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INVESTIGATING KEY FACTORS IN THE DIGITALIZATION OF VALUE ENGINEERING IN THE MALAYSIAN CONSTRUCTION INDUSTRY

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Abstract. Value Engineering (VE) is widely recognized for enhancing value and minimizing unnecessary costs in construction projects. As the industry moves toward digital transformation, integrating digital tools into the VE process offers new opportunities to improve efficiency, collaboration, and decision-making. This study aims to identify and evaluate the critical factors influencing the digitalization of VE in the Malaysian construction industry and to propose a validated conceptual framework tailored to its specific context. A quantitative approach was employed, using data from 199 Malaysian construction professionals and analyzed through Structural Equation Modelling (SEM). The confirmatory factor analysis revealed high factor loadings (≥ 0.8) for key enablers such as real-time information access, data validation, digital workflow integration, operational scalability, regulatory compliance, decision-support systems, and long-term implementation support, including training and system maintenance. In contrast, lower loadings (< 0.7) for constructs like alternative evaluation and return on investment suggest a declining emphasis on traditional cost-centric perspectives. The findings demonstrate that digitalizing VE can lead to enhanced project value, cost efficiency, and process automation within the Malaysian construction sector. The study introduces a comprehensive, phase-based conceptual framework that integrates digital technologies with conventional VE practices, offering actionable insights for project managers, engineers, and policymakers seeking to adopt and scale digital VE in Malaysia.

Keywords: value engineering, digitalization, residential buildings, functional analysis, structural equation modelling.

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1. Introduction

The construction industry has experienced significant changes in some developing countries with the goal of achieving their economic goals. However, due to their inability to meet the demands of sustainable growth on a global scale, many countries' construction sectors are inherently ineffective. Numerous issues can arise during construction projects, including poor quality, budgetary constraints, schedule delays, noncompletion, and a significant chance of not meeting the intended objectives (Ayodele et al., 2020). Projects that encounter these obstacles may be put on hold or terminated due to the small quantity of capital available in this industry. All things considered, the construction sector in emerging nations lags well behind other industries and their equivalents and is unable to satisfy the demands of the governments, the public, and the community (Prebanić & Vukomanović, 2021). The construction industry is still facing constant obstacles despite the increasing use of digital tools and new technologies such as operational inefficiencies, exceeding budgets, and project delays. A complex network of stakeholders and long timelines, generate high levels of risk and unpredictability in a typical construction project (Gamil & Abd Rahman, 2023). Many construction companies are having difficulty surviving in the present economic situation due to the saturated domestic market (Skorobogatova et al., 2020). Construction companies need to come up with innovative cost-cutting strategies that do not reduce efficiency or quality to stay competitive. Since building projects need a significant number of resources, clients are becoming more and more demanding for quality of services (Moshood et al., 2020). Precise cost management has become a crucial component in assessing the success of projects due to the significant financial input involved. It will be crucial for the industry to eliminate waste, outdated processes, and segmentation in an effort to improve cost performance, coordination, and production (Elmousalami, 2020; Van Nguyen et al., 2022). Construction stakeholders will be driven by a paradigm shift based on efficiency, technological innovation, and collaboration if they want to succeed in today's challenging economic situation. One effective management technique for accomplishing crucial project tasks at the lowest possible cost is value engineering, or VE (Parsamehr et al., 2023).

Since its introduction in the 1950s, private engineering firms, government organizations, and contractors have used VE as standard procedure (Elhegazy, 2022). In the last 50 years, the construction sector has embraced VE broadly, using it to produce creative concepts and solutions that increase project value (Rosłon, 2022). Interestingly, however, there is relatively not much research on sharing VE expertise between organizations or the industry, or on repurposing VE concepts and solutions from previous initiatives (Kineber et al., 2022). Construction is still largely dependent on the expertise and skill of individual VE team members and still performs VE much as it did 50 years ago, beginning from scratch every time. In many building projects, VE has resulted in cost reductions of 5–10%; at this point in other projects, it has not produced significant results (Robati et al., 2021). The industry has yet to capitalize on years of collected VE knowledge (Tang & Liu, 2022). There is a chance to advance VE by developing fresh approaches to gathering, repurposing, and sharing VE information throughout every department and sector (Meena et al., 2022). In the modern construction sector, the benefits of VE are more widely accepted. Its goal is to increase efficiency and cost-effectiveness while maintaining quality to maximize value. However, the degree of VE adoption in emerging nations is quite low (Kineber et al., 2020). Even though VE requests are increasing in many countries, the local response is insufficient to alter the dynamics of the construction industry. Although VE is widely used in numerous countries, it is rarely utilized in underdeveloped nations, the Malaysian construction sector is no exception (Jaapar et al., 2009). Relevant literature has noted that no systematic studies have been conducted in Malaysia that have closely observed the degree of VE implementation and knowledge (Fathoni et al., 2013). According to research, most Malaysian construction stakeholders are not sufficiently knowledgeable about VE, which makes it difficult to carry out VE initiatives (Chia et al., 2012).

The construction industry plays a pivotal role in Malaysia's economic development, contributing approximately 4% to the national GDP and employing nearly 1.3 million people across diverse segments such as residential, commercial, infrastructure, and industrial projects (Dehdasht et al., 2022). Despite its steady growth and government-led initiatives to promote innovation and modernization, the Malaysian construction sector continues to face challenges including cost overruns, project delays, quality inconsistencies, and limited adoption of advanced project management methodologies (Tan & Latiffi, 2024). Since its introduction in the 1950s, private engineering firms, government organizations, and contractors globally have adopted VE as a standard procedure. Over the last 50 years, the construction sector has widely embraced VE, using it to generate innovative design alternatives and solutions that enhance project value (Levitt, 2007). However, relatively little research has examined how VE knowledge and solutions are shared or repurposed across organizations and projects. The process often remains reliant on individual expertise, with teams restarting from scratch each time VE is conducted (Markus, 2001). While VE has led to cost reductions in many construction projects, its outcomes vary significantly, and its potential remains underutilized. The situation in Malaysia reflects these global shortcomings. Literature has noted the lack of systematic studies that assess the degree of VE implementation and understanding within the Malaysian construction sector (Masyhur et al., 2024). Many stakeholders remain unfamiliar with VE's principles and application methods, limiting its strategic use. This gap presents a significant opportunity to explore how digitalization can enhance VE practices in the Malaysian construction industry. While previous studies have independently examined VE, BIM, and risk management frameworks using structural equation modeling (SEM), there remains a lack of empirical models that integrate these approaches to identify and validate the key factors necessary for digital VE adoption. Addressing this gap, the current research seeks to develop a conceptual framework that evaluates the critical factors influencing digital VE in Malaysia and provides actionable insights for improving project outcomes through digital integration. Nonetheless, it is clear from the literature that prior studies involved practitioners who were not well informed about the implementation concept (VE) that was the subject of the inquiry (Kineber et al., 2021a). For instance, three research studies concerning VE, building information modelling (BIM) and quantifying the factors that influence reverse logistics to improve its results all employed structural equation modeling (SEM). Descriptive statistics were also utilized to examine the implementation of risk management (Memon & Rahman, 2013).

Considering the limited understanding and low adoption of VE practices in Malaysian construction projects particularly regarding their digital transformation, this study seeks to address the following research question: What are the critical factors that influence the successful digitalization of value engineering in construction projects? To answer this question, the study sets out the following objectives: (1) to identify and evaluate the key factors that impact digital VE adoption in the construction industry using empirical methods; (2) to develop and validate a conceptual framework that integrates these factors into a systematic VE management model; and (3) to provide actionable recommendations for construction stakeholders to optimize VE through digital tools. The novelty of this research lies in its integrated use of Structural Equation Modelling (SEM) to analyze VE from a digital implementation perspective an area with limited prior exploration, particularly in the Malaysian context. The remainder of this paper is structured as follows: Section 2 presents a detailed literature review on VE and its digitalization; Section 3 outlines the research methodology; Section 4 presents the analysis and results; Section 5 discusses the findings and implications; and Section 6 concludes with a summary of contributions and suggestions for future research.

2. Literature review

Value engineering is an effective method for determining and optimizing value for money whereas value is the sum of what is given (such as costs) and what is gained (such as benefits) (de Paula Ferreira et al., 2022). VE aims to maximize features for the lowest possible overall cost on a project while maintaining peak performance and quality (Newell et al., 2023). VE was introduced to the construction industry in 1963 as a way to improve project management which was initially used in the 1940s in the industrial sector (Oke et al., 2023). The primary target of VE is to solve problems creatively and proactively while offering the highest value to customers (Taher & Elbeltagi, 2023). Thus, VE makes decision-making at all phases of development more efficient. A crucial result is cost and function optimization for the project (Lin et al., 2022). VE teams provide creative solutions and ideas that improve the usefulness and worth of projects. It also gives organizations the ability to become more competitive and enhance customer satisfaction (Vornichesku et al., 2023). VE is used in construction to save money while preserving the quality, safety, and performance standards of the project.

