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Research Article

Identification and Evaluation of the Key Decision Support Factors for Selecting Off-site Construction in Canada: A Building Information Modeling (BIM)-enabled Approach

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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 (IBS), 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 a viable solution 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*:** OSC, OSM, decision support system, success factors

1. Introduction

According to the scientific literature and industrial reports, many mega-projects suffer from cost overruns and delay [1, 2]. This is because of various reasons while poor productivity is the primary reason [3-5]. Moreover, the McKinsey Global Institute [6] has also supported this finding, reporting that the construction sector has considerably lower average profit margins than other sectors. Bertram et al. [3] 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

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factors causing the issue, adopting the off-site construction (OSC) methodology has proven effective in enhancing efficiency in construction projects [7]. Various terminologies have been used to define the concepts of OSC. Some of them are presented in the following paragraphs.

OSC 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 [8]. 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 to expedite and improve efficiency in the construction of a permanent structure. In other words, OSC moves large percentage of the traditional on-site process to an industrial manufacturing environment.

Off-site manufacturing (OSM) is defined by the Construction Industry Council (CIC) [9] 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 [10]. Recently, digital fabrication and OSM have gained prominence in the construction industry as potential solutions to its problems [11]. However, there is a lack of research in this domain that links OSC to the concept of design for manufacturing and assembly (DfMA) which is a prerequisite for the success of project using OSC [2].

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 [12]. 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 [13]. The integration of these technologies should be considered from the planning and design phase, with a focus on their integration into a Building Information Modeling (BIM) environment and connection to the Internet of Things (IoT) for real-time performance information [14]. A study was carried out in 2020 investigating the impact of digitization technologies on productivity examining case studies in Germany's building construction industry [15]. The study suggests that while companies may perceive the effects of digitization 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 digitization technologies.

Among various construction methods and technologies, selecting an appropriate system 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 [16].

As far as this research is concerned, validation and evaluation of the key decision support factors (KDSFs) for OSC projects in Canada are yet to be established. Thus, the objective of this research is to identify, evaluate and validate the relevant factors, and to propose a systematic road map for the development of a system supporting the selection of an appropriate construction method for a given building project in Canada. The research aims to accomplish the following objectives:

- To identify, evaluate and validate KDSFs for OSC projects in Canada,
- To assess, analyze and rank the most relevant KDSFs for OSC projects in Canada,
- To define a road map for the development of a decision support system (DSS) for OSC projects in Canada.

This research is a first part of a doctoral research project to develop a two-stage BIM-enabled DSS for the selection of a suitable industrialized building system (IBS). The development of the proposed DSS involves two main aspects: 1) identifying and evaluating KDSFs for selecting the appropriate OSC approach, and 2) using a ranking system to choose the most suitable approach for a building project based on BIM.

The outcome of this project will contribute to the body of knowledge by conducting an in-depth discussion of the main trends in OSC, research gaps, and recommendations for near-future direction in OSM. 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 KDSFs for OSC projects in Canada. For theoretical purposes, this research will constitute a comprehensive checklist of the most relevant factors for selecting OSC. In addition to theory, this project will contribute to the practice and managerial purposes by facilitating a road map to a better decision-support process in OSC projects in Canada.

1.1 *Research background of OSC and KDSFs 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 [17]. 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 phases. The initial stage of this project is the identification of potential decision support factors for OSC by investigating the characteristics of prefabricated and modular OSC from the previous study.

Available research work studied different terminologies and related technologies integrated with OSC methodology. Previous studies used modern methods of construction (MMC), off-site production (OSP), and off-site prefabrication (OSF) [11, 18-21]. Eventually, pioneer researchers introduced the integration of automation, digital fabrication, BIM and DfMA 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 [22]. The prefabrication method would reduce the overall project duration since on-site and off-site processes are carried out simultaneously [23].

The British government used the term 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 [18, 19, 24]. The terms OSC, OSM, and 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 [25].

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 [26]. Previous research has explored the decision-making factors related to OSC. The OSC 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 [27]. Moreover, the selection of a proper IBS to improve project performance and building quality has increased recently [28]. 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 to make a quick and reliable choice during the early design stage [16, 28]. Decision-making factors related to the OSC domain were discussed by previous researchers. Wuni et al. [29] identified the top 5 decision-making factors in the selection of modular integrated construction consisting of available skilled workers and management, project timeline, transportation, limitation in size and equipment availability.

2. 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 [16]. 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 KDSFs 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 1 shows the multistage methodological approach for this research.

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 [30]. Scopus was preferred as well by Jin et al. [2] as the search engine in the domain of construction compared to other databases such as the 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 can produce a bibliometric map of authors or journals based on co-citation data, or a map of keywords based on co-occurrence data [31].

In collaboration with BIM-based construction networks, Oraee et al. [32] employed VOSviewer for 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 et al. [12], Jin et al. [2], Mengist et al. [33], Oraee et al. [32], and Yin et al. [30], 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 [2, 12, 30, 32, 33]. Figure 2 shows the SLR applied in this research and Table 1 shows the dimensions and KDSFs for selection of OSC approach identified through SLR and expert interviews.

