Ain Shams Engineering Journal 16 (2025) 103228

Contents lists available at ScienceDirect

Ain Shams Engineering Journal

journal homepage: www.sciencedirect.com

Full Length Article

Offsite modular construction adoption in developing countries: Partial least square approach for sustainable future

Syed Saad [a], Kumeel Rasheed [a], Syed Ammad [b], Muhammad Hasnain [c], Habib Ullah [d], Abdul Hannan Qureshi [e], Aawag Mohsen Alawag [f], Muhammad Altaf [b], Touseef Sadiq [g,*]

[a] *Department of Civil Engineering, CECOS University of IT & Emerging Sciences, 25000, Peshawar, KPK, Pakistan*
[b] *School of Engineering and Built Environment, Griffith University, Gold Coast QLD4215, Southport, Australia*
[c] *Center for Sustainability Studies, Bemidji State University, 1500 Birchmont Drive North-East 56601, MN, United States*
[d] *School of Architecture, Southeast University, Sipailou Campus, Xuanwu District, Nanjing, China*
[e] *Department of Building and Real Estate, The Hong Kong Polytechnic University, Kowloon 999077, Hong Kong, China*
[f] *Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, Seri Iskandar 32610, Malaysia*
[g] *Centre for AI Research, Department of Information and Communication Technology, University of Agder, Grimstad, Norway*

ARTICLE INFO

Keywords:
Prefabricated
Offsite
Modular
Industrialised building system (IBS)
Partial least square (PLS)
Structural equation model (SEM)
Sustainable Development

ABSTRACT

The construction industry is significant in the economic growth of developing countries and is recognized globally for its high potential in sustainable development. Offsite Modular Construction (OMC) has the potential to revolutionize this sector. However, the adoption of OMC in developing nations remains limited due to various barriers. This study fills a critical gap by developing a novel framework that integrates the analysis of Offsite Modular Adoption Barriers (OMABs), i.e. resource availability, process management, and issues/perceptions, with the pursuit of overall sustainable future needs (OSFN) in residential projects. For this study, 314 construction specialists in Malaysia, a developing country with high construction activity, were surveyed. The study further employs PLS-SEM for latent variable relationship identification between OMABs and OSFN, which has not been researched comprehensively in the literature. The study reveals that there is a moderate positive correlation between OMABs and 33.6 % of the sustainable outcomes in residential projects. The path coefficient ($\beta = 0.316$) also provides evidence of the importance of eliminating these barriers in improving sustainability goals. This research is innovative in its approach as it seeks to address both the issues of OMC and sustainability in the developing nations. It is highly beneficial for policymakers as it provides a clear guideline on how to improve the OMC usage and promote sustainable construction. The SEM model can be used as a reference for other developing economies that are interested in the modernization of the construction industry for sustainable development.

1. Introduction

In a world where sustainability and technological innovation intertwine within the construction domain, humans are faced with the imperative to not only adapt but to proactively shape the future of the built environment. These imperative gains further significance when considering recent data that reveals the construction sector's substantial impact. It accounts for 32 % of global resource consumption and contributes to approximately 40 % of anthropogenic greenhouse gas emissions. Moreover, the sector generates waste equivalent to around 40 % of the materials consumed, underscoring the urgency of identifying sustainable solutions in construction practices [1]. In alignment with this imperative, the Chartered Institute of Buildings (CIOB) shares an insight in its 'Global Construction 2030′ report, which predicts a remarkable 85 % growth in the volume of construction output, reaching a staggering $15.5 trillion worldwide by 2030 [2].

Turning our focus to residential construction, it holds a pivotal role in developed/developing economies, contributing between 3 % and 7 % to the gross national product [3]. Nevertheless, the CIOB's 2015 report did not factor in the unforeseen impact of the COVID-19 pandemic, which gave rise to economic challenges and a downturn in the residential sector. This assertion is reinforced by reputable reports from developed countries. For instance, in Australia, Master Builders Australia's (MBA) latest building and construction industry forecasts

* Corresponding author at: Jon Lilletuns vei 9 4879, Grimstad, Norway.
E-mail address: touseef.sadiq@uia.no (T. Sadiq).

https://doi.org/10.1016/j.asej.2024.103228
Received 14 May 2024; Received in revised form 6 December 2024; Accepted 9 December 2024
Available online 25 December 2024

indicate that housing starts currently fall below the required annual rate of 200,000 to meet demand between 2022 and 2025 [4]. Meanwhile, in the United States, the National Association of Realtors (NAR) reports a housing shortage of between 5.5 and 6.8 million units, with the gap between supply and demand widening each year [5]. Similarly, in the UK, the Home Builders Federation (HBF) report suggests that house-building in England is expected to dip below 120,000 homes annually in the years ahead [6].

Taking transitive property into consideration, "if developed countries are experiencing a fall in residential sector construction, developing countries are experiencing a similar fall" which is evident from published literature [7,8]. In an era where environmental consciousness and efficiency converge and motivated by Ali Hassan et al.'s recommendation to use offsite modular construction (OMC) in developing countries with Egyptian construction stakeholders [9], this paper focuses on the Malaysian residential construction crisis as a developing country, exploring OMC as a potential solution.

This mode of construction encompasses a range of pre-assembly techniques conducted away from the primary construction site. During the initial stage, offsite modular elements are fabricated, and subsequently, they are transported to the assembly location. OMC not only addresses the pressing need for affordable and rapid construction in Malaysia but also aligns with sustainability goals. By reducing construction waste, minimising energy consumption, and utilising environmentally friendly materials, prefabrication not only expedites construction but also contributes significantly to reducing the sector's carbon footprint [10]. Moreover, it promotes resource efficiency and reusability, thus embodying the principles of a circular economy that can further enhance the sustainability of the construction industry in Malaysia.

In the scenario of Malaysian construction industry (MCI), with a projected 35 million population, the prevalence and potential of OMC has become increasingly pronounced. Based on data from the Malaysian Department of Statistics (MDS), there was a significant decline of 44.9 percent in the second quarter of 2020 within traditional construction. This situation stands in contrast to the Malaysian government's ambitious objective of providing one million low-cost homes. Clearly, the traditional construction approach has its limitations in addressing Malaysia's residential crisis, emphasising the necessity for the adoption of OMC.

Based on the Nationally Determined Contribution (NDC) report, following Malaysia's ratification of the Paris Agreement on 16th November 2016 [11], Malaysia has committed itself to taking substantial steps to reduce carbon emissions. As part of its pledge under the Paris Agreement, Malaysia has set ambitious targets for reducing its carbon footprint in various sectors, including construction. This commitment aligns with the global effort to combat climate change and underscores the need for sustainable and eco-friendly practices in all industries, including construction [12]. In this context, the adoption of OMC methods emerges as a promising avenue for Malaysia to meet its environmental goals while simultaneously addressing its housing crisis.

In theory, the Malaysian government recognises the benefits of OMC and has established the Construction Industry Development Board Industrialised Building System (CIDB-IBS) to research and invest in these methods. However, in practice, adoption within the private construction sector lags behind, notably in achieving the goal of delivering/managing one million construction units by 2028 [13,14]. Since 2008, projects valued over RM 50 million are required to achieve a 50 percent OMC score, but a recent 2018 report indicates that only 35 percent have met this target [15].

The problem statement of the study is Malaysia's traditional construction techniques are inadequate to address the sustainable housing needs. OMC is acknowledged as a solution but its implementation is not widespread. In such a scenario, a research question arises, "What are the critical success factors (CSFs) influencing the widespread adoption of OMC methods for sustainable future development in the MCI, and how can these factors be leveraged to address the housing crisis while meeting environmental goals?". While the research gap is that CSFs for OMC adoption in Malaysia are under-researched. Near to none study has explored the link between OMC barriers and sustainability using PLS-SEM. The study aims to bridge the research gap by mathematically identifying CSFs for overall sustainable future needs (OSFN) in relation to offsite modular adoption barriers (OMABs) in MCI using a partial least square structure equation modeling (PLS-SEM) approach. The study's significance stems from the observed gap between the Malaysian government's acknowledgment of OMC potential and its actual implementation in the construction sector, attributable to a lack of knowledge regarding OMC and OSFN in Malaysia. The study's objectives will be accomplished through the following:

1. Determining the OMABs and OSFN factors.
2. Investigating the relationship between overcoming OMABs and achieving OSFN using the PLS-SEM technique.
3. Developing a model for OMC adoption.

The novelty and relevance of this work are in the analysis of OMC as a viable solution to the housing deficit in Malaysia in the context of global and regional threats. As construction practices are being put under the spotlight for their sustainability, this research fills the existing literature gap between the theoretical advantages of OMC and its application in the Malaysian construction sector. Through identifying the CSFs and barriers to OMC adoption by using the PLS-SEM modeling approach, this research not only reveals the possibility of OMC in promoting affordable housing construction but also provides valuable information for addressing challenges for future requirements. This work is useful as it brings Malaysia's construction practices in line with international sustainability standards, and presents a model that can be used in other developing nations experiencing similar crises.

The paper is structured as follows, in the next section literature review is discussed. Section 3, Section 4 and Section 5 discuss methodology, results and discussion. Finally, towards the end, Section 6 and Section 7 point out conclusions, study's limitations and future research direction.

2. Literature review

2.1. OMC as a strategy for sustainable construction

In an era where sustainability has become a central concern in construction practices worldwide, the adoption of OMC emerges as a critical strategy for achieving eco-friendly and efficient building processes.

OMC has significant benefits over conventional construction practices when implemented in developing nations [14]. In terms of efficiency, OMC cuts costs by assembling structures more quickly, requiring fewer workers, and minimizing material waste to meet immediate housing needs [16]. Environmentally, it reduces site pollution and optimizes waste disposal because of factory-like production, and increases energy utilization with green materials [17]. In social terms, OMC enhances the speed of delivery of good quality homes, minimizes risks on site, and provides employment in manufacturing [9]. On the other hand, conventional construction is known to be more expensive, resource-intensive, and time-consuming than modular construction [14].

OMC has proven its effectiveness in Malaysia and neighboring Asian countries construction, such as, China with 611 OMC manufacture enterprises word wide, and 1786 OMC production lines. Despite the growing recognition of OMC's potential in Malaysia, a noticeable gap persists in our understanding of the CSFs driving its adoption within the MCI. As a consequence, many researchers have identified barriers for linked with OMC implementation from several perceptions.

2.2. Barriers to OMC implementation

A combination of previous studies by [13], [18 = 25] and others recognised a range of barriers for implementation of OMC for residential building projects. These are (1) insufficient comprehension of OMC knowledge resources [26,27]; (2) lack of manufacturing supplies [28,29]; (3) insufficient understanding of OMC knowledge resources [26,27]; (4) lack of maintenance methods in OMC [30,31]; (5) failure in team collaboration [16,32]; (6) redesigning process imposes hurdles in OMC [27,30]; (7) existence of negative social perception among OMC stakeholders [21,33]; (8) fragmentation associated with OMC will increase transportation cost [34,35]; (9) fear of stakeholder investment in OMC [25,36].