2.1. Role of VE in construction industry

The fundamental idea of VE is to use specialized tools to systematically reevaluate designs (Jiya et al., 2023). The objective is to find and remove wasteful spending. This complies with the requirements for dependability, quality, performance, and safety. VE strategies are frequently used in construction such as using alternative materials, building systems, or construction techniques; updating specifications to cut out costly overdesign; standardizing parts and streamlining excessively complicated designs; reconfiguring inefficient building layouts and site plans; and optimizing construction schedules by cutting out unnecessary time (Olanrewaju et al., 2022). Typically, a workshop is held throughout the design development process to integrate VE (Kabaca & Yalnız, 2021; Kineber et al., 2023). Several stages of the VE process, the elements that are connected to it on several levels (digital, organizational, project, and external), as well as the effects that each of these aspects has. For each step, it explores the relevant literature, theoretical underpinnings, research methods, and potential future study avenues. The multifaceted aspect of this subject is highlighted by analyzing each step through the lenses of linked variables, digital enablers, organizational factors, project factors, and external factors. In areas like data management, stakeholder engagement, functional analysis methodologies, creativity and innovation, decision analysis, risk management, design optimization, prototyping, communication and visualization, project monitoring, and continuous improvement practices, the literature analysis column provides the body of research already done on these subjects. This approach aids in identifying holes and openings for more research. The theoretical foundations of each phase are derived from a variety of disciplines, including systems thinking, information management, creative theories, decision theories, design theories, communication theories, project management techniques, and theories of learning organizations. These theoretical frameworks provide a solid conceptual foundation for further research projects. The inclusion of digital technology and VE Job plan in construction projects has been examined by several researchers as discussed in Table 1 below.

2.2. Critical success factors for implementing VE

Increasing the value derived from construction projects is a goal that requires accurate tools and approaches to be achieved. VE is a methodology that employs tactics that provide a financial incentive to achieve higher value for money. The Function Analysis System Technique (FAST) diagram, life-cycle costing, and creative thinking are some of the prerequisite knowledge and awareness of the VE approach that are necessary to accomplish the VE's goal. Karunasena and Rajagalgoda Gamage (2017), the use of VE is relatively low when compared to advanced countries, according to their study of the technology's application in Sri Lanka's building sector. This has been linked to a lack of awareness and information about VE. Owners also play a significant role in the way building projects are carried out. It is therefore impossible to overstate their contribution to the VE application in their project (Dahooie et al., 2020). This training is expected to be thorough and must include all the procedures required for applying VE.

Kineber et al. (2021b) suggest that this practice be included in the duties and competencies required of the technical players in the building sector. This will make it easier for the building industry to quickly implement VE. Similarly, Bohari et al. (2020) argue that VE training is essential to its acceptance by experts in the building industry.

Table 1. A detailed structure explaining the various stages of digitalizing VE in construction projects

Phase	Related Factors	Impact	Digital Enablers	Organizational Factors	Project Factors	External Factors	Literature Analysis	Theoretical Foundations	Research Methodologies	Future Research Directions	References
Information Phase	Comprehensive project data collection	Establishes a solid foundation for VE study	BIM models	Top management support	Project complexity	Regulatory environment	Data management in construction projects	Information management theories	Case studies	Explore integrating blockchain technology for secure data sharing	Pan and Zhang (2021)
	Stakeholder identification and engagement	Ensures alignment with project goals	Cloud-based data repositories	Organizational culture	Project delivery method	Industry standards and guidelines	Studies on stakeholder engagement practices	Stakeholder theory	Surveys	Investigate AI-assisted stakeholder mapping and analysis	Bahadorestani et al. (2020), Xue et al. (2020)
	Clear definition of project objectives and constraints	Facilitates effective communication and collaboration	Stakeholder management platforms	Knowledge management practices	Contract type	Market conditions			Interviews		Abioye et al. (2021), Ciardiello et al. (2020)
Function Analysis Phase	Functional analysis techniques (FAST, VAVE)	Enhance understanding of project functions	Function analysis software	Cross-functional team structure	Design maturity	Best practices and case studies	Functional analysis methodologies	Systems thinking	Experiments	Develop AI-powered function analysis tools	Perera et al. (2011), Spaulding et al. (2005)
	Cross-functional team collaboration	Reveals opportunities for value improvement	Virtual collaboration tools	Diversity and inclusion	Project schedule	Technological advancements	Studies on multidisciplinary team dynamics	Value management theories	Simulations	Investigating the impact of team diversity on VE outcomes	Laurent and Leicht (2019), Olopade and Franz (2018)
Creative Phase	Ideation tools and techniques (brainstorming, TRIZ)	Generates a wide range of potential alternatives	Ideation platforms	Incentives for innovation	Design flexibility	Market trends and benchmarking	Creativity and innovation in construction	Creativity theories	Design experiments	Explore the use of generative AI for ideation	Chou (2014), Hua et al. (2006)
	Diverse team composition	Fosters creativity and out-of-the-box thinking	Virtual reality (VR) simulations	Psychological safety	Availability of resources	Emerging technologies	Studies on ideation techniques and methods	Innovation management models	Action research	Investigating the role of gamification in fostering creativity	Han and Leite (2021), Lucas (2020)
	Openness to unconventional solutions	Encourages risk-taking and innovation	AI-assisted idea generation	Risk tolerance	Stakeholders buy-in	Socio-economic factors			Grounded theory		Jones et al. (2016), Pernites et al. (2020)
Evaluation Phase	Multi-criteria decision analysis (MCDA)	Enables systematic evaluation of alternatives	Decision support systems	Evaluation criteria and weightings	Project constraints	Regulatory requirements	Decision analysis in construction	Decision theory	Optimization models	Develop integrated decision support platforms	Jato-Espino et al. (2014), Ogrodnik (2019)
	Life cycle cost analysis (LCCA)	Considers long-term costs and benefits	Cost estimation tools	Availability of historical data	Stakeholder priorities	Industry standards	Studies on risk management practices	Life cycle assessment	Monte Carlo simulations	Investigate the use of machine learning for risk prediction	Dwaikat and Ali (2018)
Development Phase	Detailed design and engineering	Refines and validates selected alternatives	Computer-aided design (CAD)	Design review processes	Design complexity	Building codes and regulations	Design optimization and prototyping	Design theory	Participatory design	Explore the use of digital twins for virtual prototyping	Sarbini et al. (2021), Trani et al. (2015)
	Value engineering change proposals (VECPs)	Facilitate implementation of value-enhancing changes	Virtual prototyping	Change management procedures	Construction methods	Labor availability		Product development models	Usability testing		Chen et al. (2010), Rad and Yamini (2016)
Presentation Phase	Effective communication and visualization	Clearly conveys VE recommendations	Presentation software	Communication strategies	Stakeholder diversity	Public perception	Literature on communication and visualization in construction	Communication theories	Content analysis	Explore the use of immersive technologies for VE presentations	Kamat et al. (2011)
	Stakeholders buy-in and consensus-building	Promotes stakeholder acceptance and support	Interactive dashboards	Leadership support	Project governance	Political factors	Studies on stakeholder management practices	Persuasion models	Focus groups	Investigating the impact of gamification on stakeholder engagement	Hiraoka et al. (2016), Scott and Halkias (2016)
	Change management strategies	Facilitates smooth transition and adoption	Augmented reality (AR) visualizations	Conflict resolution mechanisms	Decision-making processes	Community engagement		Change management frameworks	Social network analysis		Arefazar et al. (2022), Sanatgar Boboldashti and Nik-Bakht (2024)

End of Table 1

Phase	Related Factors	Impact	Digital Enablers	Organizational Factors	Project Factors	External Factors	Literature Analysis	Theoretical Foundations	Research Methodologies	Future Research Directions	References
Implementation and Monitoring Phase	Project management and execution	Ensures successful implementation of VE recommendations	Project management software	Performance measurement systems	Construction progress	Environmental impacts	Project monitoring and control	Project management methodologies	Longitudinal studies	Develop predictive analytics for project performance	Kim et al. (2015), Zhang et al. (2019)
	Continuous improvement	Tracks and measures value realization	Data analytics platforms	Continuous improvement culture	Quality control measures	Regulatory changes	Studies on continuous improvement practices	Learning organization theories	Retrospective analysis	Investigate the use of digital twins for project monitoring	Kor et al. (2023), Shahzad et al. (2022)

Using VE specialists from industrialized countries to supply all VE tools and procedures is another possible training modality. Kineber et al. (2024) further implies that compensating VE study participants might promote the use of VE in building projects. Faten Albtoush et al. (2020) argues and believes a clear barrier to the widespread use of VE in Sri Lanka is the divide of professionals in the building sector. This suggests that getting the help of all the construction partners is essential to getting beyond this obstacle. A solid alliance among construction experts is not supported by the traditional construction procurement approach.

