	8%
07	Thermal and Moisture Protection	3%	10%
08	Openings	6%	13%
09	Finishes	8%	11%
10	Specialties	1%	20%
13	Special Construction	14%	15%
22	Plumbing	6%	11%
23	HVAC	12%	11%
26	Electrical	6%	7%
31	Earthwork and Sitework	6%	12%
Percentage of claim amount due to inflation against contract sum			14%

VIII.4.4 Correlation Coefficient

After investigating inflation patterns of building construction prices, the influence of inflation on claims for change orders (price increases due to inflation submitted to the client) was examined. To measure this relationship, correlation analysis was performed. The selection of a suitable correlation test, it should be noted, depends on the nature of the given variables. For linear data, the Pearson correlation test is recommended, whereas, for nonlinear data, the Spearman's correlation test is a more suitable alternative. Equation A VIII.3 was used to determine the linearity of the data:

$$\frac{\Delta X}{\Delta Y} = 1 \qquad \text{(A VIII.3)}$$

where:

ΔY represents a change in the amount of claim to the contract, and

ΔX represents a change in the inflation rate.

In our calculations, the dependent variable was the inflation of building construction prices, denoted by “Y”, and the independent variable was the amount of claim to the contract, denoted by “X”. In this case, the value is not equal to 1 which determines the nonlinearity behaviour of the data. In calculations of this nature, correlation coefficients fall within the range [−1,1]. Table A VIII.7 shows the categorization of correlation coefficients within this range.

Table VIII.7 Categorization of correlation coefficients within the range of possible values

Correlation Coefficient	Range
Very Weak	$\lvert r\rvert < 0.1$
Weak	$0.1 \leq \lvert r\rvert < 0.3$
Moderate	$0.3 \leq \lvert r\rvert < 0.5$
Strong	$0.5 \leq \lvert r\rvert$

$$\text{Rs} = 1 - \left(\frac{6\sum d_i^2}{n(n^2-1)}\right) \qquad \text{(A VIII.4)}$$

where:

Rs = Spearman correlation coefficient

di = Difference between the two ranks of each observation

n = Number of observations

To gain insights into the relationship between the claim amount for each specific building division and the inflation rate, Spearman’s correlation test was conducted using the percentages of inflation and the percentages of the claim amount relative to the total contract amount, as presented in Table A VIII.8.

Table A VIII.8 Percentage of claim amount according to scope of work and inflation

Description	% of Inflation (X)	% of Claim amount against Contract Sum (Y)
General Requirement	8.81%	0.09%
Existing Condition	5.21%	0.05%
Metals	20.57%	5.55%
Wood	7.94%	0.71%
Thermal and Moisture Protection	10.11%	0.30%
Openings	12.98%	0.78%
Finishes	11.03%	0.88%
Specialties	19.51%	0.20%
Special Construction	15.14%	2.12%
Plumbing	10.84%	0.65%
HVAC	10.55%	1.27%
Electrical	6.81%	0.41%
Earthwork and Sitework	11.97%	0.72%
Total % of Claim amount against Contract Sum		13.73%

VIII.4.5 Sensitivity Coefficient

The sensitivity coefficient (SC) is a valuable tool used to quantify the relationship between the percentage change in inflation and the corresponding percentage change in the claim amount for different building divisions. By analyzing this relationship, project managers can identify the components of a project most sensitive to inflationary pressures. This allows for better informed decision-making and resource allocation. In keeping with the description above, the SC was calculated for each building division by dividing the percentage change in the claim amount by the percentage change in the inflation rate, where a higher SC indicates greater sensitivity to inflation.

$$SC = \frac{\text{Percentage Change in Claim Amount (Y)}}{\text{Percentage Change in Inflation Rate (X)}} \tag{A VIII.5}$$

The SC provides a quantitative measure of how changes in inflation affect the financial aspects of different divisions within a construction project. The SC values calculated were analyzed to determine which divisions are most affected by inflation (see Table A VIII.8).
The Correlation Coefficient and SC analysis pointed to the analytical connection between inflation and OSC by indicating the strength of the relationship between the inflation rate and the selection of OSC as the construction approach (as a strategy to overcome the adverse impact of inflation on the overall project cost).