2.3. Barriers to OMC adoption in Malaysia

Furthermore, [37] have identified numerous barriers to OMC adoption in Malaysia, including lack of OMC technology familiarity, large expenses on OMC facilities, and lack of equipment to transmit enormous OMC components. Moreover, [14] discusses different challenges that delay the adoption of OMC in Malaysia, such as lack of governmental support, unavailability of standard guidelines for OMC, and absence of buyer education.

2.4. Categorization of barriers

According to [37–39] the barriers are divided into 3 main constructs: resource availability, process management and issues and perception as mentioned in Table 1. Resource availability barriers are related to the reserves in a project, regulatory delays, and environmental restrictions. Process management barriers are associated with OMC's corporate strategy, procurement, and collaboration among stakeholders. Lastly, issues and perception barriers, are related to adoption of OMC in building sector, stakeholder perspectives, public opinion, and social factors.

2.5. The OSFN approach and sustainability dimensions

In this study OSFN is grounded on "Sustainability Theory" that focuses on the three pillars of economy, environment, and society. It is useful for implementing sustainability in industry, as well as for assessing the impact of such approaches as OMC on sustainability objectives. The OSFN approach combines economic viewpoints [40,41], environmental accountability [42,43], and social consciousness [27,43]. These are given importance in the aims of construction projects.

For developing countries, such as Malaysia, OMC offers prosperity in sustainability. Economically, OMC is cost efficient as it consumes less build/assemble time. Due to control manufacturing OMC follows a minimalist waste strategy [40]. The monitored production line of OMC components reduce environmental carbon footprints and energy consumption, which offsets the negative effects of conventional construction [42]. Socially, OMC enhances the safety of the workers, generates employment opportunities for the people in the local area, and enhances the provision of affordable houses to the needy people in Malaysia and other developing countries [43]. Table 1 identifies 22 OMABs and 3 OSFN factors gathered from the literature.

Based on the discussion shared above this study deduces the following hypotheses:

- Hypothesis 1 Resource availability Barriers (SN1) positively influences the Overall Sustainable Future Needs (OSFN).
- Hypothesis 2: Process management Barriers (SN2) positively influences the Overall Sustainable Future Needs (OSFN).

Table 1
Indicators and their corresponding coding systems for Independent and dependent constructs.

Construct	Type	Indicator	Indicator Code	References
Resource Availability Barrier (SN1)	Independent Variable (IDV)	Arguments on the lack of skilled Labor in OMC	RA_1	[14,18]
		Insufficient comprehension of OMC knowledge resources	RA_2	[26,27]
		Arguments suggesting there is a lack of design standards in OMC *	RA_3	[19,44]
		Lack of manufacturing supplies to fulfill OMC orders	RA_4	[28,29]
		Claims that governmental Incentives are insufficient for OMC against traditional construction methods	RA_5	[45,46]
		Claims that governmental Initiative support is insufficient *	RA_6	[20,27]
Process Management Barrier (SN2)	IDV	Design phase management in OMC is poor	PMF_1	[13,47]
		Lack of maintenance methods in OMC	PMF_2	[30,31]
		Impossible renovation capabilities	PMF_3	[48,49]
		Lack of quality management in OMC	PMF_4	[13,50]
		Impossible stocks control ability in OMC	PMF_5	[21,51]
		Failure in team collaboration	PMF_6	[16,32]
		Arguments that Innovative customisation imposes several limitations in post construction processes	PMF_7	[52,53]
		Redesigning process imposes hurdles in OMC *	PMF_8	[27,30]
		Claims that procurement system is poor in OMC	PMF_9	[22,54]
		Claims that design Integration is impossible in OMC	PMF_10	[27,42]
Issues and Perception Barrier (SN3)	IDV	Existence of negative social perception among OMC stakeholders	IPF_1	[21,33]
		The concern that fragmentation associated with OMC will add more to the cost in transportation	IPF_2	[34,35]
		Claims that design complications associated with OMC are more than traditional construction *	IPF_3	[23,50]
		Existence of complex documentary weightage/score mechanism using traditional construction simultaneously with OMC in Malaysia	IPF_4	[30,55]
		Claims that un-controlled carbon emissions in OMC poses threats to environment *	IPF_5	[24,56]
		Fear of stakeholder investment in OMC	IPF_6	[25,36]
Overall Sustainable Future Needs (OSFN)	Dependent Variable (DV)	Economic (i.e., Integrating a OMC cost measurement platform to emerging technology)	FNF_1	[40,41]
		Social (i.e., Development of an integrated OMC time measurement approach with a perspective against traditional construction method)	FNF_2	[27,43]
		Environmental (i.e., Developing a OMC carbon emission measurement technology (CEMT) integrated with an emerging construction technology platform)	FNF_3	[42,43]

* Elements added as a part of pilot survey to satisfy the comments of industry/academic experts.

- Hypothesis 3 Issues and perceptions Barriers (SN3) positively influences the Overall Sustainable Future Needs (OSFN).

3. Research methodology

This study follows a three-stage approach, outlined in Fig. 1. The stages included are (1) Conducting an extensive literature review to pinpoint challenges associated with adopting OMC methods OMABs; (2) Developing a questionnaire to gauge the importance of overcoming identified challenges for achieving OSFN; and (3) Correlating OMABs and OSFN as a mathematically validated PLS-SEM model in terms of residential projects.

3.1. First stage: An extensive literature review

Conducting a comprehensive review aimed at categorising the model's constructs and indicators involved an exhaustive search for sustainable OMC. This thorough investigation utilised various internet databases, including Google Scholar, Scopus and Web of Science. Specific keywords and their combinations, such as 'Offsite modular Construction,' 'Barriers in Offsite modular Construction,' 'Malaysia,' 'Sustainability,' 'Sustainable Construction,' and 'Developing Countries,' were employed during the search. The primary objective of this review was to meticulously identify and amalgamate all pertinent research findings related to the designated subject matter.

Conducting a thorough examination of the current body of literature, the scholars endeavoured to comprehensively explore, scrutinise, and integrate research findings. This endeavour encompassed the acquisition, refining, and classification of data at various junctures. In the pursuit of constructing our theoretical framework, it became imperative to embark upon a crucial measure aimed at extracting the OMABs. To develop our theoretical model, a meticulous examination of the data was undertaken, compelling the need to reduce the influx of information through careful selection, simplification, and extraction of pertinent data and information. A careful selection process ensured the exclusion of redundant elements and unnecessary studies within the researched subjects. Examining OMABs over 14 years, from 2009 to 2023, provided a comprehensive understanding of the investigations. In the exploration of scholarly works Saad et al. highlighted the utility of this methodology in conducting a thorough literature review [14]. Illustrated in Fig. 2 is the theoretical model underpinning the coding system for the present study.

3.2. Second stage: Developing the questionnaire survey

Focusing on residential projects within Malaysia, an emerging nation, the survey questionnaire was designed to investigate how overcoming OMABs influences the attainment of OSFN. The questionnaire consists of four principal segments, encompassing (1) an overview of the demographic characteristics of the respondents; (2) structured questions with predetermined responses, exploring the respondents' perspectives on the influences of OMABs to attain OSFN; (3) structured questions to assess the respondents' opinions on environmental, social, and economic aspects of OSFN; and (4) allowing respondents to identify any significant barriers they perceive in the pursuit of OSFN using an open-ended inquiry. The participants assessed the OMABs and OSFN, drawing upon their expertise and understanding, employing a five optioned Likert scale for evaluation. This method has been commonly used in many previous studies such as Hannan et al [57].

3.2.1. Pilot test for the study

After initiating a preliminary investigation, a pilot study appraised the questionnaire's effectiveness, consistency, and thoroughness [58]. Following the investigation by Abdul et al., the commencement of a pilot study is essential, underscoring the need to demonstrate the achievement of the study's objectives using the selected methodology [59]. At the outset, adhering to the prescribed minimum of 10 participants for a pilot study [58], a pilot questionnaire was crafted and distributed among 20 participants, encompassing 15 experts from the construction sector and 5 scholars with a decade of academic experience. In the course of this study, participants critically examined question phrasing, identified issues in the questions, validated the survey's OMABs and OSFN factors, and offered valuable feedback. Following the valuable input provided by the 20 experts, certain inquiries underwent restructuring in alignment with the suggested proposals. These changes are identified in Table 1.

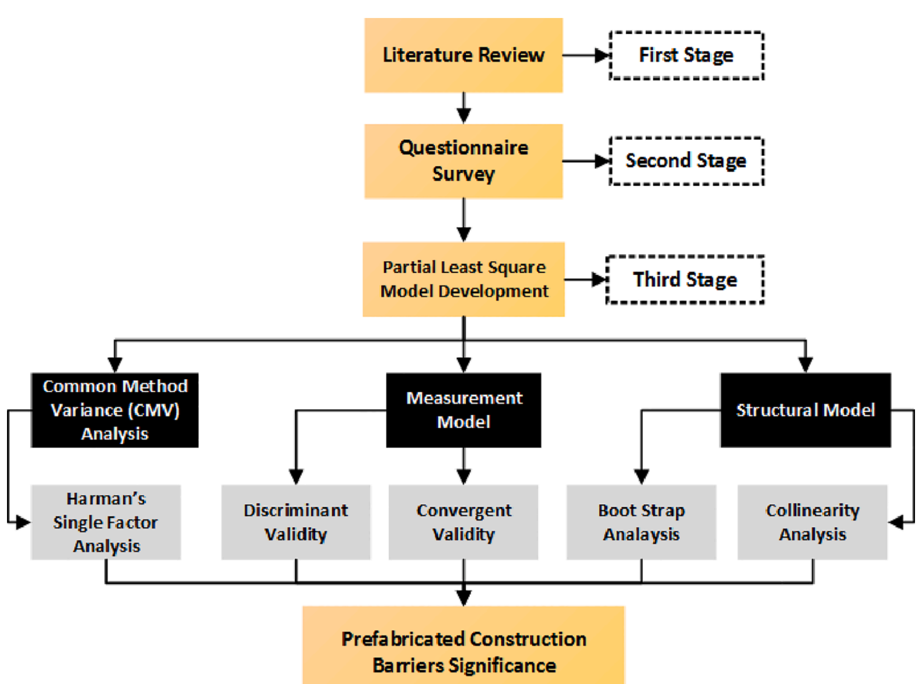

Fig. 1. Schematic representation of the study's three-staged research flowchart.