Li et al. (2022) acknowledges this and suggests that adopting VEs in concert with these professionals might improve working relationships and reduce unethical behavior amongst stakeholders. Gunarathne et al. (2022) have demonstrated that adequate VE training not only helps native construction professionals but also encourages its widespread use. Elhegazy (2022) also claims that increasing project owners' knowledge of VE will lead to broader use of it in building projects. Additionally, he argues that one cannot undervalue the role played by the government in enacting new laws and rules like VE. Consequently, the US government's and its parastatals' initiatives are contributing to a greater adoption of VE across the US construction industry. Othman et al. (2020) stated that VE approval is required for all government construction projects, which emphasizes the efforts of the Malaysian government. Aghimien et al. (2018) observed that one of the key issues impeding the adoption of VE is project owners' lack of collaboration. As a result, the client's commitment and involvement are crucial to enhancing VE implementation. Similarly, decision-makers in the construction industry ought to be open to integrating this practice into their corporate culture. Jaapar et al. (2009) makes clear that the adoption and application of VE should not be restricted to groups of people in his study of the practice in Malaysia's private sector.

Instead, it is necessary to recruit the assistance of the entire community of building specialists. Olanrewaju et al. (2022) explored how using building information modelling (BIM) could help VE studies during the project design phase. The research results showed that using BIM led to greater value delivery. BIM allowed for more effective visualization, coordination, and evaluation of design choices (Chen et al., 2020). Virtual reality (VR) enhanced stakeholder involvement and decision-making by providing immersive visualizations of suggested design alterations, according to analysis of the use of VR in in construction industry towards digitalization and Industry 4.0. In addition to BIM and VR, other digital platforms and technologies have also been investigated by researchers as potential means of optimizing VE operations. These studies were made more transparent and efficient by real-time information sharing and communication among project team members was made possible via the web-based system. developed a cloud-based platform with databases and other analytical tools integrated to provide more thorough and data-driven assessments. While these studies have highlighted the possible advantages of digitization in VE, they have mostly focused on certain technologies or applications (Fathoni et al., 2013). Sensing the need for deeper understanding, a growing number of specialists have explored the elements required for the effective use of digital VE in building projects. In the Malaysian region, for instance, conducted survey-based research and identified key elements that support the adoption of digitalization in the construction industry, such as collaborative communication, workflow integration, and functional analysis. As the construction industry continues to adopt digitization, there is an increasing need for further study to comprehend the complex linkages between digital technologies, VE methodologies, and project management practices. Through the identification and resolution of crucial success criteria, researchers and practitioners may facilitate the wider and more efficient implementation of digital VE. Improvements in project value, cost-effectiveness, and overall performance will result from this.

Recent advancements in the digitalization of construction and VE have introduced new tools and methodologies that warrant inclusion in contemporary discussions. Studies over the past five years have emphasized the growing role of technologies such as digital twins, artificial intelligence (AI), blockchain, and cloud-based collaboration platforms in enhancing VE practices and decision-making efficiency (Gill et al., 2019; Mihai et al., 2022). These tools not only facilitate real-time data sharing and design visualization but also support advanced functions such as predictive modeling, stakeholder engagement, and lifecycle cost optimization. The integration of digital VE frameworks within BIM environments has further enabled improved functional analysis, stakeholder coordination, and regulatory compliance. Furthermore, post-pandemic shifts in remote collaboration and digital workflows have accelerated the need for automated and cloud-supported VE systems, as documented in recent construction technology studies. These developments underscore the urgency for frameworks that not only incorporate traditional VE principles but also align with the evolving digital infrastructure of the construction industry. The present study builds on this emerging body of work by integrating these insights into the development of a comprehensive, empirically validated framework for digital VE adoption.

2.3. Identified research gap

Despite a substantial body of literature on the principles, processes, and benefits of VE and the growing interest in integrating digital tools such as BIM, VR, and AI into construction workflows, a significant research gap remains in understanding the comprehensive and systemic digitalization of VE as a structured methodology. Most existing studies either focus narrowly on individual technologies or on traditional VE implementation without sufficiently addressing the challenges and enablers specific to digital VE adoption in a real-world construction context. Particularly in Malaysia, the adoption of VE practices is limited, and there is a lack of empirical studies that quantify or model the critical success factors that influence digital VE uptake across different phases of construction projects. Furthermore, little attention has been paid to the interaction between organizational culture, technological infrastructure, and project-specific constraints in enabling or hindering digital VE practices.

2.4. Contribution and innovation of this study

This study addresses these gaps by developing and validating a comprehensive conceptual framework for the digitalization of VE in the construction industry using SEM. Unlike previous research, this study adopts a holistic, phase-based analysis aligned with the VE job plan and identifies 41 critical factors through both literature review and expert consultation. The innovation of this work lies in its structured methodological approach that combines qualitative insights with quantitative SEM validation to prioritize and evaluate these factors in the Malaysian context. The research offers new insights into how digital tools can enhance VE outcomes by improving communication, collaboration, data accuracy, regulatory compliance, and decision-making. In doing so, it provides construction professionals and policymakers with a validated model for more effective and sustainable implementation of VE through digital technologies.

3. Methodology

This research adopted a logical, structured methodology grounded in established theories of Value Engineering (VE) and digital transformation in the construction industry. A mixed-methods approach was employed, beginning with a comprehensive literature review to identify an initial set of forty-one critical success factors (CSFs) relevant to the digitalization of VE. These factors were drawn from previous studies on VE adoption, digital technologies in construction, and project performance optimization. To contextualize and validate these factors in the Malaysian construction environment, a round of semi-structured interviews was conducted with 12 industry experts. These participants included senior project managers, BIM specialists, VE consultants, and digital transformation officers from both the public and private sectors. The interviews focused on validating the relevance of the initially identified CSFs, identifying any missing factors, and gaining practical insights into barriers and enablers of digital VE implementation. The qualitative data gathered also informed the wording, grouping, and prioritization of items in the survey instrument. Based on the literature review and interview findings, a structured questionnaire was developed. The questionnaire consisted of closed-ended items using a 5-point Likert scale, grouped under the constructs identified for subsequent factor analysis. The clarity, face validity, and internal consistency of the survey instrument were then evaluated through a pilot survey involving 30 respondents from the construction industry. Feedback from the pilot phase led to refinement in the phrasing of several items for better comprehension and the removal of ambiguous or overlapping questions. The revised questionnaire was then distributed more broadly to a purposive sample of construction professionals, yielding 199 valid responses. For the quantitative analysis, Structural Equation Modelling (SEM) using AMOS was employed to evaluate both the measurement and structural models. SEM was chosen for its ability to analyze complex, multi-construct frameworks while accounting for measurement errors and testing multiple interrelated hypotheses simultaneously. This made it particularly suitable for modeling the interactions between constructs such as knowledge of VE, information management, digital implementation, and project lifecycle phases. Unlike simpler regression techniques, SEM allows for simultaneous validation of latent variables and their observed indicators, ensuring both theoretical and statistical rigor. This comprehensive methodological framework consisting of literature synthesis, expert interviews, pilot testing, large-scale survey deployment, and advanced statistical modelling ensured a robust, context-sensitive examination of digital VE adoption in Malaysian construction projects. The entire process is sequentially illustrated in Figure 1, which outlines the methodological flow from factor identification to framework validation. Each stage of this sequence is further elaborated in the subsequent sections of the methodology.