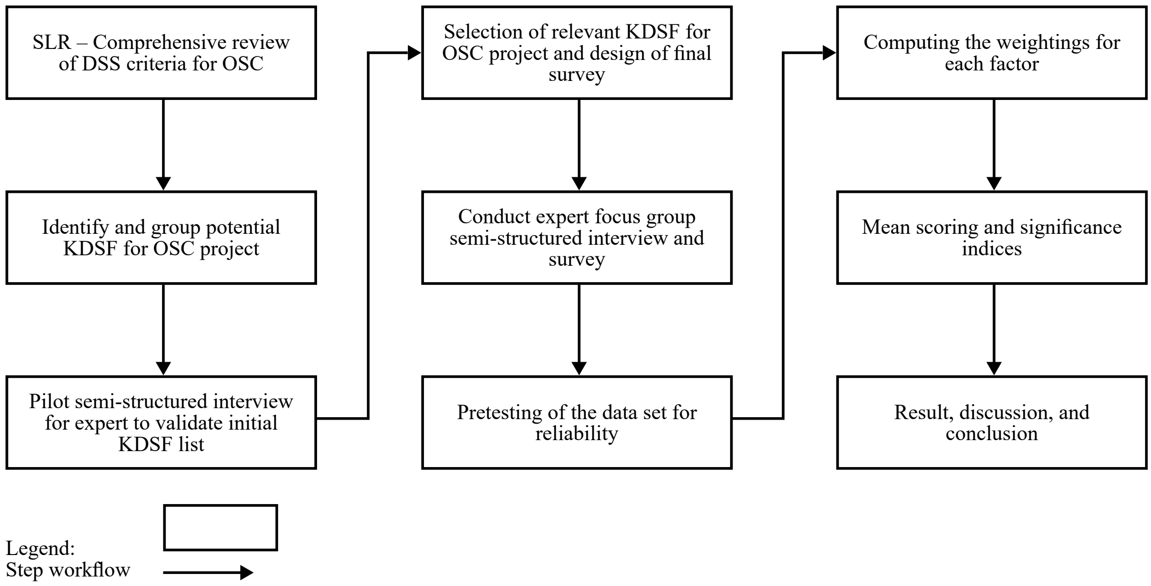

Figure 1. Multistage methodological approach

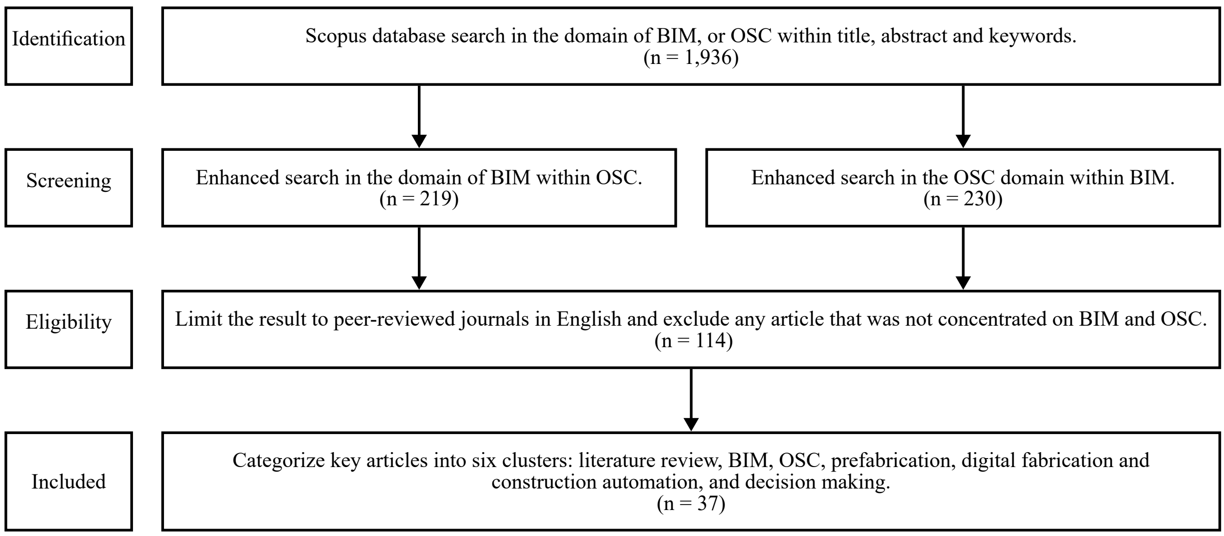

Figure 2. SLR process map

Table 1. Dimensions and KDSFs for selection of OSC approach

Dimension (D)	Factor's label	KDSFs	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	[2] [3] [4] [5] [8]
Time (D3)	F12	Design period	[1]
	F13	Production time	[8]
	F14	Mobilization and transfer time	[1] [3] [4] [8]
	F15	Assembly and construction period	[1] [4]
Cost (D4)	F16	Design	[1] [2] [3] [4] [5]
	F17	Material	[1] [2] [3] [4] [5]
	F18	Production and manufacturing	[2] [3] [4] [8]
	F19	Logistic	[2] [4] [8]
	F20	Assembly and construction	[2] [3] [4] [5]
	F21	Management	[2] [3] [4] [7]
	F22	Maintenance	[4] [7]
Quality (D5)	F23	DfMA + disassembly	[5] [8]
	F24	Defect liability period	[2] [3]
	F25	Standards and protocols	[3] [4] [5] [8]
	F26	Sustainability (carbon emission, energy consumption, waste)	[2] [4] [7]
	F27	Construction safety	[2] [4]
Procurement (D6)	F28	Type of procurement and delivery method	[4] [8]
	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 syndicate)	Expert interview

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 data set 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 37 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.