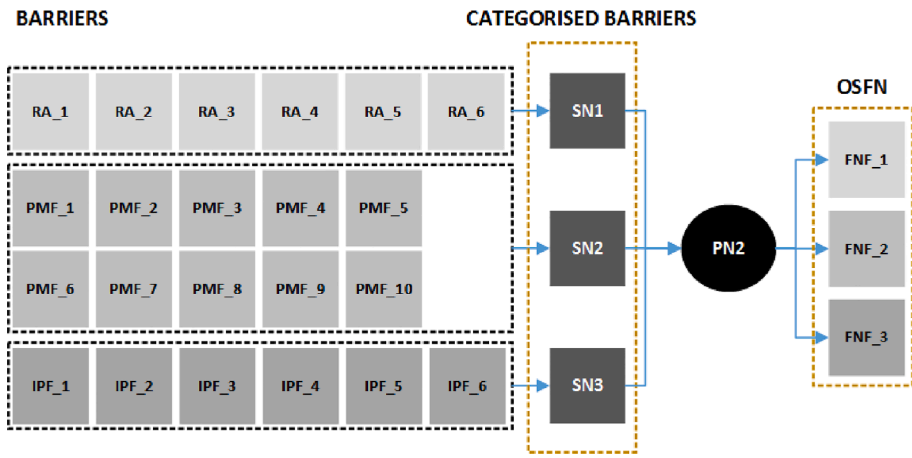

Fig. 2. The coding system of the study as depicted by the theoretical model.

3.2.2. *Reliability and consistency of responses*

Ensuring the uniformity of the pilot questionnaire involves employing the Cronbach's alpha coefficient, an evaluative metric for gauging its reliability [60]. To guarantee the steadfastness of respondents' assessments, specifically in appraising the impact of addressing OMABs and OSFN factors within housing initiatives, the reliability of the Likert scales measurement techniques is ascertained through this calculation.

Illustrating the Cronbach alpha coefficient is Equation (1), wherein the total number of barriers is denoted by (K), the variance in the current sample for respondents is represented by (S^2i), and the summation of variance for respondents is expressed as (S^2 sum).

$$\text{Cronbach alpha coefficient}\,(\alpha) = \left(\frac{K}{K+1}\right)\left[1 - \frac{\sum S^2 i}{S^2 Sum}\right] \tag{1}$$

Indicative of a commendable level of consistency, the value for the overall Cronbach's alpha coefficient within the pilot sample was 0.91, as emphasised by Keinbar et al [9].

3.2.3. *Questionnaire target population*

Derived from the criteria delineated by Keinbar et al. [9], the selection of participants involved the application of two specific conditions: a requisite for individuals to hold a construction project management or civil engineering or degree (Criterion 1), along with an imperative necessitating a practical experience of at least 5 years (Criterion 2).

3.2.4. *Sample size selection*

Given the nascent status of OMC within the Malaysian context, an approach grounded in random probability sampling was adopted for this investigation [14]. This methodology ensured that experts across Perak and Selangor were afforded an equitable opportunity for selection. Its application aimed at facilitating the acquisition of responses that are both dependable and precise by the authors. Utilising the dataset furnished by the Construction Industry Development Board (CIDB), one observes a populace of 23,714 stakeholders involved in prefabrication [61]. With a 5 % margin of error and a confidence level of 92.5 %, accounting for a response distribution of 50 %, the application of the Glenn Israel method yields a determined sample size of 314 responses as identified and located by GIS via CIDBs portal in Fig. 3 [62].

Within this investigation, structural equation modelling (SEM) served as the employed analytical method. According to Ammad et al. a minimum of 100 cases is imperative for a robust dataset, i.e. convenient sampling [63]; however, our collection surpassed this requirement with 314 cases, affirming its suitability for the chosen methodological approach. In the pursuit of data acquisition, an electronic survey was sent to chosen respondents in the Perak and Selangor regions of Malaysia meeting the predefined inclusion criteria. Out of 510 questionnaires disseminated, 319 valid responses were received, achieving a 62.5 % response rate, surpassing the specified minimum threshold for acceptability.

3.2.5. *Profiles of respondents*

Sourced from a diverse assembly of professionals actively engaged in Malaysian construction industry, the demographic particulars of the participants are meticulously laid out in Table 2. Based on the presented dataset, it is evident that a significant portion of participants possessed an experience level of fewer than 10 years. A notable number were engineering professionals. The majority favoured offsite modular residential projects, though not all were exclusively experienced in this

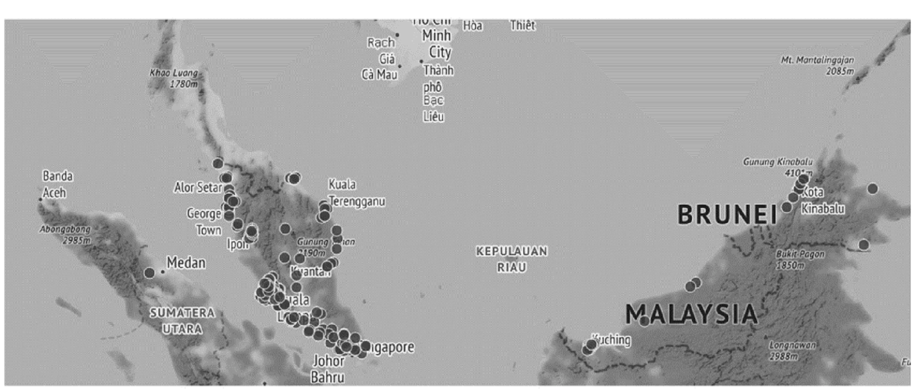

Fig. 3. Malaysian offsite modular stakeholders GIS based locations extracted from the CIDB portal.

Table 2
Respondent demographics.

Question	Demographics	Frequency	Percentage
1	**Level of Education**		
1.1.	Diploma/Advanced Diploma	163	51.9
1.2.	Bachelor's Degree/ Professional Qualification	87	27.7
1.3.	Master's Degree/PhD Degree	64	20.4
1.4.	Others	0	0
2	**Position at Organisation**		
2.1.	Project Director	26	8.3
2.2.	Professional Technologist	89	28.3
2.3.	Engineer	157	50.0
2.4.	Professor/ Lecturer	42	13.4
3	**Construction Industry Experience**		
3.1.	1 to 5 Years	55	17.5
3.2.	6 to 10 Years	131	41.7
3.3.	11 to 15 Years	85	27.1
3.4.	More than 15 Years	43	13.7
4	**Type of Organisation**		
4.1.	Public Organisation	262	83.4
4.2.	Private Organisation	48	15.3
4.3.	Non-Governmental Organisation (NGO)	4	1.3
4.4.	None	0	0
5	**Employees in Organisation**		
5.1.	1 to 10 Employees	0	0.0
5.2.	11 to 20 Employees	0	0.0
5.3.	21 to 30 Employees	33	10.5
5.5.	More than 30 Employees	281	89.5
6	**Offsite modular Residential Projects conducted in the last 3 years**		
6.1.	1 to 10 Projects	162	51.6
6.2.	11 to 20 Projects	51	16.2
6.3.	More than 20 Projects	6	1.9
6.4.	None	95	30.3
7	**Work volume in the last 3 years (USD)**		
7.1.	Less than $2 Million	151	48.1
7.2.	$2 Million – less than $4 million	61	19.4
7.3.	$4 million – less than $8 million	78	24.8
7.4.	$8 million – less than $10 million	0	0.0
7.5.	More than $10 million	24	7.6

area. This is noteworthy, given the unconventional use of OMC in this context. Therefore, the scrutiny enlisted adept individuals from the domains of construction-commercial. For the study an informed consent was obtained from all participants at the stage of questionnaire distribution, and their confidentiality was ensured in accordance with ethical guidelines.

3.3. Third stage: Developing the PLS-SEM

Overcoming barriers to prefabrication adoption in residential projects is the central focus of this study, exploring its significant impacts. Reinforcing the prerequisite, OMC adoption and OSFN are the primary subjects under investigation, with a scientific methodology employed to assess their interconnection. In addition, developmental and contemplative factors, derived from existing literature, were incorporated into the investigation to authenticate the proposed theoretical framework. Employing the prevalent statistical method of PLS-SEM, investigators analysed the interconnectedness among latent variables in a structural equation model to achieve study objectives, including the validation of the proposed theoretical framework [63].

With enhanced flexibility compared to covariance-based structural equation modeling (CB-SEM), PLS-SEM was chosen for this study, providing a methodologically advanced statistical foundation for evaluating diverse factors and ensuring precision in predictions, along with the effective reallocation of experimental outliers [64]. Distributional assumptions aside, CB-SEM, unlike PLS-SEM, generally demonstrates increased sensitivity to sample size [64]. At the crux of the data's foundational framework, the PLS-SEM technique finds its relevance in studies that focus on forecasting outcomes rather than evaluating hypotheses. PLS-SEM uses bootstrapping procedures to determine path coefficients and p-values, which makes it possible to obtain accurate results even with a limited number of cases (e. g., below 100). Confirmatory factor analysis (CFA) is the initial step in the two-stage process of PLS-SEM, a method employed for validation. Here, the measured indicators serve to represent the relevant constructs in the validation of the measurement model [65]. In the subsequent step, path analysis is employed at the outset to test research hypotheses, with the formulation of the structural model following suit.

3.3.1. Reliability testing of PLS-SEM model

In PLS-SEM model the indicator reliability (IR) is assessed through outer loadings of the indicators on their latent constructs. Loadings above 0.70 are preferred, though values as low as 0.40 can be acceptable in exploratory models, whereas the composite reliability (CR) measures internal consistency of the construct, with values between 0.70 and 0.95 indicating good reliability.

3.3.2. Validity testing

The convergent validity in PLS-SEM is evaluated using Average Variance Extracted (AVE), which reflects the average variance shared between a construct and its indicators. An AVE value above 0.50 suggests adequate convergent validity. While, the discriminant validity is assessed using the Fornell-Larcker Criterion and HTMT ratio. For Fornell-Larcker Criterion square root of the AVE for each construct should be greater than the correlations with other constructs, while for HTMT ratio values below 0.85 (or 0.90) suggest discriminant validity.

3.3.3. Structural model evaluation

The SEM in PLS is evaluated using (1) Collinearity (VIF), where variance inflation factor (VIF) should be below 5 to avoid multicollinearity, (2) Path Coefficients, where significance and strength of relationships between constructs are tested using bootstrapping for t-values and p-values, (3) R^2, which indicates the explanatory power of endogenous constructs, showing how well the model explains the variance in the dependent variables, (4) Predictive Relevance (Q^2), which utilises blindfolding, Q^2 values above 0 suggest the model has predictive relevance.

4. Results

4.1. First order measurement model construct

Convergent and discriminant validity play pivotal roles in evaluating the measurement model. Emphasising the significance of construct alignment, it becomes essential to estimate both types of validities to identify potential distinctions. For the assessment of convergence, a thorough analysis of the average variance extracted (AVE) [66], composite reliability [67], Cronbach's alpha [68], and outer loading is imperative [69]. Fornell and Larker's criterion takes precedence in addressing discriminant validity within this framework, with the secondary criterion specifically focused on cross-loading [70].