3.1. Identification of factors

The state of the construction operations has changed, requiring new methods for project management. This change is a reaction to the growing complexity of building projects. A thorough analysis of the literature using

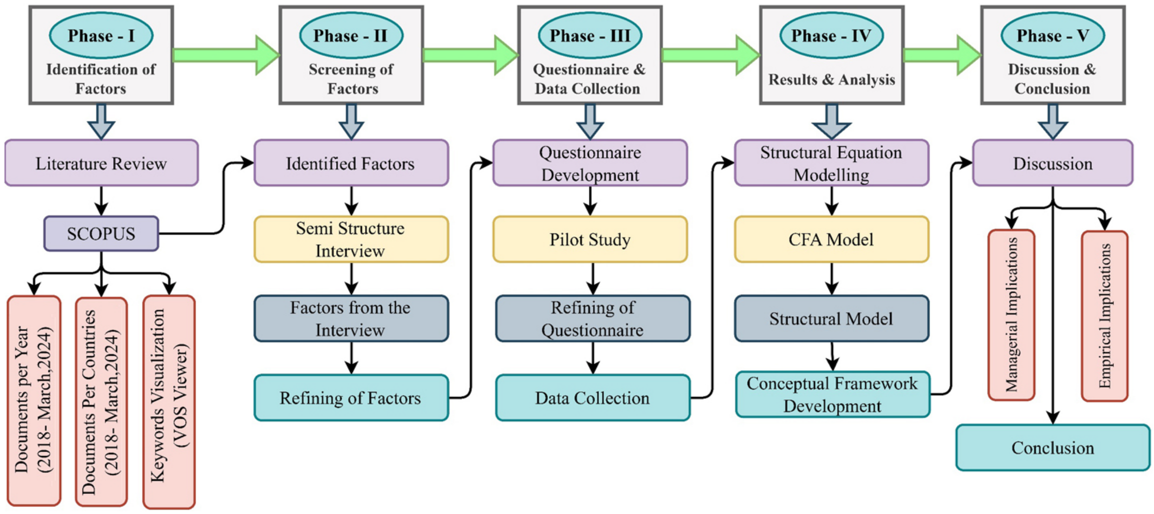

Figure 1. 5-step methodology for digitalization of value engineering in construction projects

the Scopus database was conducted to identify the factors that influence the overall performance of VE in construction projects as well as the quality of project management. This study illustrates the critical factors that need to be taken into consideration to optimize the use of VE for digitalization in construction projects. Prioritizing key components is necessary to optimize the benefits of VE in project management, including precise project planning, improved cost control, well-trained project teams, and effective communication channels.

The original keyword search using the phrases "Value engineering" AND "Building" OR "Construction" AND "Factors" OR "Project Management" found 679 publications. Date filters were used to cover articles published between 2018 and 2024, focusing the study on current research and reducing the number of relevant documents to 223. Additional filters were invented to distinguish between publications in the engineering topic area, document type as articles, and English language. 106 papers were released between 2018 and 2024, with eight in 2024, twenty-one in 2023, twenty-four in 2022, fifteen in 2021, twelve in 2020, fourteen in 2019 and twelve in 2018 as shown in Figure 2.

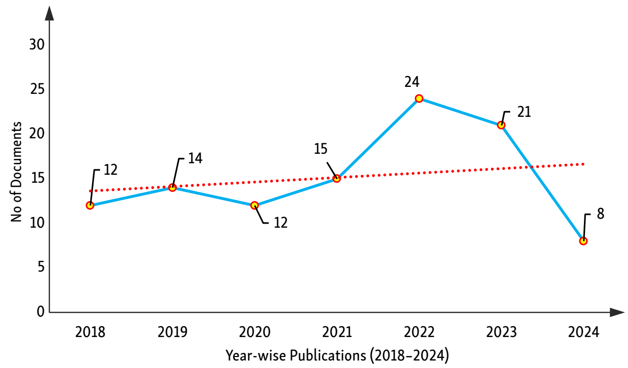

Figure 2. Documents from year 2018 to 2024 (data source: SCOPUS)

The top sources identified by country-specific literature analysis were as follows: eighteen from China, eleven from Iran, eleven from Indonesia, ten from the UK and USA, nine from Egypt, eight from Australia, eight from Taiwan, and three from Malaysia and Turkey as shown in Figure 3. The goal of this evaluation was to pinpoint the most often mentioned crucial factors impacting the digital VE in construction. These crucial factors were underlined in the literature as a means of ensuring the effective use of digital VE and optimizing advantages in construction projects around the world. Using VOS viewer, a bibliometric analysis of the keywords from the 106 literature publications was carried out to find clusters and occurrence rates. Figure 4 depicts the four key clusters noticed by the analysis: project planning, management, and delivery; cost and value optimization; methodologies and techniques; and sectors and scale. The high frequency of terms related to project planning, management, and delivery, such "decision making", "construction management" and "project planning", demonstrated the element's value. Frequently occurring terms that relate to costs and value optimization were "cost analysis", "value engineering", and "budget control", emphasizing the significance of cost control. Keywords like "artificial intelligence", "risk analysis", and "analytical hierarchy process" were found in the methods and techniques cluster, indicating how frequently VE tools and processes are discussed.

The keyword visualization (Figure 4) offers valuable insights into prevailing research themes in the domain of digital Value Engineering (VE) within the construction industry. Prominent terms such as "value engineering", "construction industry", "cost-benefit analysis", "budget control", and "construction projects" emerged as frequently co-occurring keywords, indicating a consistent academic emphasis on optimizing project value while managing costs and resources. Additionally, the inclusion of domain-specific keywords like "residential buildings", "commercial buildings", and "project scale" highlights the growing relevance of VE practices across diverse construction sectors and project typologies. The visualization revealed several thematic clusters, with major concentrations around project planning, cost management, VE methodologies, and construction process optimization. These thematic groupings align with the core constructs identified in literature, particularly those categorized in Table 2, namely, cooperation, complexity, functional analysis, knowledge management, and structured execution. Keywords related to planning, communication, methodology, and oversight further emphasize the interdisciplinary nature of digital VE, highlighting the importance of integrating technical, managerial, and collaborative components for successful implementation. The VOS viewer keyword analysis reinforces the study's findings by validating the critical importance of function analysis, phased implementation, stakeholder coordination, and leadership commitment.