OSM 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 [34]. The literature uses different terms to describe OSM, including OSC, MMC, OSP, and OSF.

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 [35]. The CIC defines OSM 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 OSM 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 systems, and components and sub-assembly systems.

Digital fabrication in OSM is a production process that relies on robotics and computer-aided design (CAD) techniques [36]. Digital fabrication can be defined as a construction methodology that involves designing, manufacturing, and assembling structures using digital tools [37]. However, to transition from traditional planning and on-site construction to digitalized and automated OSC, advanced machinery such as computer-numeric-controlled machines must interpret data generated from drawings and BIM. Therefore, designers must comprehend the process and interoperability between BIM and automated machinery to utilize digital fabrication in OSM [38].

Moreover, IBS 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, efficiency, reduces production time, accelerates assembly, and improves cost-effectiveness in projects [39]. Additive manufacturing (AM) is a common term in automated construction systems that has the potential to manufacture large structures in digital fabrication [40]. Although AM has been successfully employed in other sectors such as automotive design, aerospace, and medical industries, Ding et al. [13] argued that in the construction industry, AM processes are only suitable for small and medium-scale manufacturing due to the challenge of delivering various kinds 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 CAD, computer-aided manufacturing, numerical control technology, new material technology, and BIM to enhance the efficiency of AM for large-scale projects [13]. However, there is a gap between industry and academia for the integration of OSC and digital fabrication. While academic proposals for BIMAC systems have emphasized AM or discrete assembly, industry efforts have primarily focused on automating conventional earth-moving equipment and adopting prefabrication techniques [41]. Therefore, it is necessary to develop and DSS, able to integrate with BIM and other above-mentioned technologies, to assist a decision maker in the selection of proper IBS for OSC building projects.

2.1 *Validation of KDSFs and evaluation of their importance*

After completing an SLR and administering a pilot study, the KDSFs affecting the decision-making process in OSC, listed in Table 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 [27]. 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 [42, 43].

Due to the lack of a central database for OSC experts, non-probability sampling methods using judgment/purposive sampling were used. This sampling method has been commonly used in expert surveys [16, 44]. 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 et al. [44] evaluated the critical success criteria for prefabricated prefinished volumetric construction projects internationally, while there were only 8 responses from Canada. Attouri et al. [16] 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 et al. [43] 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.

2.2 *Data analysis*

The Statistical Package for the Social Science (IBM SPSS v.25) was employed to analyze the data set. The reliability of both the data and survey instrument was evaluated using Cronbach's alpha. To assess the internal consistency of the responses, Tavakol et al. [45] 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 [45]. The level of reliability corresponding to the alpha value is presented in Table 2.

Table 2. Level of reliability (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

The analysis generated a Cronbach's alpha value of 0.825 which is higher than the acceptable threshold and considered a highly reliable data set. Table 3 shows the variable and internal consistency value according to Cronbach's alpha (1).

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

Table 3. Internal consistency

Variable	Description	Value	Internal consistency
K	Number of KDSFs	32	
$\sum S^2 y$	The sum of each KDSFs' variance	26.71	0.825
$S^2 x$	The variance of a sum of KDSFs' value	132.90	

2.2.1 *Mean scoring and ranking of KDSFs for OSC projects*

The statistical mean scoring is widely used in the construction management domain to evaluate and rank performance indicators [16, 43, 46]. The mean score (MS), and standard deviation (SD) of each KDSFs computed to assess the level of importance and the ranked factors are shown in Table 4.

$$\mathrm{MS} = \frac{\sum(s \times f)}{n}, 1 \le \mu \le 5 \tag{2}$$

MS of KDSFs were computed using equation (2) where MS = mean index of a KDSFs, f = frequency of each rating (1-5) for each factor, S = score assigned to each factor by expert using scale system of 1 to 5, and n = total number of experts. In case of having two or more factors with same 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 shows the overall ranking for each KDSFs based on MS and SD in its relevant dimension.

Table 4. KDSFs ranking (based on MS)

KDSFs	Dimension	MS	SD	Rank	KDSFs	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 the time-related dimension (D3) - assembly and construction period (F15). Furthermore, the time-related dimension (D3) consisting of F12 to F15 with an MS of 4.35 ranked first and is considered the most important dimension in the decision support process in the OSC project. Table 5 shows the result of the MS calculation for each dimension to determine its ranking.