Initiating with the assessment of outer loadings, which gauges interconnections amongst the contributions made by each indicator to its designated construct, Ammad et al. advocate for an acceptable outer loading limit of 0.50 [63]. This limit falls within the range of 0.40 to 0.70 [71], reflecting the inherent variation in indicators. In Fig. 4, the outer loadings for all variables in the modified measurement model are illustrated, while the corresponding values in the first model are presented in Table 3. In accordance with the study's findings, outer loadings, excluding RA_1, PMF_3, and PMF_10 were considered suboptimal. The relevant constructs influence diminished as outer loading factors measured less than 0.5 [71]. Consequently, these indicators were excluded from the starting measurement model. The elimination of the identified variables necessitated a re-assessment of the model's overall structure.

At the core of variable measurement lies the assessment of coherence

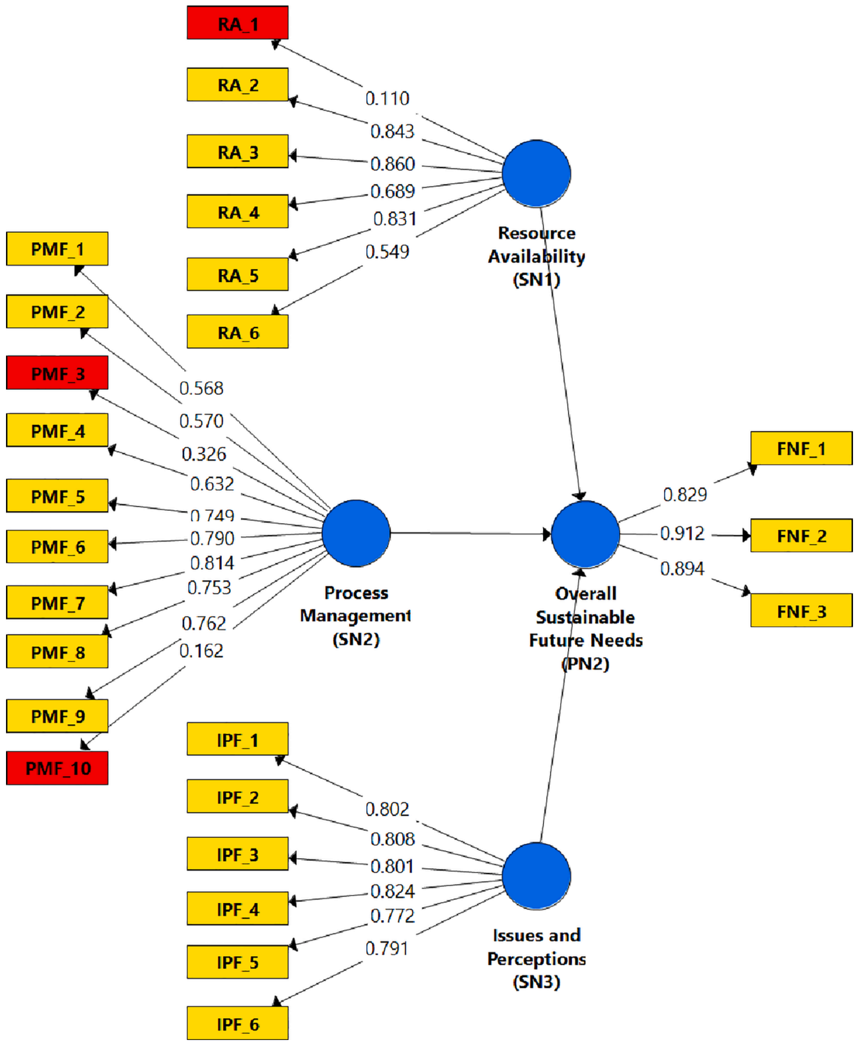

Fig. 4. Order measurement model with outer loading values for offsite modular construction adoption barriers.

through the Cronbach alpha, emphasising the coefficient of consistency. To ensure alignment with composite reliability, a critical threshold surpassing 0.7 is imperative, mitigating concerns about Cronbach's alpha performance [68,71]. The conditions defined are met by the variables of structural equation model (SEM) in Table 3.

In response to the limitations posed by Cronbach's alpha, which gauges sensitivity to various factors, an evaluation of composite reliability was conducted. Achieving acceptance in this analysis necessitates a composite reliability threshold exceeding 0.7 [67,71]. A positive demonstration by the variables of SEM is illustrated in Table 3.

Average Variance Extracted (AVE) serves as a customary metric for evaluating the congruence credibility of the model's constructs, representing a commendable practice. Values surpassing 0.50 are deemed satisfactory [71], a further affirmation supported by the positive values for AVE in the discussed SEM is outlined in Table 3.

Upon meeting the prescribed standards, discriminant validity is established when the construct diverges suitably from other constructs. Discriminant validity is applied to ensure the safeguarding of the distinctiveness and independence of each construct within Partial Least Squares [64]. At the outset, this guarantees the model's ability to gain insights missed by other constructs. Commencing with an analysis rooted in Fornell and Larcker's criteria, the scrutiny unfolds in exploring the correlation between a construct and the square root of its AVE [66]. To gauge discriminant validity, two distinct methods present themselves: the cross-loading criterion and Fornell Larcker's criterion [70]. Under Fornell Larcker's criterion, a prerequisite for validity emerges: the relationship between the constructs should not surpass the square root of the AVE of the construct [72].

In accordance with the provided model, the discernment validity is effectively showcased through the results depicted in Table 4. In assessing construct validity, it is imperative to ensure that, on a given row, the loading value of each indicator, coupled with its corresponding construct, surpasses the loading value of the alternative construct. This criterion is effectively employed through the cross-loading analysis, highlighting the necessity for discerning relationships between indicators and constructs. Table 5 presents Cross loadings results, confirming significant singularity for each construct, underscoring study implications.

4.2. Second order measurement model construct

In delineating secondary-order constructs, primary constructs, depicted as autonomous, assume a central role. OMABs, prominently featuring a formative construct, have the OSFN at its core as a reflective construct. Evaluating the importance of individual first-order constructs employed the bootstrap method [73]. Predictions of closely correlated indicators are rare in formative measurement models. The collinear nature among significant formative factors gives rise to a pertinent issue [71,73].

Setting a maximum threshold value of 5, the evaluation of

Table 3
Construct reliability and validity tests for the structural equation model.

Latent Variables	Items	Outer Loadings		Composite Reliability	Cronbach's Alpha	Average Variance Extracted (AVE)
		Initial Model Values	Modified Model Values			
SN1	RA_1	0.11	**Deleted**	0.914	0.816	0.586
	RA_2	0.843	0.843			
	RA_3	0.86	0.859			
	RA_4	0.689	0.697			
	RA_5	0.831	0.835			
	RA_6	0.549	0.545			
SN2	PMF_1	0.568	0.545	0.873	0.867	0.581
	PMF_2	0.57	0.596			
	PMF_3	0.326	**Deleted**			
	PMF_4	0.632	0.64			
	PMF_5	0.749	0.741			
	PMF_6	0.79	0.786			
	PMF_7	0.814	0.81			
	PMF_8	0.753	0.748			
	PMF_9	0.762	0.744			
	PMF_10	0.162	**Deleted**			
SN3	IPF_1	0.802	0.802	0.914	0.888	0.640
	IPF_2	0.808	0.808			
	IPF_3	0.801	0.801			
	IPF_4	0.824	0.824			
	IPF_5	0.772	0.772			
	IPF_6	0.791	0.791			
PN2	FNF_1	0.829	0.828	0.911	0.855	0.773
	FNF_2	0.912	0.912			
	FNF_3	0.894	0.895			

Table 4
Fornell-Larcker's discriminant validity and construct correlation.

Constructs	SN3	PN2	SN2	SN1
SN3	0.8			
PN2	0.555	0.879		
SN2	0.616	0.402	0.707	
SN1	0.522	0.22	0.686	0.766

Table 5
Assessing discriminant validity of indicators through cross loadings.

Construct/Indicators	SN3	PN2	SN2	SN1
FNF_1	0.381	0.828	0.301	0.142
FNF_2	0.458	0.912	0.316	0.16
FNF_3	0.589	0.895	0.421	0.257
IPF_1	0.802	0.433	0.469	0.404
IPF_2	0.808	0.391	0.495	0.41
IPF_3	0.801	0.368	0.475	0.375
IPF_4	0.824	0.451	0.54	0.476
IPF_5	0.772	0.487	0.48	0.334
IPF_6	0.791	0.502	0.491	0.493
PMF_1	0.104	0.075	0.545	0.42
PMF_2	0.696	0.484	0.596	0.403
PMF_4	0.38	0.158	0.64	0.522
PMF_5	0.27	0.209	0.741	0.472
PMF_6	0.353	0.234	0.786	0.587
PMF_7	0.404	0.231	0.81	0.562
PMF_8	0.35	0.225	0.748	0.477
PMF_9	0.361	0.236	0.744	0.463
RA_2	0.446	0.215	0.515	0.843
RA_3	0.461	0.15	0.528	0.859
RA_4	0.312	0.137	0.432	0.697
RA_5	0.539	0.196	0.622	0.835
RA_6	0.15	0.118	0.538	0.545

collinearity in the formative elements of the constructs within the model, especially during the application of PLS modeling, is efficiently conducted through the Variance Inflation Factor (VIF) [71].

In the context of OMC, three core subscales surface, covering resource availability, process management, and Issues and perceptions. Notably, a path coefficient β and p values alignment manifest within these domains. The model construct, depicting interrelations among its components, is aptly measured by the β statistical metric, offering valuable correlation insights. Acceptance hinges on path coefficients, with a requisite that the p-value threshold stays below 0.05 [71].

At the forefront of analysis are the VIF and path coefficient (β) values, with Table 6 and Fig. 5 providing visual representation. The examination reveals that the foremost β value, standing at 0.529, pertains to matters and viewpoints, while the least significant β value is marked at 0.204. Consequently, SN3 demonstrates a greater extent of variance and influence on OMABs, whereas SN1 exhibits the least variance and impact on OMABs. Indicating the autonomous role of these subdomains within the higher-order construct, the VIF values adhere to the prescribed threshold of 5.

4.3. *Structural equation model's path analysis*

In SEM, the path analysis investigates direct and indirect relationships among variables within a theoretical framework [74]. The primary analysis phase of SEM involves employing the structural model to understand interconnections among theoretical components. This method strategically positions logical constructs and concludes with path analysis, providing a comprehensive investigative flow in scholarly research [63].