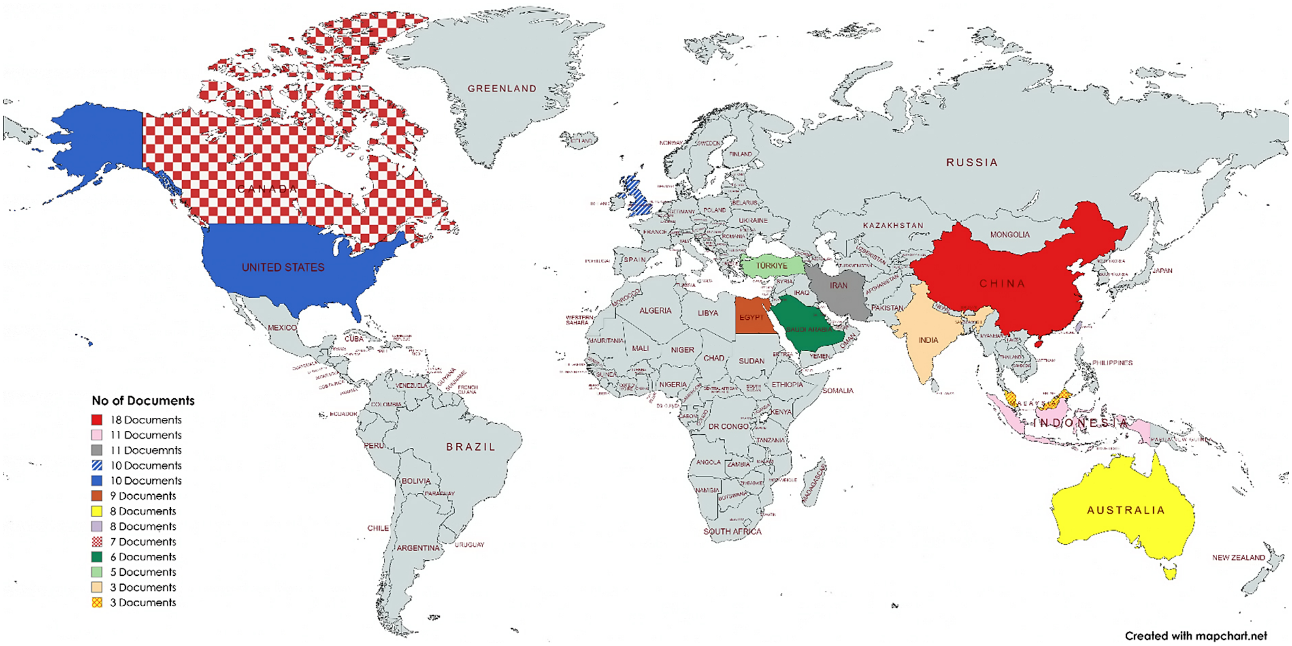

Figure 3. Documents by countries from year 2018 till 2024

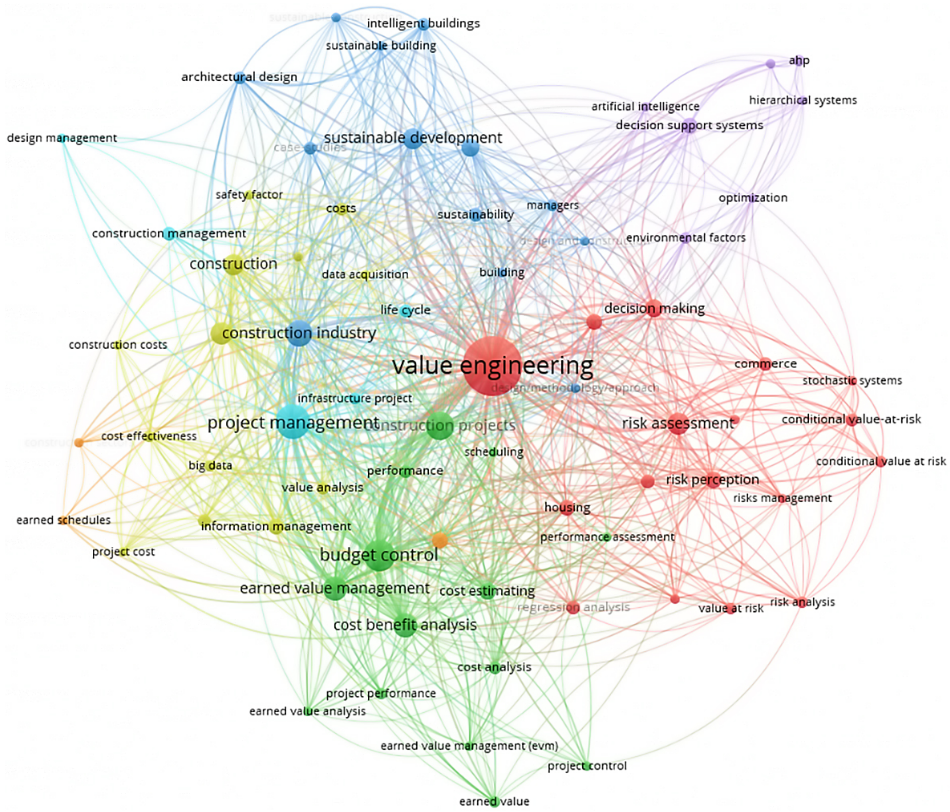

Figure 4. Keywords visualization through VOS viewer from year 2018 till 2024

Table 2. Hypothetical constructs and factors with codes for the implementation and adoption of digital Value Engineering (VE) practices

Constructs	Code	Factors	Status	Modified Factors	References
Knowledge of Value Engineering (VE)	VE1	Knowledge of VE or similar terms	Selected	–	Taher (1991), Zhang et al. (2009)
	VE2	VE is an enhanced tool rather than a method of cost reduction	Modified	Recognizing VE as a value optimization tool, not just cost-cutting	Ellis et al. (2005), Miles (2015)
	VE3	VE reduces costs by creative alternative design	Selected	–	Keeney (2004), Tang and Bittner (2014)
	VE4	Clients can achieve better value for money if VE is implemented	Selected	–	Ma and Tam (2013), Olatunji et al. (2017)
	VE5	Expertise must cover engineering principles, costs, and product functions across disciplines	Selected	–	Chandrasegaran et al. (2013), Sage and Lynch (1998)
Evaluation of Critical Factors for VE Adoption	VECFA1	The VE team uses an accurate cost model to evaluate the current project	Selected	–	Chen (2014), Kim and Reinschmidt (2011)
	VECFA2	The VE team conducts a comprehensive functional analysis to identify the essential and non-essential functions of the product or service	Modified	Thorough functional analysis to distinguish essential and non-essential functions	Chen et al. (2022), JaiSai et al. (2024)
	VECFA3	The VE team uses a systematic process to select the most promising alternatives for further evaluation	Selected	–	Moon et al. (2016), Yang et al. (2014)
	VECFA4	VE team considers the lifecycle cost of the current project in its evaluation	Selected	–	Abdelghany et al. (2015), Shi and Xie (2009)
	VECFA5	The VE team uses a robust evaluation process to identify the best alternative for the current project	Selected	–	Ibusuki and Kaminski (2007), Taher and Elbeltagi (2023)
Digital Implementation of VE	DIVE1	It can improve the speed and efficiency of the VE process	Selected	–	Boock and Chau (2007)
	DIVE2	It can increase the accuracy and reliability of VE results	Selected	–	Nikitenko (2019)
	DIVE3	It can enable a more comprehensive and creative VE process	Selected	–	Nikmehr et al. (2021)
	DIVE4	It can improve the communication and collaboration of VE teams	Modified	Enhancing communication and collaboration among VE teams through digitalization	Aghimien et al. (2022)
	DIVE5	Utilization of digital platforms and tools contributes to making VE more accessible to a wider audience or users	Modified	Improving accessibility of VE to a broader user base through digital platforms and tools	Sezer et al. (2021)
	DIVE6	Digital implementation can make VE more accessible and affordable	Selected	–	Hautala et al. (2017)
Information Phase	IP1	It is important for digital VE to meet the primary needs and requirements of users	Selected	–	Rad and Yamini (2016)
	IP2	It is important for digital VE facilitation in collaboration and communication within the project team	Selected	–	
	IP3	It is important in digital VE for users to easily access and retrieve relevant information during VE study	Modified	Enabling easy access and retrieval of relevant information during digital VE studies	Chen et al. (2010)
	IP4	It is important in digital VE to provide transparent information about the sources and methodology used in VE analyses	Modified	Ensuring transparency about sources and methodologies used in digital VE analyses	Green (1994)
	IP5	It is important in digital VE capability to validate and ensure the accuracy of data input during the information phase	Modified	Validating and ensuring data accuracy during the information phase of digital VE	Naderpajouh and Afshar (2008)

End of Table 2

Constructs	Code	Factors	Status	Modified Factors	References
Functional Analysis Phase	FAP1	It is crucial to integrate digital VE with the existing Revit environment for your workflow	Modified	Integrating digital VE with existing Revit workflows	Spaulding et al. (2005)
	FAP2	The ability for users to customize and tailor digital VE to meet specific project requirements	Selected	–	Cariaga et al. (2007)
	FAP3	Complete documentation for digital VE features and functionalities is required	Modified	Comprehensive documentation of digital VE features and functionalities	Stocks and Singh (1999)
	FAP4	Robust error handling and reporting functionality within digital VE to ensure data accuracy	Selected	–	Olawumi et al. (2016)
	FAP5	Version control functionality is essential for managing changes made through the plugin in a collaborative project environment	Selected	–	Song and Chua (2006)
Operational Phase	OP1	Cost-effectiveness and potential return on investment when considering digital VE adoption	Modified	Evaluating cost-effectiveness and potential ROI of digital VE adoption	Irawan et al. (2023)
	OP2	It will easily gather user input in the digital VE process and features during its usage	Modified	Facilitating easy user input gathering during digital VE usage	Kanapeckiene et al. (2011)
	OP3	It is critical for the digitalization of VE to assist in ensuring regulatory compliance related to VE practices	Modified	Ensuring regulatory compliance through the digitalization of VE practices	Raouf and Al-Ghamdi (2023)
	OP4	Digitalization of VE can scale effectively across various types and sizes of elements	Selected	–	Basbagill et al. (2013)
	OP5	Digitalization of VE can seamlessly integrate with other calculations commonly used in the VE study	Selected	–	Teng et al. (2019)
Evaluation Phase	EP1	Efficient handling of data input and output for digital VE analysis is important	Modified	Efficient data input/output handling for digital VE analyses	Waris et al. (2012)
	EP2	Digitalization of VE can effectively generate reports and visualizations for alternative assessments	Modified	Effective report generation and visualization for alternative assessments in digital VE	Thyssen et al. (2010)
	EP3	Digitalization of VE can empower users to make informed decisions during the VE study	Selected	–	Chen et al. (2010)
	EP4	Digitalization of VE can integrate diverse sources of information to enhance the analysis process	Selected	–	Valle and Soares (2006)
	EP5	The ability of digital VE can manage information at various levels of granularity, accommodating both detailed and summary data for comprehensive analysis	Modified	Handling information at varying granularity levels in digital VE for comprehensive analysis	Madushika et al. (2020)
Implementation Phase	IMPP1	It is critical for satisfactory support and maintenance for the long-term use of digital VE in projects	Modified	Ensuring satisfactory support and maintenance for long-term digital VE usage	Chen and Liao (2010)
	IMPP2	It is critical for user-friendliness for both novice and experienced Revit users when considering a digital VE process	Selected	–	Tanko et al. (2018)
	IMPP3	It is important for digital VE to provide user-friendly training materials and onboarding processes	Selected	–	Hwang et al. (2015)
	IMPP4	It is critical for digital VE to adhere to security and privacy standards in handling project data	Selected	–	Cha and O'Connor (2005)
	IMPP5	The ability of digital VE can automate routine tasks and processes during the VE implementation, reducing manual effort	Modified	Automating routine tasks and processes in digital VE to reduce manual effort	Alsolami (2022)

For instance, terms related to collaboration (e.g., communication, stakeholder engagement, consensus) underscore the need for transparent information sharing and alignment among project participants. Similarly, complexity-related keywords point to the necessity for early-stage integration of VE into project workflows, supported by risk assessment and adaptive staging strategies. A deeper interpretation of the clusters suggests that successful digital VE adoption relies on five interdependent dimensions: open communication channels, incremental and flexible implementation phases, rigorous functional evaluation of design components, continuous learning and upskilling, and strong leadership. These findings are consistent with project management theory, where the interplay of time, cost, and quality objectives is recognized as a determinant of project success. The alignment of these factors emphasized both in literature and through keyword frequency supports their inclusion in the proposed conceptual framework for digital VE. The keyword visualization not only corroborates the thematic priorities of current VE research but also illustrates the multi-dimensional nature of digital VE implementation. High-level topics such as value optimization, process control, and strategic planning are prominently featured, while more nuanced themes such as stakeholder alignment, knowledge transfer, and regulatory compliance are revealed through detailed analysis. Together, these insights offer a comprehensive understanding of the research landscape and reinforce the foundation upon which this study's framework is built.