Table 5. Dimension ranking (based on MS approach)

Dimension (D)	Factors	Dimension MS	Dimension rank
D1 - Project characteristics	F1 - Size	3.68	4
	F2 - Material		
	F3 - Location		
	F4 - Design complexity		
	F5 - Design flexibility		
D2 - Supply chain	F6 - Financing	3.40	6
	F7 - Manufacturer		
	F8 - Raw material		
	F9 - Equipment		
	F10 - Software		
	F11 - Expert and skilled worker		
D3 - Time	F12 - Design period	4.35	1
	F13 - Production time		
	F14 - Mobilization transfer time		
	F15 - Assembly and construction period		
D4 - Cost	F16 - Design	3.14	7
	F17 - Material		
	F18 - Production and manufacturing		
	F19 - Logistic		
	F20 - Assembly and construction		
	F21 - Management		
	F22 - Maintenance		
D5 - Quality	F23 - DfMA + disassembly	3.95	2
	F24 - Defect liability period		
	F25 - Standard and protocols		
	F26 - Sustainability (carbon emission and waste)		
	F27 - Construction safety		
D6 - Procurement	F28 - Type of procurement and delivery method	3.67	5
	F29 - Number of tenderers		
D7 - Sociocultural	F30 - Lack of awareness among all stakeholders	3.75	3
	F31 - Cultural resistance		
	F32 - Local authority regulation		

2.2.2 *Sample grouping and one-way analysis of variance (ANOVA)*

Data set was grouped to test whether significant differences exist among more than two groups of experts [47]. 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 ANOVA was carried out to test the significant difference. Furthermore, to test the consistency of the three different groups of respondents' one-way 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 [46]. 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 [48]. The null hypothesis assumed there is 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 6 shows the grouping and P-value in one-way ANOVA.

Table 6. KDSFs ranking (based on MS)

Dimension	Factors	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

3. Discussion and research findings

The seven dimensions and their associated factors were used to develop a conceptual framework for DSS in OSC projects. Figure 3 shows the proposed framework of a DSS based on key factors in OSC projects.

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 shows the KDSFs dimension ranking based on MS. The findings are discussed in more detail below.