Examining the adequacy of the model fit precedes the analysis of the structural model, which highlights the interconnections amongst the constructs [75]. The evaluation primarily centers on assessing overall model adequacy and conjectured parameter estimations. Following this, attention is given to determining the significance of the relationships, their direction, and the magnitude of their effects [76].

In the study, bootstrapping generated samples resembling the original dataset through random re-sampling [73]. The examination focused

Table 6
Bootstrapping second order reflective construct results.

Path	β	p − Values	Inner VIF
SN1 → PN2	0.204	<0.001	1.946
SN2 → PN2	0.216	<0.001	2.281
SN3 → PN2	0.529	<0.001	1.662

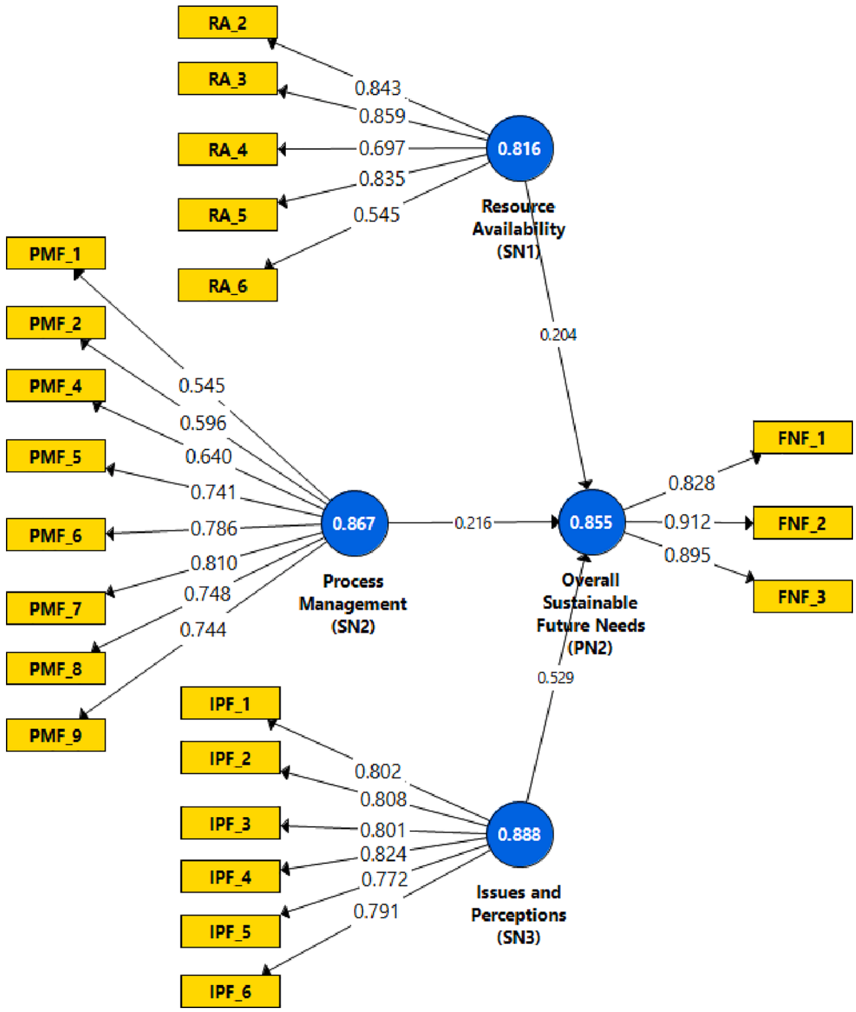

Fig. 5. Second order measurement model with outer construct loading values and Cronbach alpha values in latent/endogenous variables.

on the hypothesis within the framework illustrated in Fig. 4, centering the analysis on the hypothesis which is the impact of overcoming OMABs to achieve OSFN for residential projects. To evaluate the significance of the hypothesis, the study employed the bootstrapping method, taking into account statistical significance and dataset reliability [71].

For the bootstrapping method applied, $\beta_{SN1\rightarrow PN2} = 0.204$, $\beta_{SN2\rightarrow PN2} = 0.216$, and $\beta_{SN3\rightarrow PN2} = 0.529$ highlight the statistically advantageous and noteworthy impact of addressing OMABs on OSFN, depicted by Fig. 5 and Table 6.

4.3.1. *SEM's explanatory power with R^2*

The explanatory power of the structural model denotes its ability to account for the variance in the dependent variable. The coefficient of determination (R^2) reflects the degree to which the independent variables explain the variance in the dependent variable, thereby indicating the explanatory power of the structural model from 0 to 1 [71]. The efficacy of the structural model lies in its ability to gauge the variation of the dependent parameter it elucidates. Through the PLS algorithm, numerous squared correlations are computed for the dependent element. Elevated R^2 value signifies enhanced predictability, indicating how well the model captures variability in the data. For a specific endogenous variable in SEM, the explanatory power is quantified by its R^2 value as follows:

$$R^2 = 1 - \frac{\text{Variance of the residuals (unexplained variance)}}{\text{Total variance}} \tag{2}$$

For this study, an R^2 value of 0.336 for the endogenous latent variable OSFN in SEM indicates that about 33.6 % of its variance is explained by the included predictors, which according to Hair et al. reflects a moderate level of explanatory power as depicted in Table 7 [71].

4.3.2. *SEM's predictive relevance (Q^2)*

Predictive relevance (Q^2) in SEM measures the model's predictive power by assessing how well it forecasts endogenous variables based on exogenous ones. It is calculated through cross-validation methods, showing the proportion of variance predicted beyond the sample data. Predictive relevance's importance lies in validating model predictability, aiding in generalisability and decision-making regarding model reliability. For the given data in Table 8, the Q^2 value of 0.249 (greater than zero) reinforces study's SEM's reliability of predicting dependent variable from an independent variable beyond sample data. Thus, based on Hair et al., the SEM demonstrates notable predictive relevance [71]. The general formula for Q^2 is as following, where Y_{actual}, $Y_{predicted}$, and Y_{Mean} refer to the actual, predicted and mean values of the endogenous constructs.

Table 7
The coefficient of determination (R^2) values for SEM.

Latent Variable (Endogenous)	$0 < R^2 < 1$	Adjusted R^2	Size Classification
OSFN	0.336	0.329	Moderate

Table 8
Predictive relevance (Q^2) values for SEM.

Latent Variable (Endogenous)	Sum of squares of observations (SSO)	Sum of squared errors (SSE)	$Q^2 = $ (1-SSE/SSO)
OSFN	133.743	100.489	0.249

$$Q^2 = 1 - \frac{\sum (Y_{\text{actual}} - Y_{\text{predicted}})^2}{\sum (Y_{\text{actual}} - Y_{\text{Mean}})^2} \tag{3}$$

5. Discussions

5.1. Resource availability barriers

Resource availability barrier in the OMC industry denote limitations in access, allocation, and management of essential materials, manpower, equipment, and technology throughout the construction process [77]. In our SEM analysis, the resource availability barrier scored a path coefficient of $\beta = 0.204$, ranking third. This is in line with Saad et al., where they note that knowledge resources and resource management of OMCs are critical in developing nations [27]. This suggests a notable impact on OMC efficiency, highlighting the need for strategic resource management in projects. OMC demands coordinated logistics and skilled labour for both on-site assembly and component production, distinguishing it from traditional construction processes [14].

Developing countries can tackle the resource availability challenge in OMC by investing in infrastructure, building supplier partnerships, training the workforce, and using technology to optimise resource use [27]. This enhances construction efficiency and promotes sustainable development. A study by Saad et al. underscores the significance of comprehending OMC knowledge resources for successful adoption within the MCI, emphasising the critical role of understanding in facilitating OMC implementation effectively in developing countries [27]. Lu et al also note an insufficient comprehension of OMC knowledge resources among the identified 24 risks inhibiting OMC implementation in Asian countries, underscoring the pivotal role of government in addressing such challenges through appropriate policies and regulations [26]. Azman et al highlight the challenge of the lack of manufacturing supplies to fulfill OMC orders in MCI, where the number of OMC manufacturing plants surged from 21 in 2002 to 143 factories in 2010, with precast concrete being the most favored system, but saw a slight decline in coming years [28,78]. This statement is supported by Rashidi et al., who noted a persistent lack of manufacturing supplies to fulfill OMC orders, particularly significant in 2020 to 2023, emphasising the imperative for enhanced productivity and innovation through the adoption of OMC in MCI to address these challenges and improve overall efficiency, which is in line with our study [29,79]. Nawi et al. assert that despite governmental support, few projects in MCI utilise OMC, citing traditional barriers and poor stakeholder integration as primary reasons [45]. Din et al. contradict with Nawi et al. and state that governmental incentives fall short in supporting OMC compared to traditional methods in developing countries like Malaysia. Despite the industry's embrace of OMC for better quality, productivity, and risk reduction, the chronology of OMC adoption reveals past challenges and foreign system limitations [46]. Furthermore, Johan et al. assert that governmental initiative support for sustainable elements in construction industries is insufficient [80]. In addition, organisational information communication technology (ICT) uptake remains a challenge for OMC adoption in developing countries [20].

5.2. Process management barriers

Process management in the context of OMC involves coordinating and controlling various aspects of a construction project to achieve a sustainable outcome within the construction life cycle [18]. Based on the SEM analysis from this study the process management barrier ranked second with a path coefficient of $\beta = 0.216$. This suggests that effective coordination and control of project aspects are crucial for achieving sustainable outcomes within the construction life cycle. Addressing process management challenges is essential to enhance project efficiency and minimise risks in OMC projects.

To reinforce the significance of process management for developing countries in offsite modular construction, the findings of this study align with Mohsin et al. emphasise the critical role of leadership in total quality management (TQM) for OMC projects, while Xie et al. propose a case-based reasoning (CBR) model to enhance decision-making in the design phase [13,47]. Similarly, Ismail et al.'s integration of defect diagnosis and BIM addresses maintenance challenges in Malaysian prefab buildings, aligning with Wang et al.'s focus on stochastic resource scheduling and machine maintenance for optimised OMC production systems. Together, these studies highlight the importance of effective process management throughout the lifecycle of offsite modular construction projects [30,31].

In terms of enhancing quality, Li et al. in their study highlight a need for Radio Frequency Identification (RFID) and Global Positioning System (GPS) technology in OMC component transport. Utilising these will enable stakeholders to track component movement with improved logistics efficiency in OMC industry [50]. Chen et al.'s study highlights key factors influencing construction time performance in offsite modular construction, including project technology system, project delivery system, and effective management of project complexity. Ahmed et al.'s study with 126 Pakistani prefab-stakeholders extends this focus to failures in team collaboration, emphasising the critical role of process management in achieving sustainability performance. These findings collectively underscore the importance of process management in addressing collaboration challenges and optimising project performance in offsite modular construction [16,32].