3.2. Quantitative survey

The quantitative research was conducted using a questionnaire survey as the main tool to obtain the required data. A questionnaire was developed based on the modified factors identified in the study, using a 5-point Likert scale ranging from 1 (Strongly Disagree) to 5 (Strongly Agree). The questionnaire comprised three main sections. As an introduction, the first section gave a brief overview of the research's objective. In the second portion, details regarding the respondents' profiles were obtained, such as years of experience and educational attainment. The third section, which focused on the identified factors, served as the research's foundation. The questionnaire was sent by email to academic universities and professionals in the construction industry in Malaysia. Seven experts participated in a prototype survey before it was distributed to make sure all the questionnaire's items were significant and dependable. The body of literature offers recommendations for the ideal size of the pilot survey sample, which is normally between 5 and 12 respondents. The decision to engage twelve experts aligns with established guidance in qualitative research, where sample sizes of 6–12 interviews are often sufficient to achieve data saturation in studies of relatively homogeneous groups (Guest et al., 2006). This range is consistent with recommendations in the methodological literature, which suggest that small-scale pilot surveys (5–12 participants) are adequate to test questionnaire clarity, reliability, and feasibility before large-scale deployment (Mason, 2010).

The expert feedback from the pilot survey was informative, and many changes were made to the questionnaire as a result. Initially, questions that were unclear were repeated to raise awareness and ensure that respondents understood the questions better. The questionnaire has been carefully reviewed and reduced by trying to eliminate any items that are unnecessary or redundant. As a result, the questionnaire was able to concentrate more on the research areas that were most important. These changes were implemented to enhance both the overall participant experience and the quality of the data collected. These changes were implemented, and the questionnaire was then ready for distribution. A precise representation of the research population depends on choosing the right sample size. The sample size was determined using the following Eqn (1), which was provided by Israel (1992) (Bujang et al., 2018):

$$n_0 = Z^2 pq / e^2, \quad (1)$$

where n_0 represents the infinite population sample size, Z is the normal curve abscissa that cuts off an area α at the tails (taken as 1.96 for a 95% confidence level), q is $1 - p$, p is the proportion of an attribute present in the population (maximum variability is obtained when $p = 0.5$), and e is the desired level of precision (taken as 0.07).

3.3. EFA analysis

Using exploratory factor analysis (EFA) to analyze the supplied data, the goal was to find underlying factors and assess their dependability. The analysis used the Varimax rotation approach with Kaiser normalization and the Principal Component Analysis extraction method. Eigenvalues were analyzed to determine the number of factors that were kept. This study only included factors whose eigenvalues were greater than one, suggesting their significance in explaining the observed variance of the variables. Factor loadings were used to ascertain the link between the variables and the discovered factors. Significant variables are those that have loadings higher than 0.6 or 0.7, which imply a substantial correlation with the associated factor. The internal consistency or dependability of each factor was evaluated by calculating the Cronbach's alpha coefficient. Higher Cronbach's alpha values signify a higher degree of internal consistency among the variables within a factor. Each component's variables had appropriate factor loadings, and the internal consistency was shown by Cronbach's alpha coefficients. This implies that the factors that were identified played a noteworthy role in enhancing the comprehension of the research subject. The EFA analysis helped to identify important elements that improved understanding of the research issue and offered insights into the structure of the variables (Howard, 2016; Yong & Pearce, 2013).

3.4. Conceptual model and hypotheses development

To examine the interrelationships between key factors influencing the digitalization of Value Engineering (VE) in construction projects, a conceptual model was developed based on the critical constructs identified through an extensive literature review and qualitative expert input. This model serves as the theoretical foundation for the Structural Equation Modelling (SEM) analysis that follows. It is designed to capture how various dimensions of VE from foundational knowledge and functional analysis to implementation and continuous improvement interact in a digital transformation context. The conceptual model is structured around eight latent constructs: (1) Knowledge of Value Engineering, (2) Evaluation of Critical Factors for VE Adoption, (3) Digital Implementation of VE, (4) Information Phase, (5) Functional Analysis Phase, (6) Operational Phase, (7) Evaluation Phase, and (8) Implementation Phase. Each construct is measured through a set of observed variables identified and refined via exploratory factor analysis (EFA), and the relationships between them reflect both theoretical assumptions and practical expectations within VE project workflows.

The development of the model is informed by VE management theory and digitalization literature. For instance, the construct "Knowledge of VE" represents the foundational awareness and conceptual understanding necessary for effective VE deployment. It is hypothesized to influence the "Evaluation of Critical Factors for VE Adoption", which encompasses practices such as lifecycle costing, alternative analysis, and function-focused evaluations. This in turn is expected to drive the "Digital Implementation of VE", which captures how effectively organizations adopt digital tools and platforms to support VE activities. A logical flow follows through the VE job plan, starting with the "Information Phase" (data collection, access, and validation), progressing through the "Functional Analysis Phase" (workflow integration and customization), and influencing operational scalability and compliance considerations in the "Operational Phase". These phases inform the "Evaluation Phase", where digital tools enable enhanced analysis, decision-making, and reporting. Finally, the "Implementation Phase" assesses support, usability, automation, and sustainability of digital VE practices.

Based on this conceptual model, a set of hypotheses is proposed to guide empirical testing. These are structured to assess both the measurement model (validity and reliability of constructs) and the structural model (causal relationships among constructs). The proposed hypotheses are as follows:

- **H1:** Knowledge of VE positively influences the Evaluation of Critical Factors for VE Adoption.
- **H2:** Evaluation of Critical Factors for VE Adoption positively influences Digital Implementation of VE.
- **H3:** Digital Implementation of VE has a positive effect on the Information Phase.
- **H4:** The Information Phase positively influences the Functional Analysis Phase.
- **H5:** The Functional Analysis Phase positively influences the Operational Phase.
- **H6:** The Operational Phase positively influences the Evaluation Phase.
- **H7:** The Evaluation Phase positively influences the Implementation Phase.
- **H8:** Each observed variable significantly loads onto its respective latent construct, confirming measurement validity.

These hypotheses are tested using SEM in AMOS to validate both the measurement and structural components of the model. This hypothesis-driven modelling approach not only ensures methodological rigor but also allows for the empirical evaluation of the underlying assumptions regarding the role of digital tools in enhancing VE performance in construction projects. The conceptual framework and its hypotheses provide a structured lens through which the dynamic, multi-phase process of digital VE can be better understood and optimized.

3.5. Note on dataset usage for EFA and CFA

In this study, both Exploratory Factor Analysis (EFA) and Confirmatory Factor Analysis (CFA) were conducted on the same dataset of 199 valid responses. Best practice in structural modelling generally recommends using separate datasets or split-sample validation for EFA and CFA to avoid potential inflation of model fit indices (Brown, 2015). However, the modest sample size in this research constrained our ability to divide the data without significantly reducing statistical power and compromising the stability of factor estimates. As such, EFA was employed primarily as a data-reduction technique to refine and retain the most theoretically relevant and statistically robust items, followed by CFA on the same dataset to assess the measurement model prior to SEM. This sequential approach has been adopted in similar construction management studies with limited sample sizes (ISA, 2023), though we acknowledge its limitations. Future studies are encouraged to implement split-sample validation, bootstrapped cross-validation, or use of independent datasets to confirm the factor structure.