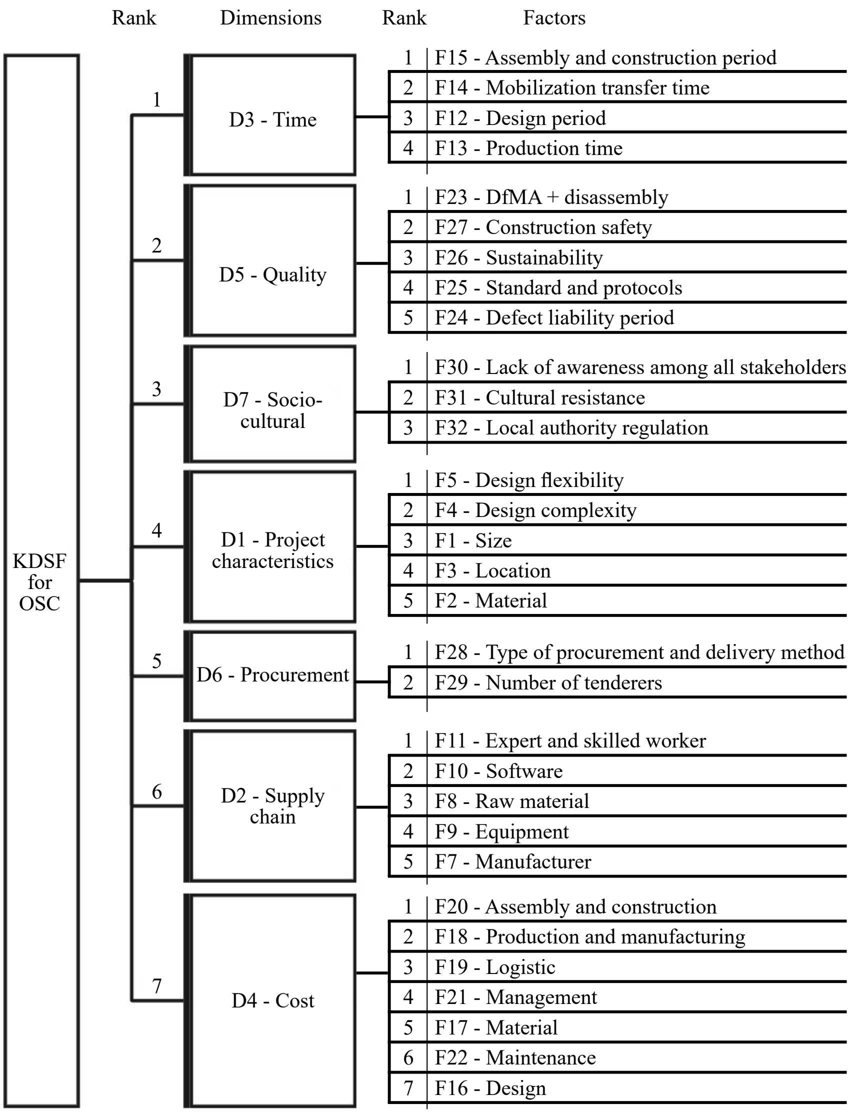

Figure 3. The proposed framework of a DSS

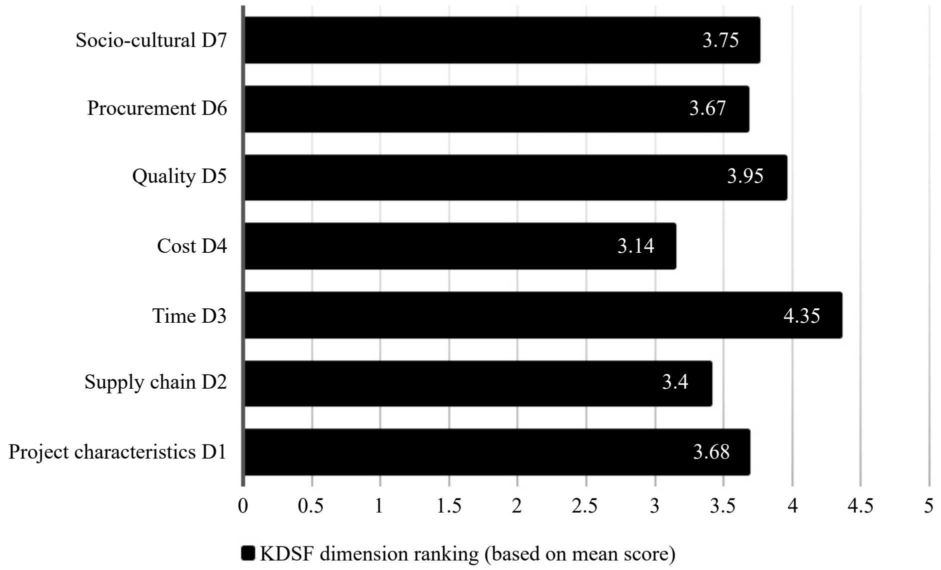

Figure 4. KDSFs dimension bar chart

3.1 *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 the 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 KDSFs with a score of 3.14. The literature also discusses and proposes selecting the OSC methodology as a solution for overcoming construction project delays [20, 46, 49]. Gusmao Brissi et al. [49] states that time is one of the most important factors influencing decisions regarding the use of OSC in multifamily housing in the US.

Table 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 7. Time-related factors (D3) scoring

	Time-related factors (D3)				
	Design period (F12)	Production time (F13)	Mobilization and transfer time (F14)	Assembly and 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	

3.2 *Quality factors (D5)*

The D5 factors consist of 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 KDSFs. According to experts, "*choosing OSC not only reduces carbon emissions and saves energy due to less 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 MS of 4.42 and a SD of 0.67, making it the most important KDSFs 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 criteria 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 [16, 20, 44, 50].

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 [51]. 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 [52]. Therefore, it can be concluded that government agencies are selecting the 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.

3.3 *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 off-site 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 et al. [43], poor client understanding, receptivity, and acceptance of modular projects 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 KDSFs 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.

3.4 *Project characteristics factors (D1)*

The dimension related to project characteristics (D1) scored a total MS of 3.68, with the most important KDSFs being design flexibility (F5) with an MS of 4.50 and SD of 0.80. Design flexibility in the OSC domain has been frequently discussed in the literature, mainly regarding adaptable buildings for sustainable built environments, which is also related to D5. The KDSFs of design flexibility, which drives "change of use", is a specific criterion in adaptable building within the OSC cluster [53]. 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 [54].

The second important KDSFs in D1 is design complexity (F4) with an MS of 4.33, which is the degree of difficulty in successfully meeting specified functional requirements and constraints, considering the probability of success within project parameters. It 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 8 shows the distribution of scoring among different groups of respondents for factors related to D1. It should be mentioned that the KDSFs 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 one-way ANOVA showed that the null hypothesis H0 is rejected; thus, there is no difference between different groups of respondents evaluating KDSFs in D1.

Table 8. Project characteristics (D1) scoring

Dimension	Factors	MS			MS	SD	Single 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			

3.5 *Procurement factors (D6)*

The factors related to the procurement dimension, with a total MS score of 3.67, are type of procurement and 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 [29], according to experts, "the majority of government projects are based on conventional contracts, and collaborative methods such as integrated project delivery or design and build are mainly acceptable for private projects". The results still support the importance of project delivery methods and the benefits of collaborative 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.

3.6 *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 digitization in OSC projects [55], 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 digitization in the construction industry increases, particularly in the OSC domain, the importance and necessity of the availability of software and equipment would 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 panels and glulam beams) were even more economical compared to similar locally provided products [56].

3.7 *Cost-related factors (D4)*

The cost dimension (D4) comprised of KDSFs related to the cost of design, material, production and manufacturing, logistics, assembly and construction, management, and maintenance, ranked the lowest with a total MS of 3.40. Despite frequent discussions in the literature on the cost-saving benefits of OSC projects [10, 57, 58], 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 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, labor costs, and cultural norms can significantly impact the decision-making process for construction methodology.