Piroozfar et al. and Bischof et al. address the limitations imposed by innovative customisation in post-construction processes in offsite modular construction. Piroozfar et al. propose a solution that utilises the principles of configuration and BIM, demonstrating potential improvements through a case study of a customisable façade system. In line with this, Bischof et al. propose a value-driven approach that combines traditional construction and digital fabrication processes to tackle environmental sustainability challenges. Together, these studies provide complementary insights and offer different perspectives on addressing the limitations of innovative customisation in offsite modular construction, emphasising the importance of both configuration and environmental sustainability considerations [52,53].

Both Ariffin et al. and Chen et al. state the importance of process management in offsite modular construction and propose solutions to address the poor procurement system. Ariffin et al. suggest Separation of IBS from Main Contract, Partnering, and Integrated Project Delivery (IPD), while Chen et al. offer a mathematical model and genetic algorithm for optimised procurement, resulting in reduced construction duration and cost savings. These studies reinforce the significance of effective process management in improving procurement practices in offsite modular construction [22,54]. Saad et al. adds to this and advocates for increasing skilled labor, introducing renovation capabilities, and addressing negative social perceptions, while Ismail et al. suggest integrating defect diagnosis and BIM to enhance maintenance management practices and improve knowledge transfer of OMC component defects in Malaysian prefab buildings [27,30].

5.3. Issues and perceptions barriers

In the scenario of developing countries OMC adoption, the "Issues and perceptions" refer to an array of barriers as included in the Literature Review Table. The barrier ranked first with a path coefficient of $\beta = 0.529$. This value indicates a critical influence of identified indicators in SEM, i.e., perceptions on social/finances, complex design/

documentation and carbon emissions affirming the given concern of OMC adoption in developing countries. This aligns with Riduan et al.'s emphasis on improving contractor satisfaction and Izatul et al.'s focus on better communication and education in modular construction [21,33]. Nasrun et al.'s recommendation for integrated design to reduce fragmentation and transportation costs also supports our findings [34].

Riduan et al. suggest boosting contractor satisfaction and integrating sustainability in IBS implementation to improve stakeholder perceptions and project competitiveness. This complements Izatul et al.'s proposal of enhancing communication and education to address similar challenges in offsite modular construction projects [21,33]. Nasrun et al. proposed an integrated design and construction approach to minimise fragmentation gaps, potentially mitigating transportation expenses. Also, Tezel et al. recommends enhancing stakeholder collaboration and optimising logistics strategies to mitigate potential transportation cost escalations [34,35].

Li et al. suggests integrating defect diagnosis and BIM to address design complications in OMC, aim to enhance maintenance management practices and mitigate repeated defects. Wasana et al. stresses on adoption of panelised OMC method to mitigate design complications, improving time and quality performance [23,50]. Ismail et al. recommends integrating defect diagnosis with BIM to enhance maintenance management of OMC in developing countries. This matches with Mohammad et al. research of unifying assessment framework integrating traditional and offsite modular elements to mitigate barriers, reduce costs, and ensure quality of life [30,55].

Liu et al.'s solution introduces a real-time carbon emission monitoring system for OMC, integrating cyber-physical systems to address uncontrolled carbon emissions, offering a timely and proactive means to monitor environmental impacts. Xiang et al. proposes a micro-level transportation carbon emissions calculation method, presenting reliable data for optimising transportation efficiency [24,56]. Zhou et al. solution includes an evaluation index system and quantitative model, facilitating decision-making for the distribution of external benefits. Zairul et al. study introduces effective risk assessment and communication strategies, emphasising sustainability of OMC to strengthen stakeholder confidence and encourage investment [25,36].

5.4. Overall sustainable future needs

Findings reveal that addressing the OMABs contributes to 33.6 % of the PN2 for residential projects. Emphasising the significance of addressing this barrier is crucial to achieving a high degree of sustainability in these projects. Moreover, the study's average β value of 0.316 suggests that dealing with OMABs is strongly linked with OSFN, which states that for each unit increase in the firm's potential to address the OMABs, there is a correlation of 0.316 increase in the OSFN of construction projects. Similarly, a consistency of study's outcomes is linked with OSFN. The objective of this section has been achieved, and the results are in line with earlier research, indicating the critical importance of environmental, social, and economic objectives in sustainable construction activities [81]. The OSFN of a project is significantly affected by these factors.

5.5. Proposed strategies for overcoming OMC barriers

The technological readiness and infrastructure development in developing countries are critical in the application of OMC. High technological readiness enables the use of sophisticated tools such as BIM and automation that are crucial in design and production. On the other hand, low technological readiness leads to skill gaps and low efficiency in the implementation of the technology. Also, there is a need to have strong structures for production, movement of modular parts, and availability of utilities. Lack of infrastructure may result in time delays, cost implications, and poor quality of services. Therefore, better technology and structures greatly increase the effectiveness and effectiveness of OMC projects.

On the cultural level, the reluctance to change, the belief that products of OMCs are of lower quality, and the desire for unique designs may become an obstacle to the acceptance of OMCs. At the institutional level, there are challenges such as; policy challenges, lack of government support, and poor facilities. To make OMC an integral part of sustainable strategies, education campaigns, policy reforms and designs that can be adapted, are a need. The governments should alter the rules and policies, back OMC, and improve the infrastructure; the government and private sector can play a role in the advancement and application of OMC practices.

Past research lacked focus on addressing the challenges of OMABs and developing strategies to overcome these barriers to achieve OSFN in residential construction ventures. Considering this, the present study suggests a unified collection of methods and approaches essential to effectively address the complex network of challenges simultaneously. The proposed strategies are policy relevant because they involve the use of local resources, training of the workforce, and public–private partnerships in the developing countries.

1. *For resource availability barrier:* (1) Forge alliances with local suppliers to ensure a consistent supply of materials; (2) empowering local labor forces with the requisite skills, the dependency on specialised external resources can be minimised; (3) utilising alternative materials or construction techniques that are abundant locally can help circumvent resource shortages; (4) Facilitate technology transfer and knowledge-sharing initiatives to transfer best practices and expertise in prefab construction to local stakeholders
2. *For process management barrier:* (1) develop standardised processes and procedures for prefabrication projects, outlining clear steps from design to installation; (2) Implement a robust monitoring and evaluation system to track project progress, identify potential blockages, and address issues in a timely manner; (3) Develop comprehensive risk management strategies such as proactive planning for contingencies or regulatory challenges to achieve project timelines and budgets.
3. *For issues and perception barrier:* (1) Implement demonstration projects showcasing successful offsite modular construction initiatives in diverse settings within developing countries; (2) Establish knowledge sharing platforms dedicated to sharing best practices, case studies, and research findings related to offsite modular construction in developing countries; (3) Develop capacity building programs targeted at local construction firms and workers to enhance their skills and capabilities in offsite modular construction techniques; (4) Promoting supportive regulatory frameworks and incentives at the governmental level to promote the adoption of offsite modular construction methods.

5.6. Validation

Following the development of the statistical model, validation of the study's results was conducted. Within this framework, verification involves evaluating whether the method has effectively fulfilled its intended objective [82]. Consequently, the research findings were subjected to expert verification to assess the validity and authenticate the proposed structure. This step was taken to certify thorough, detailed, effective and impartial research results. A questionnaire survey was selected as the chosen method for validating the research outputs in this study. Shared with 20 experts who took part in the pilot test and showed curiosity for the topic. Using a Likert scale, respondents were requested to express their level of agreement with each question in the survey, aimed at managing the verification procedure. Designed to evaluate knowledge, resilience, and openness, the questionnaire aimed to identify areas requiring enhancement as well. Derived from previous studies, four questions were applied in the current study to evaluate the authenticity of the results.

The survey comprised two sections: open ended questions and closed ended questions. Respondents were encouraged to express their agreement levels for each verification pillar in the closed-ended questions, whereas they were encouraged to propose areas for improvement in the open-ended question. The five closed ended questions for verifications are as follows:

Q1. Is the study offering a rational and agreeable perspective in context of constraints associated with OMC adoption?

Q2. Are the strategies identified by the study for overpowering barriers to OMC adoption considered reasonable, acceptable, and applicable?

Q3. Does this study accurately establish the causal sequence between mastering OMABs and accomplishing OMC to attain OSFN?

Q4. Do the results presented in this study produce reliable and practical findings?

Q5. Does the OMC adoption model from this study apply in a general context?

6. Conclusion

The novelty and relevance of this study are evident from the fact that it has provided a solution to the acute housing and sustainability problems in the Malaysian construction industry through the implementation of OMC. Despite the benefits of OMC in terms of speed, cost and sustainability, the implementation of OMC in Malaysia is still limited, mainly due to the lack of extensive research and knowledge of the challenges. This study addresses this gap by developing a comprehensive list of 22 OMABs from a literature review and by collecting data from 314 experts in the Malaysian construction industry. The study, therefore, shows that there is a positive relationship between the elimination of these barriers and OSFN in terms of resource availability, process management, and perception-related factors. The policymakers and stakeholders can overcome these barriers if they focus on the use of local resources, improve the training of the workforce, simplify the OMC procedures, and increase the awareness through demonstration projects.

The conclusion derived from this study is relevant to other developing countries that experience similar challenges in the adoption of OMC. The effective applicability of framework to the other such depends on local economy, regulations, culture and technological access. This means if a country has regulatory support, accessible and high skill resources OMC adoption will be easier against those countries where the discussed are not available.

This research is useful as it offers practical recommendations and a validated SEM framework for increasing OMC use in Malaysia and other developing countries, which can help to improve construction sustainability and efficiency and support the achievement of international environmental objectives.

7. Limitations and future direction

Despite achieving all research objectives and contributing to both knowledge and practice, the study shares some limitations that present future research opportunities. First limitation is the study's geographical scope, i.e. questionnaire was distributed amongst the Peninsular (West) Malaysia and Malaysia (East) Borneo, but due to accessibility issues open ended validation survey only consisted of experts from Peninsular (West) Malaysia. It is recommended that future research should incorporate experts from Malaysia (East) Borneo. The second limitation is that the study used the sustainability theory; therefore, future research should use any other behavioral theories as they may produce a remarkable result that will depict a different version of the same research.

CRediT authorship contribution statement

Syed Saad: Writing – original draft, Visualization, Validation, Project administration, Data curation, Conceptualization. **Kumeel Rasheed:** Writing – review & editing, Software. **Syed Ammad:** Writing – original draft, Visualization, Validation, Project administration, Data curation, Conceptualization. **Muhammad Hasnain:** Visualization. **Habib Ullah:** Formal analysis. **Abdul Hannan Qureshi:** Data curation. **Aawag Mohsen Alawag:** Methodology, Investigation, Formal analysis. **Muhammad Altaf:** Visualization. **Touseef Sadiq:** Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study appreciates the contributions of all the authors and the generous resources provided by CECOS University and University of Agder.