VIII.5 Results and Discussions

In this section, the evaluation conducted on the changing behaviour of BCPIs for major cities in Canada is presented. Figure A VIII.5 shows that there was a consistent rise in construction costs over the observed period. Seasonal trends observed in some cities, like Ottawa and Toronto, show a pattern of higher construction prices in Q2 of the observed years, possibly due to seasonal factors or increased construction activity during certain months.

Table A VIII.3 provides a comprehensive view of the percentage deviation in Building Construction Prices in Montréal. As can be seen, the overall Building Construction Price in Montréal was subject to a consistent upward trend over the study period.
Our analysis interpreted the patterns observed in the percentage deviations in overall Building Construction Price in Montréal. The observed trends in these percentages can provide valuable insights for decision-makers and policymakers, even though the specific causes of these fluctuations are not identified in the data.

Commencing with the third quarter of 2021 and extending to the third quarter of 2023, the fluctuations in percentage deviation follow a dynamic trajectory that is reflective of the construction market's responsiveness to various economic and industry-specific determinants.

The initial quarters i.e., the third quarter of 2021 to the fourth quarter of 2021 witnessed an initially moderate and then accelerated ascension in construction prices until the second quarter of 2022, indicative of potential influences such as heightened demand or escalating material and labour costs.

Subsequent quarters from the third quarter of 2022 to the third quarter of 2023, indicated by reduced percentage deviations, suggest a stabilization in the rate of ascent, attributable to factors such as market corrections, regulatory adjustments, or external economic dynamics. This could be a result of market corrections or regulatory adjustments. For decision-makers, this trend might allow for more flexible project planning and budgeting.

The data in Table A VIII.3, while not specifying the causes of the observed trends, can still provide valuable insights for decision-making with respect to budgeting, project planning, and resource allocation in the construction sector in Montréal.

Additionally, policymakers can use this analysis to gain a deeper understanding of the economic well-being of the construction industry and to make specific interventions to maintain stability in the face of changing conditions such as monitoring market trends closely and adjusting fiscal policies or incentives to align with broader economic goals while supporting the construction sector's growth and resilience.

The inflation analysis presented in Table A VIII.5 shows that metal works saw the highest inflation, followed by specialties (toilet compartments, accessories, and signage). This is due to the fact that these specialty works were scheduled for relatively late in the project, and, as such, were subject to 2023 prices. However, as shown in Table A VIII.6, in spite of the high rate of inflation for this category, specialties from Division 10 represented only 1% of the total project cost. Special Construction (Division 10), consisting of prefabrication works for roof cassettes, wall supports, and ceiling and corridor cassettes, had the third highest rate of inflation. This was due to high rates of inflation for particular materials used in these prefabricated components, such as light gauge steel (21% inflation) and oriented strand board (8% inflation).

Using the BCPI data and the percentages presented in Table A VIII.6, the correlation analysis was carried out. Using equation VIII.1, the relationship between inflation and the amount of claim was found to be nonlinear, so Spearman's correlation test was performed to assess the relationship between the two variables.

Table A VIII.8 shows the effects of inflation based on the project's ECA, as well as the corresponding breakdown of claim amounts as percentages of the overall contract sum. The percentage of inflation (X) delineates the percentage increase in costs due to inflation for each specific scope. For instance, the inflation rate for metals is notably high, at 20.57%, signifying a substantial potential cost escalation in this division.

The percentage of claim amount against the Contract Sum (Y) quantifies the percentage attributed to each scope relative to the total contract sum. For example, Special Construction, with a 15.14% inflation rate, accounts for 2.12% of the total contract sum.

The total percentage of the claim amount against the contract sum, calculated as a numerical statistic, consolidates the cumulative impact of inflation on the entire project. At 13.73%, it signifies the overall proportion of the claim amount in relation to the contract sum.

The statistical analysis was further augmented by the inclusion of Spearman's correlation test, which yielded a correlation coefficient (r) of 0.6044. Table A VIII.9 shows the detailed calculation of the r-value. This value was found to fall within the "strong" range ($0.5 < |r|$), indicating a statistically significant positive correlation between variables.