4. Conclusion, contributions, and limitations of the research

The OSC approach is rapidly gaining popularity as a preferred strategy 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 [1, 2, 11, 16, 29, 59, 60]. This paper aims to identify and assess seven major dimensions comprising 32 KDSFs to help decision-makers understand and recognize the criteria 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, and analyze the factors, a mixed-method of qualitative and quantitative approach was applied. Twelve (12) experts with extensive experience in OSC and with different backgrounds such as project managers, architects, engineers, contractors and manufacturers 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 the decision-making process for OSC projects. In addition, although there have been numerous studies in the literature highlighting the cost-saving advantages of using the OSC methodology, the importance of reducing costs was found to be outweighed by other factors in the selection of the 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 PhD research project that aims to create a two-stage BIM-enabled DSS for the selection of an appropriate IBS in OSC projects. However, the primary focus of this paper is to identify, validate, and analyze the KDSFs for the selection of the OSC methodology for building projects. The research has stablished a list of success factors for the selection of the OSC methodology based on validated KDSFs 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, labor 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. Furthermore, comprehensive lifecycle analyzes 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.

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Conflict of interest

There is no conflict of interest for this study.

References

[1] Jansen Van Vuuren T, Middleton C. *Methodology for quantifying the benefits of offsite construction*. London: CIRIA; 2020. https://doi.org/10.17863/CAM.64181

[2] Jin R, Gao S, Cheshmehzangi A, Aboagye-Nimo E. A holistic review of off-site construction literature published between 2008 and 2018. *Journal of Cleaner Production*. 2018; 202: 1202-1219. https://doi.org/10.1016/

j.jclepro.2018.08.195
[3] Bertram N, Fuchs S, Mischke J, Palter R, Strube G, Woetzel J. *Modular construction: From projects to products*. McKinsey & Company. 2019. https://www.ivvd.nl/wp-content/uploads/2019/12/Modular-construction-from-projects-to-products-full-report-NEW.pdf [Accessed 16th April 2022].
[4] Changali S, Mohammad A, Nieuwland MV. *The construction productivity imperative*. McKinsey Productivity Sciences Center. 2015. http://dln.jaipuria.ac.in:8080/jspui/bitstream/123456789/2501/1/The%20construction%20productivity%20imperative.pdf [Accessed 21st March 2022].
[5] de Laubier R, Burfeind A, Arnold S, Witthöft S, Wunder M. *The offsite revolution in construction*. https://www.bcg.com/publications/2019/offsite-revolution-construction [Accessed 15th February 2022].
[6] Barbosa F, Woetzel J, Mischke J, Ribeirinho MJ, Sridhar M, Parsons M, et al. *Reinventing construction: A route to higher productivity*. McKinsey Global Institute. 2017. http://dln.jaipuria.ac.in:8080/jspui/bitstream/123456789/2898/1/MGI-Reinventing-Construction-Full-report.pdf [Accessed 25th March 2022].
[7] Abdul Nabi M, El-adaway IH. Modular construction: Determining decision-making factors and future research needs. *Journal of Management in Engineering*. 2020; 36(6): 04020085. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000859
[8] Liu H, Holmwood B, Sydora C, Singh G, Al-Hussein M. Optimizing multi-wall panel configuration for panelized construction using BIM. In: *Proceedings of the 2017 International Structural Engineering & Construction Conference (ISEC)*. Valencia, Spain: ISEC Press; 2017. p.24-29. https://doi.org/10.14455/isec.res.2017.15
[9] House of Lords Science and Technology Select Committee. *Off-site manufacture for construction: Building for change oral and written evidence*. https://www.parliament.uk/globalassets/documents/lords-committees/science-technology/off-site-manufacture-for-construction/off-site-manufacture-construction-ev.pdf [Accessed 15th April 2022].
[10] Abanda FH, Tah JHM, Cheung FKT. BIM in off-site manufacturing for buildings. *Journal of Building Engineering*. 2017; 14: 89-102. https://doi.org/10.1016/j.jobe.2017.10.002
[11] Wang M, Wang CC, Sepasgozar S, Zlatanova S. A systematic review of digital technology adoption in off-site construction: Current status and future direction towards industry 4.0. *Buildings*. 2020; 10(11): 204. https://doi.org/10.3390/buildings10110204
[12] Bowmaster J, Rankin J. A research roadmap for off-site construction: Automation and robotics. In: *Proceedings of the 2019 Modular and Offsite Construction (MOC) Summit.* Alberta, Canada: University of Alberta Library; 2019. p.173-180. https://doi.org/10.29173/mocs91
[13] Ding L, Wei R, Che H. Development of a BIM-based automated construction system. *Procedia Engineering*. 2014; 85: 123-131. https://doi.org/10.1016/j.proeng.2014.10.536
[14] Tang X, Chong H-Y, Zhang W. Relationship between BIM Implementation and Performance of OSM Projects. *Journal of Management in Engineering*. 2019; 35(5): 04019019. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000704
[15] Berlak J, Hafner S, Kuppelwieser VG. Digitalization's impacts on productivity: a model-based approach and evaluation in Germany's building construction industry. *Production Planning & Control*. 2021; 32(4): 335-345. https://doi.org/10.1080/09537287.2020.1740815
[16] Attouri E, Lafhaj Z, Ducoulombier L, Linéatte B. The current use of industrialized construction techniques in France: Benefits, limits and future expectations. *Cleaner Engineering and Technology*. 2022; 7: 100436. https://doi.org/10.1016/j.clet.2022.100436
[17] Marcher C, Giusti A, Matt DT. Decision support in building construction: A systematic review of methods and application areas. *Buildings*. 2020; 10: 170. https://doi.org/10.3390/buildings10100170
[18] Rahman MM. Barriers of implementing modern methods of construction. *Journal of Management in Engineering*. 2014; 30(1): 69-77. https://doi.org/10.1061/(ASCE)ME.1943-5479.0000173
[19] Pan W, Gibb AGF, Dainty ARJ. Perspectives of UK housebuilders on the use of offsite modern methods of construction. *Construction Management and Economics*. 2007; 25(2): 183-194. https://doi.org/10.1080/01446190600827058
[20] Abu Hammad A, Salem O, Hastak M, Syal M. Decision support system for manufactured housing facility layout. *Journal of Architectural Engineering*. 2008; 14(2): 36-46. https://doi.org/10.1061/(ASCE)1076-0431(2008)14:2(36)
[21] Hwang B-G, Shan M, Looi K-Y. Knowledge-based decision support system for prefabricated prefinished volumetric construction. *Automation in Construction*. 2018; 94: 168-178. https://doi.org/10.1016/j.autcon.2018.06.016
[22] Tatum CB, Vanegas JA, Williams JM. *Constructability improvement using prefabrication, preassembly, and modularization*. Austin, TX: Bureau of Engineering Research, University of Texas at Austin; 1987.