References

[1] P. F. Rocha, N. O. Ferreira, F. Pimenta, and N. B. Pereira, "Impacts of Prefabrication in the Building Construction Industry," *Encyclopedia*, vol. 3, no. 1. MDPI, pp. 28–45, 2023. doi: 10.3390/encyclopedia3010003.

[2] CIOB, "Global Construction 2030 – Executive Summary," London, United Kingdom, 2015.

[3] S. J. Smith, *International Encyclopedia of Housing and Home*, 1st ed. Oxford, United Kingdom: Elsevier, 2012.

[4] Warwick A, Crosby R. Construction industry falling behind on housing. Australia: Master Builders Australia; 2023.

[5] W. Shaw, "Once In a Generation Response Needed to Address Housing Supply Crisis," *National Association of Realtors*. National Association of Realtors, 2021.

[6] Home Builders Federation, "HBF Report- Watt a Save," *www.hbf.co.uk*. HBF, London, United Kingdom, 2023.

[7] M. Elkaftangui and M. Basem, "Optimizing prefabricated construction techniques in UAE as a solution to shortage of middle-income housing," *MATEC Web of Conferences*, vol. 221. EDP Sciences, p. 1006, 2018. doi: 10.1051/matecconf/201822101006.

[8] P. Ghannad, Y.-C. Lee, and J. O. Choi, "Investigating Stakeholders' Perceptions of Feasibility and Implications of Modular Construction-Based Post-Disaster Reconstruction," *Modular and Offsite Construction (MOC) Summit Proceedings*. University of Alberta Libraries, pp. 504–513, 2019. doi: 10.29173/mocs132.

[9] A. H. Ali, A. F. Kineber, A. Elyamany, A. H. Ibrahim, and A. O. Daoud, "Identifying and assessing modular construction implementation barriers in developing nations for sustainable building development," *Sustain. Dev.*, vol. n/a, no. n/a, May 2023, doi: doi: 10.1002/sd.2589.

[10] S. Saad, S. Ammad, and K. Rasheed, *AI in Material Science: Revolutionizing Construction in the Age of Industry 4.0*. Boca Raton: CRC Press, 2024. doi: 10.1201/9781003438489.

[11] T. Rao and S. I. Mustapa, "A Review of Climate Economic Models in Malaysia," *Sustainability*, vol. 13, no. 1. MDPI, 2021. doi: 10.3390/su13010325.

[12] Kumar G, et al. Utilizing E-waste as a sustainable aggregate in concrete production: a review. Buildings Aug. 2024;14(8):2495. https://doi.org/10.3390/buildings14082495.

[13] Mohsen Alawag A, et al. Critical success factors influencing total quality management in industrialised building system: a case of Malaysian construction industry. Ain Shams Eng J 2023;14(2):101877. https://doi.org/10.1016/j.asej.2022.101877.

[14] Saad S, Alaloul WS, Ammad S, Qureshi AH. A qualitative conceptual framework to tackle skill shortages in offsite construction industry: a scientometric approach. Eng Constr Archit Manag Dec. 2022;29(10):3917–47. https://doi.org/10.1108/ECAM-04-2021-0287.

[15] S. R. M. Noor, R. Yunus, A. H. Abdullah, S. Nagapan, and S. M. S. S. Mazlan, "Insights into the adoption of lean management in Industrialised Building System (IBS) implementation: The drivers and challenges," *Int. J. Eng. Technol.*, vol. 7, no. 3.23 Special Issue 23, pp. 22–31, 2018, doi: 10.14419/ijet.v7i3.23.17253.

[16] Chen Y, Zhu D, Tian Z, Guo Q. Factors influencing construction time performance of prefabricated house building: a multi-case study. Habitat Int 2023;131:102731. https://doi.org/10.1016/j.habitatint.2022.102731.

[17] Hao JL, et al. Carbon emission reduction in prefabrication construction during materialization stage: a BIM-based life-cycle assessment approach. Sci Total Environ 2020;723. https://doi.org/10.1016/j.scitotenv.2020.137870.

[18] M. Arashpour, R. Wakefield, N. Blismas, and J. Minas, "Optimization of process integration and multi-skilled resource utilization in off-site construction," *Autom. Constr.*, vol. 50, no. C, pp. 72–80, 2015, doi: 10.1016/j.autcon.2014.12.002.

[19] Fateh MAM, Mohammad MF. Industrialized building system (IBS) provision in local and international standard form of contracts. J Constr Develop Countries 2017:67–80. https://doi.org/10.21315/jcdc2017.22.2.5.

[20] P. A. Soon Ern, N. Kasim, M. A. Nasid Masrom, and G. Kai Chen, "Overcoming ICT Barriers in IBS Management Process in Malaysia Construction Industry," in *MATEC Web of Conferences*, EDP Sciences, 2017, p. 3007. doi: 10.1051/matecconf/201710303007.

[21] I. laili Jabar, F. Ismail, and A. R. Abdul Aziz, "Stakeholder's Perception of Industrialized Building System (IBS) Implementation," *Asian J. Behav. Stud.*, vol. 3, no. 10, p. 159, 2018, doi: 10.21834/ajbes.v3i10.90.

[22] Chen G, et al. Optimal procurement strategy for off-site prefabricated components considering construction schedule and cost. Autom Constr 2023;147:104726. https://doi.org/10.1016/j.autcon.2022.104726.

[23] K. H. I. Wasana, S. Gunatilake, and M. F. F. Fasna, "Performance Comparison of Prefabricated Building Construction Projects vs. Traditional On-site Construction Projects," *2019 Moratuwa Engineering Research Conference (MERCon)*. IEEE, 2019. doi: 10.1109/mercon.2019.8818676.

[24] Xiang Y, Ma K, Mahamadu A-M, Florez-Perez L, Zhu K, Wu Y. Embodied carbon determination in the transportation stage of prefabricated constructions: A micro-level model using the bin-packing algorithm and modal analysis model. Energy Build 2023;279:112640. https://doi.org/10.1016/j.enbuild.2022.112640.

[25] Zhou J, Li Y, Ren D. Quantitative study on external benefits of prefabricated buildings: from perspectives of economy, environment, and society. Sustain Cities Soc 2022;86:104132. https://doi.org/10.1016/j.scs.2022.104132.

[26] Luo L-Z, Mao C, Shen L-Y, Li Z-D. Risk factors affecting practitioners' attitudes toward the implementation of an industrialized building system: a case study from China Risk factors affecting practitioners' attitudes toward the imple. Archit Manag Iss Archit Manag Iss Eng Constr Archit Manag 2015;22(6):669–91. https://doi.org/10.1108/ECAM-04-2014-0048.

[27] Saad S, Alaloul WS, Ammad S, Altaf M, Qureshi AH. Identification of critical success factors for the adoption of Industrialized Building System (IBS) in Malaysian construction industry. Ain Shams Eng J 2021;13(2):101547. https://doi.org/10.1016/j.asej.2021.06.031.

[28] M. N. A. Azman, M. S. S. Ahamad, T. A.Majid, and M. H. Hanafi, "Status of Industrialized Building System Manufacturing Plant in Malaysia," *Journal of Civil Engineering, Science and Technology*, vol. 2, no. 2. UNIMAS Publisher, pp. 8–16, 2011. doi: 10.33736/jcest.89.2011.

[29] Rashidi A, Ibrahim R. Industrialized construction chronology: the disputes and success factors for a resilient construction industry in Malaysia. Open Constr Build Technol J 2017;11(1):286–300. https://doi.org/10.2174/1874836801711010286.

[30] Ismail Z-A, Mutalib AA, Hamzah N. Case study to analyse problems and issues in IBS building maintenance. Int J Appl Eng Res 2016;11(1):226–32.

[31] Wang J, Liu H. Integrated optimization of stochastic resource scheduling and machine maintenance in prefabricated component production processes. Autom Constr 2023;154:105030. https://doi.org/10.1016/j.autcon.2023.105030.

[32] Ahmed W, et al. Analyzing the impact of environmental collaboration among supply chain stakeholders on a firm's sustainable performance. Oper Manag Res 2020;13(1–2):4–21. https://doi.org/10.1007/s12063-020-00152-1.

[33] R. Yunus, M. A. N. Masrom, A. H. Abdullah, and F. Mustakim, "Conceptual Model of Contractor Satisfaction in the Industrialized Building System (IBS) Implementation," *Applied Mechanics and Materials*, vol. 773. Trans Tech Publications, Ltd., pp. 828–833, 2015. doi: 10.4028/www.scientific.net/amm.773-774.828.

[34] M. N. Mohd Nasrun, L. Angela, A. Mohamed Nor Azhari, and M. K. Kamarul Anuar, "Fragmentation Issue in Malaysian Industrialised Building System (Ibs) Projects," *J. Eng. Sci. Technol.*, vol. 9, no. 1, pp. 97–106, 2014.

[35] Tezel A, Koskela L, Aziz Z. Current condition and future directions for lean construction in highways projects: a small and medium-sized enterprises (SMEs) perspective. Int J Proj Manag 2018;36(2):267–86. https://doi.org/10.1016/j.ijproman.2017.10.004.

[36] Zairul M. The recent trends on prefabricated buildings with circular economy (CE) approach. Clean Eng Technol 2021;4:100239. https://doi.org/10.1016/j.clet.2021.100239.

[37] Wuni IY, Shen GQ. Barriers to the adoption of modular integrated construction: systematic review and meta-analysis, integrated conceptual framework, and strategies. J Clean Prod Mar. 2020;249:119347. https://doi.org/10.1016/j.jclepro.2019.119347.

[38] Charef R, Morel J-C, Rakhshan K. Barriers to implementing the circular economy in the construction industry: a critical review. Sustainability Nov. 2021;13(23):12989. https://doi.org/10.3390/su132312989.

[39] Mostafa S, Kim KP, Tam VWY, Rahnamayiezekavat P. Exploring the status, benefits, barriers and opportunities of using BIM for advancing prefabrication practice. Int J Constr Manag Mar. 2020;20(2):146–56. https://doi.org/10.1080/15623599.2018.1484555.

[40] Du J, Zhang J, Castro-Lacouture D, Hu Y. Lean manufacturing applications in prefabricated construction projects. Autom Constr 2023;150:104790. https://doi.org/10.1016/j.autcon.2023.104790.

[41] Kumi L, Jeong J. Optimization model for selecting optimal prefabricated column design considering environmental impacts and costs using genetic algorithm. J Clean Prod 2023;417:137995. https://doi.org/10.1016/j.jclepro.2023.137995.

[42] Huang MQ, Chen XL, Ninić J, Bai Y, Zhang QB. A framework for integrating embodied carbon assessment and construction feasibility in prefabricated stations. Tunn Undergr Sp Technol 2023;132:104920. https://doi.org/10.1016/j.tust.2022.104920.