Table A VIII.9 Spearman's correlation calculations

Division	X-values	Y-values	Xra	Xra-Mx	Yra	Yra-My	Sum Diffs
01	8.81	0.09	4.00	−3.00	2.00	−5.00	15.00
02	5.21	0.05	1.00	−6.00	1.00	−6.00	36.00
05	20.57	5.55	13.00	6.00	13.00	6.00	36.00
06	7.94	0.71	3.00	−4.00	7.00	0.00	0.00
07	10.11	0.30	5.00	−2.00	4.00	−3.00	6.00
08	12.98	0.78	10.00	3.00	9.00	2.00	6.00
09	11.03	0.88	8.00	1.00	10.00	3.00	3.00
10	19.51	0.20	12.00	5.00	3.00	−4.00	−20.00
13	15.14	2.12	11.00	4.00	12.00	5.00	20.00
22	10.84	0.65	7.00	0.00	6.00	−1.00	0.00
23	10.55	1.27	6.00	−1.00	11.00	4.00	−4.00
26	6.81	0.41	2.00	−5.00	5.00	−2.00	10.00
31	11.97	0.72	9.00	2.00	8.00	1.00	2.00

This statistical validation affirmed that changes in inflation rates are strongly associated with changes in claim amounts across project scopes. As such, the Spearman's correlation coefficient adds an additional layer of analytical depth, substantiating the observed relationships and fortifying the academic robustness of the interpretation, making this an attractive analytical approach for project managers, financial analysts, and other stakeholders in construction projects.

In essence, this data-driven approach provides stakeholders with concrete figures and statistical support to navigate potential financial impacts. The detailed breakdown enables a prioritised focus on scopes with higher inflation rates, such as metal, special construction (prefabricated items), HVAC, finishes, openings (doors and windows), and wood works, where careful planning and risk mitigation may be imperative.

For instance, the analysis revealed that Specialties (elements such as toilet compartments, accessories, and signage), are subject to a relatively high inflation rate of 19.51%. However, the corresponding impact on the total project cost was found to be relatively low, accounting for only 0.20% of the overall claim amount against the contract sum. Stakeholders can leverage insights of this nature to make informed decisions in project planning. In this example, the lower contribution of Specialties to the total project cost suggests that the procurement of these items can be delayed without significantly affecting the overall project timeline or budget, allowing for a more favourable market environment, potential cost savings, or the opportunity to reallocate resources to scopes with more significant financial implications, such as Metals or Special Construction.

The presented approach to analysing construction project data and inflation, as presented in the tables and reinforced by Spearman's correlation test results, offers a robust foundation for developing an appropriate material purchase plan, work execution plan, and project cash flow. By understanding the inflation rates associated with each project scope, stakeholders can strategically plan the procurement of materials. In addition, the percentage breakdown of claim amounts against the contract sum offers a granular understanding of where financial impacts are concentrated. This information is invaluable in regard to constructing an accurate project cash flow model.

The strong positive correlation between variables suggests that changes in inflation rates are strongly associated with changes in claim amounts. This relationship can be given consideration in the cash flow projection to account for potential fluctuations in project costs over time, facilitating a more realistic and adaptable financial forecast.

Integration of ECA and the inflation analysis according to Table A VIII.8, reveals that metal works have experienced the highest inflation, followed by special construction activities, including prefabrication works. Therefore, adopting OSC methods is deemed appropriate.

This approach underscores the importance of completing a significant portion of metal works and special construction off-site, with these activities collectively accounting for approximately 35% of the total project scope.

As noted above, the SC, as shown in Table A VIII.10, indicates the ratio of the percentage change in the claim amount to the percentage change in the inflation rate for each building division. Using Equation (A VIII.5), the Metals division, with an SC of 0.27, was found to be more sensitive to inflation compared to the Specialties, Earthwork, and Sitework divisions. Moreover, Special Construction and HVAC were also found to have high SC values of 0.14 and 0.12, respectively, suggesting a significant impact.