[23] Lee J, Kwon N, Ham N, Kim J, Ahn Y. BIM-based digital fabrication process for a free-form building project in South Korea. *Advances in Civil Engineering*. 2019; 2019: 1-18. https://doi.org/10.1155/2019/4163625
[24] Gibb AGF. *Principles in off-site fabrication.* Caithness: Whittles; 1999.
[25] Blismas NG, Pendlebury M, Gibb A, Pasquire C. Constraints to the use of off-site production on construction projects. *Architectural Engineering and Design Management*. 2005; 1(3): 153-162. https://doi.org/10.1080/17452007.2005.9684590
[26] Gibb A, Isack F. Re-engineering through pre-assembly: Client expectations and drivers. *Building Research & Information*. 2003; 31(2): 146-160. https://doi.org/10.1080/09613210302000
[27] Attouri E, Lafhaj Z, Ducoulombier L, Linéatte B. Development of decision-making tool for construction method selection: Choosing and optimizing offsite construction. In: *Proceedings of the 2022 Modular and* Offsite Construction (MOC) Summit. Alberta, Canada: University of Alberta Library; 2022. p.25-33. https://doi.org/10.29173/mocs261
[28] Daget YT, Zhang H. Decision-making model for the evaluation of industrialized housing systems in Ethiopia. *Engineering, Construction and Architectural Management*. 2019; 27(1): 296-320. https://doi.org/10.1108/ECAM-05-2018-0212
[29] Wuni IY, Shen GQ. Towards a decision support for modular integrated construction: An integrative review of the primary decision-making actors. *International Journal of Construction Management*. 2019; 22(5): 929-948. https://doi.org/10.1080/15623599.2019.1668633
[30] Yin X, Liu H, Chen Y, Al-Hussein M. Building information modelling for off-site construction: Review and future directions. *Automation in Construction*. 2019; 101: 72-91. https://doi.org/10.1016/j.autcon.2019.01.010
[31] van Eck NJ, Waltman L. Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics*. 2010; 84: 523-538. https://doi.org/10.1007/s11192-009-0146-3
[32] Oraee M, Hosseini MR, Papadonikolaki E, Palliyaguru R, Arashpour M. Collaboration in BIM-based construction networks: A bibliometric-qualitative literature review. *International Journal of Project Management.* 2017; 35(7): 1288-1301. https://doi.org/10.1016/j.ijproman.2017.07.001
[33] Mengist W, Soromessa T, Legese G. Method for conducting systematic literature review and meta-analysis for environmental science research. *MethodsX*. 2020; 7: 100777. https://doi.org/10.1016/j.mex.2019.100777
[34] Goulding JS, Rahimian FP. *Offsite production and manufacturing for innovative construction: People, process and technology*. Routledge; 2019.
[35] Liu H, Singh G, Lu M, Bouferguene A, Al-Hussein M. BIM-based automated design and planning for boarding of light-frame residential buildings. *Automation in Construction*. 2018; 89: 235-249. https://doi.org/10.1016/j.autcon.2018.02.001
[36] Agustí-Juan I, Habert G. Environmental design guidelines for digital fabrication. *Journal of Cleaner Production*. 2017; 142(4): 2780-2791. https://doi.org/10.1016/j.jclepro.2016.10.190
[37] Agkathidis A. *Digital Manufacturing in design and architecture*. Amsterdam: BIS Publishers; 2010.
[38] Iwamoto L. *Digital fabrications: architectural and material techniques*. New York: Princeton Architectural Press; 2009.
[39] He R, Li M, Gan VJL, Ma J. BIM-enabled computerized design and digital fabrication of industrialized buildings: A case study. *Journal of Cleaner Production*. 2021; 278: 123505. https://doi.org/10.1016/j.jclepro.2020.123505
[40] Khoshnevis B. Automated construction by contour crafting—related robotics and information technologies. *Automation in Construction*. 2004; 13(1): 5-19. https://doi.org/10.1016/j.autcon.2003.08.012
[41] Melenbrink N, Werfel J, Menges A. On-site autonomous construction robots: Towards unsupervised building. *Automation in Construction*. 2020; 119: 103312. https://doi.org/10.1016/j.autcon.2020.103312
[42] Hosseini MR, Martek I, Zavadskas EK, Aibinu AA, Arashpour M, Chileshe N. Critical evaluation of off-site construction research: A Scientometric analysis. *Automation in Construction*. 2018; 87: 235-47. https://doi.org/10.1016/j.autcon.2017.12.002
[43] Wuni IY, Shen GQ, Osei-Kyei R. Quantitative evaluation and ranking of the critical success factors for modular integrated construction projects. *International Journal of Construction Management*. 2020; 22(11): 2108-2120. https://doi.org/10.1080/15623599.2020.1766190
[44] Wuni IY, Shen GQ, Osei-Kyei R. Evaluating the critical success criteria for prefabricated prefinished volumetric construction projects. *Journal of Financial Management of Property and Construction*. 2021; 26(2): 279-297. https://doi.org/10.1108/JFMPC-03-2020-0013
[45] Tavakol M, Dennick R. Making sense of Cronbach's alpha. *International Journal of Medical Education*. 2011; 2: 53-55. https://doi.org/10.5116/ijme.4dfb.8dfd
[46] Hussain S, Zhu F, Ali Z, Xu X. Rural residents' perception of construction project delays in Pakistan. *Sustainability.*