3.6. SEM algorithm

The degree to which the indicators (variables) within each construct (group) measure the same underlying concept is assessed by convergent validity. It ensures that a certain concept is accurately captured by the variables intended to evaluate it. The loadings show how strongly and in which direction each variable is related to the respective construct. The stronger the link between the variable and the construct, the higher the loading value. The degree of correlation between variables inside a construct is known as multicollinearity, and it is measured by the Variance Inflation Factor or VIF. While VIF values are not given for every variable in the table, they are usually used to assess whether correlations between variables are excessive. Values higher than 5 or 10 could be a sign of possible multicollinearity issues. Composite reliability evaluates the dependability or internal consistency of a construct's indications. It shows the extent to which factors inside a construct accurately reflect the same underlying idea. Higher than 0.7 composite reliability ratings are ideal and signify higher reliability (Bijivemula et al., 2024). The variance that the indicators describe in relation to measurement inaccuracy is called the Average Variance Extracted (AVE). It shows how effectively a construct's variables communicate the core idea. A value of 0.5 or higher is generally considered appropriate for AVE (AL-Fadhali, 2024; Shek & Yu, 2014).

3.7. Model fit and evaluation

To ensure the reliability and validity of the constructs, internal consistency was first assessed using Cronbach's Alpha, calculated as:

$$\alpha = \frac{N \times \bar{c}}{\bar{v} + (N-1) \times \bar{c}}, \tag{2}$$

where N – number of items; $\bar{c}$ – average inter-item covariance; $\bar{v}$ – average variance of the items.

Cronbach's Alpha values between 0.70 and 0.90 are generally regarded as good reliability, values above 0.90 may indicate redundancy among items, and values below 0.70 suggest moderate to low consistency (Tavakol & Dennick, 2011).

Following reliability assessment, model fit was evaluated using a set of Goodness-of-Fit (GOF) indices, widely adopted in Structural Equation Modelling (SEM) (Byrne, 2013).

- **Chi-square (χ^2):** A non-significant p-value (> 0.05) indicates good fit; however, because χ^2 is sensitive to sample size, the χ^2/df ratio was also used, with values ≤ 3 deemed acceptable.
- **Goodness-of-Fit Index (GFI) and Comparative Fit Index (CFI):** Values ≥ 0.90 indicate a good fit between the hypothesized model and the observed data.
- **Tucker–Lewis Index (TLI):** Values ≥ 0.90 indicate acceptable model fit.
- **Root Mean Square Error of Approximation (RMSEA):** Values ≤ 0.08 indicate reasonable fit, and ≤ 0.05 indicate close fit.

All GOF indices were computed in IBM AMOS v26, based on the confirmatory factor analysis (CFA) and structural models. Together, Cronbach's Alpha and these GOF indices provided a comprehensive evaluation of both the reliability of the constructs and the adequacy of the model fit.

4. Results and discussions

This study focuses on construction projects and the digital implementation of VE and validates the essential factors identified in the systematic review that are associated with the VE Job Plan. After reviewing the literature, thirty-five factors were found that affect the digital implementation of VE. After considering the comments of the interviewees, six new factors were added. As a result, the total extracted factors from literature and semi-structured interviews are forty-one factors. The next subsections represent the outcomes of the qualitative and quantitative surveys.

4.1. Quantitative research outcomes

The proper sample size was determined using a well-established random sampling technique to ensure adequate representation of the study area. As a result, the sample size computation was completed using the widely accepted approach Israel (1992) provided for determining sample sizes in survey research. Using Eqn (1), it was essential to ascertain that 196 responses would be the minimum sample size needed for the target demographic. Email questionnaires were distributed to over 450 construction engineers with a specific emphasis on the Malaysian construction sector, with the objective of ensuring the collection of accurate information. A wide distribution of participants was achieved using random sampling, which ensured that all individuals had an equal opportunity to be selected to take part in the survey. The data set is more accurate and adaptable because of this strategy.

4.2. Demographic details

In the questionnaire, participants were given a list of factors derived from the literature and asked to fill out the questionnaire. The research study comprised 199 participants from the Malaysian construction industry. The values of this data were evaluated utilizing the IBM SPSS-AMOS software, a highly effective SEM method that supports investigations through the expansion of conventional multivariate analytic techniques such as correlation, factor analysis, and regression. Prior to analysis, an in-depth review of the data was conducted to eliminate any errors, missed values, or inappropriate responses. There was no elimination of any of the 199 responses attributed to objectionable behavior exhibited by the respondents. The age distribution of the participants was uniform; 34% fell within the age range of 31 to 40 years, 26% were between the ages of 21 and 30, 45% were between the ages of 41 and 50, and 17% were over the age of fifty. This age range indicates a good mix between the young views of professionals and the mature viewpoints of experienced experts. The demographic details as shown in Figure 5 indicate a well-rounded sample with a balanced representation of age groups, educational levels, professional roles, work experience, and types of projects executed by the companies, especially in the Malaysian construction industry.

The sample was highly educated, with 80% of participants holding advanced degrees. Specifically, 40% had a master's or Ph.D. degree, indicating a substantial proportion of highly qualified individuals. The remaining 20% held a bachelor's degree, representing a diverse educational background. Most respondents (61%) were project managers, indicating a need for decision-makers in the sample. Additionally, 25% were civil engineers, and 15% were BIM engineers responsible for overseeing compliance. The lack of responses in the 'Other' category suggests that significant professional roles were adequately evaluated. The participants had diverse levels of work experience, broadening the research' perspectives. The largest group (28%) had 11–15 years of experience, followed by 22% with 6–10 years, and 16% with 20+ years of experience. Professionals with 0–5 years of experience (18%) and 16–20 years of experience (16%) ensured that both new and experienced perspectives were represented. The companies of the participants executed various types of projects, including residential, commercial, industrial, institutional, and infrastructure projects. Some companies also worked on other types of projects not specified.

This diversity enhances the study's credibility and applicability by capturing a range of perspectives from various stakeholders and project types. Knowledge of VE, Assessment of Critical Factors for VE Adoption, Digital Implementation of VE, Information Phase, Operational Phase, Functional Analysis Phase, Operational Phase, Assessment Phase, and Implementation Phase. The digitization of VE in construction projects was covered by these categories, which included forty-one factors in total. It was made sure that the factors found in the study were properly categorized using a thorough process to increase their reliabil-