Table A VIII.10 Sensitivity Coefficient analysis according to the scope of work

Description	Sensitivity Coefficient
General Requirement	0.01
Existing Condition	0.01
Metals	0.27
Wood	0.09
Thermal and Moisture Protection	0.03
Openings	0.06
Finishes	0.08
Specialties	0.01
Special Construction	0.14
Plumbing	0.06
HVAC	0.12
Electrical	0.06
Earthwork and Sitework	0.06

The integration of ECA, inflation analysis, correlation coefficient and SC analysis provided a comprehensive understanding of the impact of inflation on each division. The results show that the divisions most affected by inflation, (i.e., those with a high SC), such as Metals and Special Construction, are good candidates to be carried out using the OSC approach.

As noted above, OSC allows for a considerable portion of the work to be completed in a controlled environment with shorter timelines and less material waste. Additionally, the use of OSC enables bulk purchasing of materials, such as steel, which is highly susceptible to price fluctuations, further insulating projects from inflationary pressures. (Bulk purchasing agreements often come with fixed pricing, which protects against sudden price hikes.) The results underscore the importance of OSC as a collaborative approach among all stakeholders involved in construction projects.

By identifying high-risk inflationary materials and creating a price index based on historical market prices, project teams can better manage the impact of inflation on project costs. In this project's case study, various stakeholders, including the design and build team, project management consultants, clients, and financial institutions, mutually agreed on the OSC approach and collaborated closely to minimize the negative impact of inflation on the total project cost.

VIII.6 Conclusion and Recommendations

The COVID-19 pandemic has led to a sustained period of inflation in Canada that is showing signs of persistence for the foreseeable future, posing substantial challenges to the construction industry. The comprehensive analysis of construction project data presented herein involved a thorough examination of inflation trends supported by the results of Spearman’s correlation test and SC analysis. As noted above, the presented approach provides a robust foundation for devising effective plans for material procurement, work execution, and for managing the overall project cash flow.

The findings indicate that divisions with a high SC, such as Metals and Special Construction, are most affected by inflation and thus are best suited for completion using the OSC approach. OSC allows for a significant portion of the work to be carried out in a controlled environment, resulting in shorter timelines and reduced material waste.

By understanding the effect of inflation on various aspects of a project, this research underscores the importance of OSC techniques to reduce the impact of inflation. OSC approach is designed to address and mitigate the adverse effects of cost overruns resulting from issues such as increased price, material waste, and project delays (Bertram et al., 2019; de Laubier et al., 2019). Minimizing these adverse impacts allows for the safeguarding of the project budget against the detrimental effects of inflation.

Furthermore, we studied the integration of ECA with price indices, connecting it with a detailed breakdown of claim amounts and the pertinent inflation rates associated with each scope. It is essential to create a budget estimation model that incorporates ECA and the behaviour of the fluctuating inflation rate. This model should predict price variations over time during the project's initial stages, allowing for proactive budget adjustments, rather than relying on contingency costs for later modifications.

The OSC approach could be a suitable method for minimizing the cost overrun effect by addressing the inflation rate during the project duration and monitoring price behaviour over time.

The method for obtaining a detailed breakdown of claim amounts as a percentage of the contract sum can also be applied to construct accurate and precise project cash flow models. The presented approach offers insights into the financial impacts of inflation on specific project elements by identifying high-risk components that have the most significant impact on project costs. This assists decision-makers in making reliable decisions regarding the selection of OSC for a given project.

This approach can be applied not only to immediate project planning, but also to long-term strategy, fostering a resilient and cost-effective approach in the face of inflationary pressures.

The research relies on historical data for inflation rates and building construction prices. While this approach provides a useful benchmark, it may not fully capture future inflation trends or market dynamics.

The inflation analysis presented in this study primarily focused on material costs and project delays, but labour shortages can exacerbate these inflationary pressures by increasing labour costs and causing further delays. Future research should explore the interplay between labour shortages and the adoption of OSC to provide a more holistic understanding of the challenges and solutions in the construction industry.

Extended research could also investigate other potential strategies for mitigating the effects of inflation, beyond OSC. This could include exploring the role of advanced technologies, such as artificial intelligence and machine learning, in predicting inflation trends and optimizing construction costs.

Longitudinal studies could be conducted to track the long-term effects of inflation on construction projects and the effectiveness of OSC and other mitigation strategies over time. This would provide a more comprehensive understanding of the dynamics between inflation and construction costs.

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