2017; 9: 2108. https://doi.org/10.3390/su9112108
[47] Ostertagová E, Ostertag O. Methodology and application of one-way ANOVA. *American Journal of Mechanical Engineering*. 2013; 1(7): 256-261.
[48] Kim TK. Understanding one-way ANOVA using conceptual figures. *Korean Journal of Anesthesiology*. 2017; 70(1): 22-26. https://doi.org/10.4097/kjae.2017.70.1.22
[49] Gusmao Brissi S, Debs L, Elwakil E. A review on the factors affecting the use of offsite construction in multifamily housing in the United States. *Buildings*. 2021; 11(1): 5. https://doi.org/10.3390/buildings11010005
[50] Al-sarafi AHM, Alias AH, Shafri HZM, Jakarni FM. Factors affecting BIM adoption in the yemeni construction industry: A structural equation modelling approach. *Buildings*. 2022; 12(12): 2066. https://doi.org/10.3390/buildings12122066
[51] Société d'habitation du Québec (SHQ). *Programme d'habitation abordable Québec*. http://www.habitation.gouv.qc.ca/programme/programme/programme_dhabitation_abordable_quebec.html [Accessed 15th June 2022].
[52] Novoclimat. *Normative framework Novoclimat - small-multiple-unit buildings*. https://transitionenergetique.gouv.qc.ca/en/residential/programs/novoclimat/novoclimat-small-multiple-unit-buildings [Accessed 15th June 2022].
[53] Manewa A, Siriwardena M, Ross A, Madanayake U. Adaptable buildings for sustainable built environment. *Built Environment Project and Asset Management.* 2016; 6(2). https://doi.org/10.1108/BEPAM-10-2014-0053
[54] Peikko. *DeltaBEAM 2023*. https://www.peikko.ca/ [Accessed 12th April 2022].
[55] An S, Martinez P, Al-Hussein M, Ahmad R. BIM-based decision support system for automated manufacturability check of wood frame assemblies. *Automation in Construction*. 2020; 111: 103065. https://doi.org/10.1016/j.autcon.2019.103065
[56] Gordian. *2023 building construction costs book*. United States of America: The Gordian Group; 2022.
[57] Pan W, Sidwell R. Demystifying the cost barriers to offsite construction in the UK. *Construction Management and Economics*. 2011; 29(11) :1081-1099. https://doi.org/10.1080/01446193.2011.637938
[58] García de Soto B, Agustí-Juan I, Hunhevicz J, Joss S, Graser K, Habert G, et al. Productivity of digital fabrication in construction: Cost and time analysis of a robotically built wall. *Automation in Construction*. 2018; 92: 297-311. https://doi.org/10.1016/j.autcon.2018.04.004
[59] Siggner R. *Modular housing: Benefits, challenges and lessons learned*. BC Housing; 2011. https://buildhomesnotbarriers.ca/wp-content/uploads/2019/10/BK-Research-Summaries-Modular-Housing-Lessons-Learned.pdf [Accessed 25th March 2022].
[60] Ham N, Lee S. Project benefits of digital fabrication in irregular-shaped buildings. *Advances in Civil Engineering.* 2019; 2019: e3721397. https://doi.org/10.1155/2019/3721397