[43] Xu J, Zhang Q, Teng Y, Pan W. Integrating IoT and BIM for tracking and visualising embodied carbon of prefabricated buildings. Build Environ 2023;242:110492. https://doi.org/10.1016/j.buildenv.2023.110492.

[44] S. B. Namini, M. M. Meynagh, and Y. K. Vahed, "Developing IFC Standards for Implementing Industrialized Building System Components into BIM Applications," *Proc. 2012 Int. Conf. Constr. Proj. Manag. (ICCPM 2012), Dubai, 4-5 August, 2012*, no. September 2014, pp. 133–137, 2012.

[45] Nawi MNM, Lee A, Kamar KAM, Hamid ZA. Critical success factors for improving team integration in Industrialised Building System (IBS) construction projects: the Malaysian case. Malaysian Constr Res J 2012;10(1):44–62.

[46] M. I. Din, N. Bahri, M. A. Dzulkifly, M. R. Norman, K. A. M. Kamar, and Z. Abd Hamid, "The adoption of industrialised building system (IBS) construction in Malaysia: The history, policies, experiences and lesson learned," *2012 Proc. 29th Int. Symp. Autom. Robot. Constr. ISARC 2012*, vol. 1, 2012.

[47] Xie L, Wu S, Chen Y, Chang R, Chen X. A case-based reasoning approach for solving schedule delay problems in prefabricated construction projects. Autom Constr 2023;154:105028. https://doi.org/10.1016/j.autcon.2023.105028.

[48] Zanni J, et al. Application of CLT prefabricated exoskeleton for an integrated renovation of existing buildings and continuous structural monitoring. Procedia Struct Integr 2023;44:1164–71. https://doi.org/10.1016/j.prostr.2023.01.150.

[49] N. A. Hadi, W. M. N. W. Muhamad, and M. K. F. Othman, "Critical factors of implementing Industrialised Building System in Sarawak: A research on SMEs," *IOP Conf. Ser. Earth Environ. Sci.*, vol. 67, no. 1, 2017, doi: 10.1088/1755-1315/67/1/012006.

[50] Li Z, Shen GQ, Xue X. Critical review of the research on the management of prefabricated construction. Habitat Int 2014;43:240–9. https://doi.org/10.1016/j.habitatint.2014.04.001.

[51] Z.-A. Ismail, A. A. Mutalib, and N. Hamzah, "A Case Study of Maintenance Management Systems in Malaysian Complex and High-rise Industrialized Building System Buildings," *Int. J. Econ. Financ. Issues*, vol. 6, no. 3S, 2016.

[52] Piroozfar P, Farr ERP, Hvam L, Robinson D, Shafiee S. Configuration platform for customisation of design, manufacturing and assembly processes of building façade systems: a building information modelling perspective. Autom Constr 2019;106:102914. https://doi.org/10.1016/j.autcon.2019.102914.

[53] Bischof P, Mata-Falcón J, Kaufmann W. Fostering innovative and sustainable mass-market construction using digital fabrication with concrete. Cem Concr Res 2022;161:106948. https://doi.org/10.1016/j.cemconres.2022.106948.

[54] H. L. B. T. Ariffin, B. Y. H. Lynn, N. B. M. Shukery, N. B. A. Rahiman, S. H. Bin Mahmud, and F. B. M. Raslim, "Innovative procurement adoption for Industrialised Building System (IBS) projects," *Int. J. Eng. Technol.*, vol. 7, no. 2.29 Special Issue 29, pp. 887–892, 2018, doi: 10.14419/ijet.v7i2.29.14277.

[55] Mohammad MF, Baharin AS, Musa MF, Yusof MR. The potential application of IBS modular system in the construction of housing scheme in Malaysia. Procedia - Soc Behav Sci 2016;222:75–82. https://doi.org/10.1016/j.sbspro.2016.05.189.

[56] G. W. Liu, R. D. Chen, P. P. Xu, Y. Fu, C. Mao, and J. K. Hong, "Real-time carbon emission monitoring in prefabricated construction," *Autom. Constr.*, vol. 110, 2020, doi: 10.1016/j.autcon.2019.102945 WE - Science Citation Index Expanded (SCI-EXPANDED).

[57] Hannan Qureshi A, Alaloul WS, Wing WK, Saad S, Ammad S, Musarat MA. Factors impacting the implementation process of automated construction progress monitoring. Ain Shams Eng J 2022;13(6):101808. https://doi.org/10.1016/j.asej.2022.101808.

[58] K. Williamson, "Chapter 14 - Research techniques: Questionnaires and interviews," in *Topics in Australasian Library and Information Studies*, K. Williamson, A. Bow, F. Burstein, P. Darke, R. Harvey, G. Johanson, S. McKemmish, M. Oosthuizen, S. Saule, D. Schauder, G. Shanks, and K. B. T.-R. M. for S. Tanner Academics and Professionals (Second Edition), Eds., Chandos Publishing, 2002, pp. 235–249. doi: doi: 10.1016/B978-1-876938-42-0.50023-X.

[59] Qureshi AH, Alaloul WS, Wing WK, Saad S, Ammad S, Altaf M. Characteristics-based framework of effective automated monitoring parameters in construction projects. Arab J Sci Eng 2023;48(4):4731–49. https://doi.org/10.1007/s13369-022-07172-y.

[60] I. Othman, S. Norfarahhanim Mohd Ghani, and S. Woon Choon, "The Total Quality Management (TQM) journey of Malaysian building contractors," *Ain Shams Eng. J.*, vol. 11, no. 3, pp. 697–704, 2019, doi: 10.1016/j.asej.2019.11.002.

[61] CIDB Portal, "Industrialised Building System.".

[62] O. – K. Robert, A. Dansoh, and J. K. Ofori – Kuragu, "Reasons for adopting Public–Private Partnership (PPP) for construction projects in Ghana," *Int. J. Constr. Manag.*, vol. 14, no. 4, pp. 227–238, Oct. 2014, doi: 10.1080/15623599.2014.967925.

[63] Ammad S, Alaloul WS, Saad S, Qureshi AH. Personal Protective Equipment (PPE) usage in construction projects: a systematic review and smart PLS approach. Ain Shams Eng J 2021;12(4):3495–507. https://doi.org/10.1016/j.asej.2021.04.001.

[64] Sarstedt M, Hair JF, Ringle CM, Thiele KO, Gudergan SP. Estimation issues with PLS and CBSEM: where the bias lies! J Bus Res Oct. 2016;69(10):3998–4010. https://doi.org/10.1016/j.jbusres.2016.06.007.

[65] R. O. Mueller and G. R. Hancock, "Factor Analysis and Latent Structure, Confirmatory," in *International Encyclopedia of the Social & Behavioral Sciences*, Elsevier, 2001, pp. 5239–5244. doi: 10.1016/B0-08-043076-7/00426-5.

[66] dos Santos PM, Cirillo MÂ. Construction of the average variance extracted index for construct validation in structural equation models with adaptive regressions. Commun Stat - Simul Comput Apr. 2023;52(4):1639–50. https://doi.org/10.1080/03610918.2021.1888122.

[67] Bacon DR, Sauer PL, Young M. Composite reliability in structural equations modeling. Educ Psychol Meas Jun. 1995;55(3):394–406. https://doi.org/10.1177/0013164495055003003.

[68] Taber KS. The use of Cronbach's alpha when developing and reporting research instruments in science education. Res Sci Educ Dec. 2018;48(6):1273–96. https://doi.org/10.1007/s11165-016-9602-2.

[69] Silaparasetti V, Srinivasarao GVR, Khan FR. Structural equation modeling analysis using smart Pls to assess the Occupational Health and Safety (Ohs) factors on

Workers'Behavior. Humanit Soc Sci Rev 2017;5(2):88–97. https://doi.org/10.18510/hssr.2017.524.
[70] M. R. Ab Hamid, W. Sami, and M. H. Mohmad Sidek, "Discriminant Validity Assessment: Use of Fornell & Larcker criterion versus HTMT Criterion," *J. Phys. Conf. Ser.*, vol. 890, p. 012163, Sep. 2017, doi: 10.1088/1742-6596/890/1/012163.
[71] J. F. Hair, Jr., G. T. M. Hult, C. M. Ringle, and M. Sarstedt, *A Primer on Partial Least Squares Structural Equation Modeling (PLS-SEM)*, Second. SAGE Publications, Inc, 2016.
[72] Fornell C, Larcker DF. Evaluating structural equation models with unobservable variables and measurement error. J Mark Res Feb. 1981;18(1):39. https://doi.org/10.2307/3151312.
[73] A. C. Davison and D. V Hinkley, *Bootstrap Methods and their Application*. Cambridge University Press, 2013. doi: doi: 10.1017/CBO9780511802843.
[74] Sarstedt M, Ringle CM, Smith D, Reams R, Hair JF. Partial least squares structural equation modeling (PLS-SEM): a useful tool for family business researchers. J Fam Bus Strateg Mar. 2014;5(1):105–15. https://doi.org/10.1016/j.jfbs.2014.01.002.
[75] Moshagen M. The model size effect in SEM: inflated goodness-of-fit statistics are due to the size of the covariance matrix. Struct Equ Model A Multidiscip J 2012;19(1):86–98.
[76] Shi D, Lee T, Maydeu-Olivares A. Understanding the model size effect on SEM fit indices. Educ Psychol Meas 2019;79(2):310–34.
[77] Koulinas GK, Anagnostopoulos KP. A new tabu search-based hyper-heuristic algorithm for solving construction leveling problems with limited resource availabilities. Autom Constr May 2013;31:169–75. https://doi.org/10.1016/j.autcon.2012.11.002.
[78] Shariati M, et al. Flexural behavior analysis of double honeycomb steel composite encased concrete beams: an integrated experimental and finite element study. Case Stud Constr Mater Jul. 2024;20:e03299. https://doi.org/10.1016/j.cscm.2024.e03299.
[79] Faridmehr I, Nehdi ML, Nejad AF, Sahraei MA, Kamyab H, Valerievich KA. An innovative multi-objective optimization approach for compact concrete-filled steel tubular (CFST) column design utilizing lightweight high-strength concrete. Int J Light Mater Manuf May 2024;7(3):405–25. https://doi.org/10.1016/j.ijlmm.2024.01.004.
[80] Schot J, Steinmueller WE. Three frames for innovation policy: R&D, systems of innovation and transformative change. Res Policy Nov. 2018;47(9):1554–67. https://doi.org/10.1016/j.respol.2018.08.011.
[81] Liu Z-J, Pypłacz P, Ermakova M, Konev P. Sustainable construction as a competitive advantage. Sustainability Jul. 2020;12(15):5946. https://doi.org/10.3390/su12155946.
[82] Sargent RG. Verification and validation of simulation models. J Simul Feb. 2013;7(1):12–24. https://doi.org/10.1057/jos.2012.20.