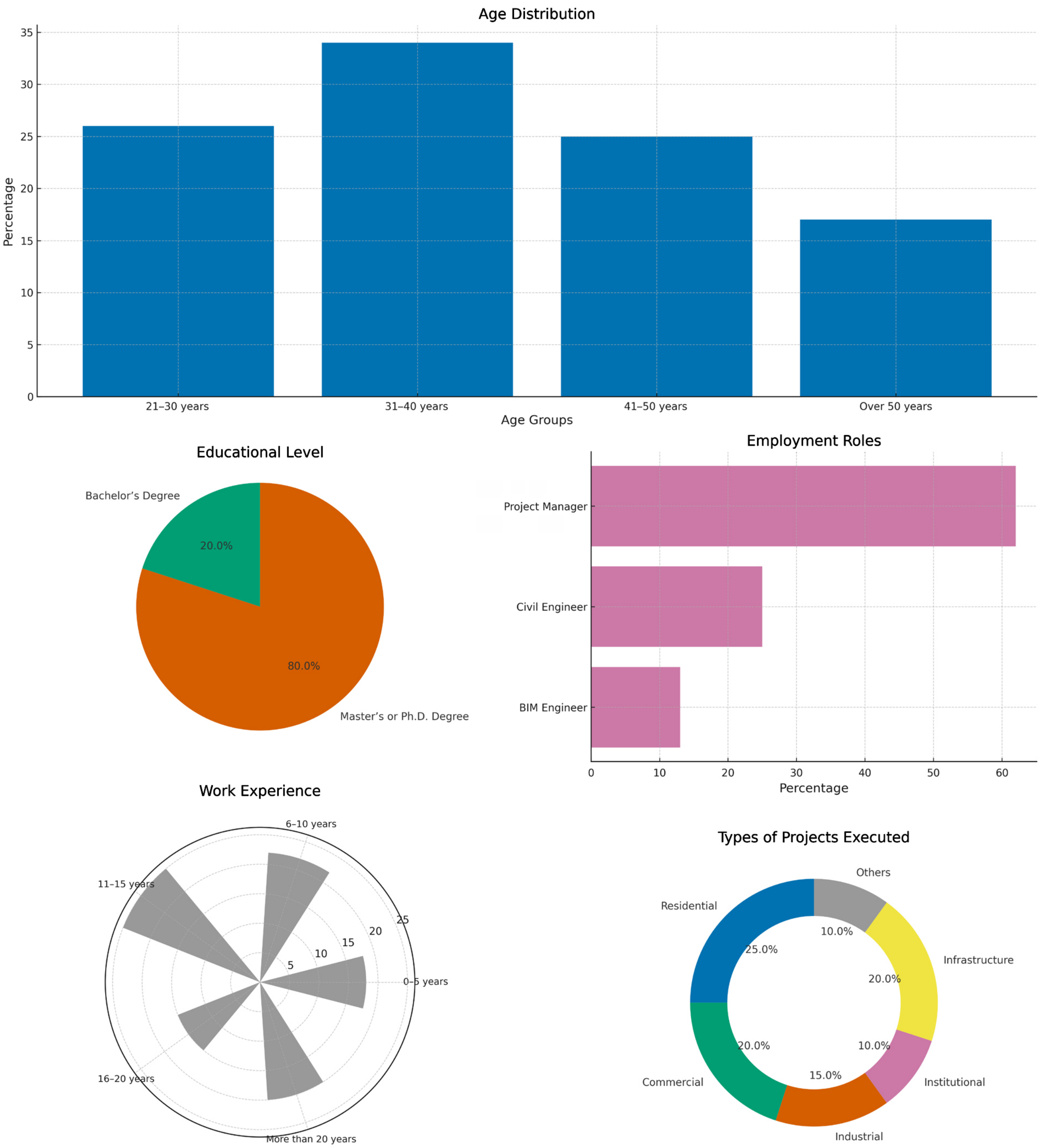

Figure 5. Demographic details of the respondents

ity. The categories and related factors were presented and discussed with participants during the semi-structured interviews. The interviewees actively participated in the classification process and offered helpful feedback. Notably, there were no complaints about how these components were categorized, confirming that their positioning within the recognized structures was appropriate and clear.

4.3. Reliability analysis (Cronbach's alpha)

The process of reliability analysis is used to evaluate form consistency. Stronger internal cohesion is indicated by a higher reliability value. The degree to which a set of things is closely connected is measured by internal consistency, which is frequently measured using Cronbach's alpha. It functions as a gauge for the reliability of the scales. Internal consistency and scale reliability were measured using Cronbach's alpha, which is considered acceptable at a threshold of 0.7 or higher (Kennedy, 2022). One approach to measuring internal consistency is by calculating the mean inter-correlation among the assessment items and dividing it by the total number of assessment items. For conceptual reasons, the formula for Cronbach's alpha calculation (Eqn (3)) is as follows:

$$\alpha = \frac{N\acute{C}}{'Y + \left(N-1\right)\acute{C}}, \tag{3}$$

where: N – number of items, $\acute{C}$ – average inter-item covariance among the items, and $'Y$ – average variance.

The statistical technique of Cronbach's alpha was used to guarantee precision and coherence. Anything below 0.50 is seen as extremely unreliable, 0.70 to 0.90 represents good reliability, and 0.50 to 0.70 represents moderate reliability. A score of 0.90 is considered highly dependable. The data clearly shows a high level of trustworthiness, with a sample size (N) of 199 and a Cronbach's alpha value of 0.915. The data dpendability for this study is shown in Table 3. The process of reliability analysis is used to evaluate form consistency and was conducted following the procedure described in Section 3.6. The calculated Cronbach's alpha for the study was 0.915, indicating excellent internal consistency across the 41 factors measured.

Table 3. Data reliability

Case Processing Summary			
		N	%
Cases	Valid	199	100
	Excluded	0	0
	Total	199	100
Cronbach's alpha		0.915	
Number of factors		41	

4.4. Structural equation modelling (SEM)

SEM is a comprehensive multivariate statistical technique used to examine hypothesized relationships between latent constructs and observed variables. It consists of two components: the measurement model, which is assessed through Confirmatory Factor Analysis (CFA), and the structural model (SM), which evaluates the directional relationships between latent constructs. In this study, Exploratory Factor Analysis (EFA) was conducted prior to SEM to ensure that the underlying structure of the dataset was empirically supported before proceeding to confirmatory analysis. EFA is particularly useful in contexts where the theoretical model is not fully established or when the dimensionality of latent constructs needs to be refined based on empirical data. Since the conceptual framework in this research was developed from a literature review and expert input rather than from a previously validated measurement model it was essential to first apply EFA. This allowed for the identification of factor groupings, examination of factor loadings, and elimination or refinement of weak or cross-loading items, ensuring that only reliable and relevant indicators were retained for the final measurement model. By conducting EFA, the study ensured that the constructs used in the subsequent SEM were not only theoretically grounded but also statistically validated through a data-driven process. This two-step approach enhances the robustness of the SEM results by first exploring the factor structure (EFA), and then confirming it (CFA), before testing the hypothesized structural relationships. The application of EFA in this context is not part of SEM per se but serves as a crucial preliminary step in the model-building process when working with newly proposed or context-specific frameworks, such as digital VE in Malaysian construction projects. The following subsections describe the CFA and structural models in detail, demonstrating how the refined constructs were validated and tested within the SEM framework.

4.4.1. Exploratory factor analysis (EFA)

The EFA aims to identify the underlying factor structure among the observed variables related to the digitalization of VE in construction projects. Table 4 presents the Rotated Component Matrix, which shows the factor loadings of each variable on the respective constructs or factors. Factor loadings represent the correlation between the observed variables and the underlying factors. Generally, factor loadings above 0.7 are considered significant and acceptable for inclusion in the factor structure (Rauf et al., 2020). However, some researchers suggest a more conservative threshold of 0.5 or higher (Lesia et al., 2024). Some factors have factor loadings lower than 0.7, such as VE1 (Knowledge of VE or similar terms), VE3 (VE reduces cost by creative alternative design), and VECFA2 (The VE team conducts a comprehensive functional analysis to identify the essential and non-essential functions of the product or service). The factors may be evaluating various aspects of the construct, or they could lack a significant link with the underlying construct, as shown by these low-factor loadings. The decision to retain or eliminate these components is made using a mix of statistical standards, including factor loadings, and theoretical considerations. A factor may still be retained even with moderate loadings if it is believed to be theoretically relevant or improves the general interpretation of the factor structure. Furthermore, factors with loadings of factors less than 0.5 should be eliminated since they are unlikely to be significant indicators of the basic idea. Care should be paid to the components whose loadings fall between 0.5 and 0.7, as their addition or removal may be necessary. The factors' theoretical significance, their overall factor structure contribution, and potential cross-loadings on multiple factors are other factors that must be given consideration.

Prior to conducting factor analysis, it is imperative to ascertain the suitability of the data through the application of diverse statistical tests, including but not limited to the Kaiser-Meyer-Olkin (KMO) test for sample adequacy and Bartlett's test of sphericity. The purpose of these tests is to determine whether the data aligns with the necessary assumptions for conducting an exploratory factor analysis (EFA) (Guad et al., 2021). Determining the degree of common variance among the variables, the KMO test assesses the sample's adequacy. The data may be suitable for factor analysis if the KMO score approaches 1. In general, a value of 0.6 or greater is considered satisfactory. In this study, the outstanding KMO score of 0.890 indicates that adequate data exists for factor analysis (Thao et al., 2022). In contrast, Bartlett's sphericity test examines the hypothesis that an identity matrix can be denoted by a correlation matrix in which every correlation coefficient is equal

Table 4. EFA analysis (Rotated component matrix)

Construct	Code	1	2	3	4	5	6	7	8
Knowledge of Value Engineering (VE)	VE2	0.808							
	VE4	0.798							
	VE5	0.780							
Evaluation of Critical Factors for VE Adoption	VECFA1		0.812						
	VECFA3		0.799						
	VECFA4		0.798						
	VECFA5		0.780						
Digital Implementation of VE	DIVE1			0.859					
	DIVE2			0.857					
	DIVE3			0.852					
	DIVE4			0.849					
	DIVE5			0.802					
	DIVE6			0.800					
Information Phase	IP1				0.832				
	IP2				0.808				
	IP3				0.758				
	IP4				0.728				
	IP5				0.710				
Functional Analysis Phase	FAP1					0.842			
	FAP2					0.818			
	FAP3					0.768			
	FAP4					0.748			
	FAP5					0.700			
Operational Phase	OP1						0.837		
	OP2						0.801		
	OP3						0.768		
	OP4						0.758		
	OP5						0.720		
Evaluation Phase	EP1							0.788	
	EP2							0.778	
	EP3							0.768	
	EP4							0.748	
	EP5							0.720	
Implementation Phase	IMPP1								0.743
	IMPP2								0.738
	IMPP3								0.729
	IMPP4								0.718
	IMPP5								0.703

to zero. A factor analysis can be conducted when the interrelation between the variables is significant, and the correlation matrix does not consist of an identity matrix. The research's substantial Bartlett's test (p < 0.001) attests to the suitability of the data for factor analysis. Reliability is added to the results by the KMO and Bartlett's test values, which demonstrate that the data satisfies factor analysis standards. According to the results of these tests, conducting an EFA on the selected data set is viable. A thorough investigation is required to decide whether to keep variables with factor loadings less than 0.7. Theoretical considerations and the factors' general interpretability inside the factor structure should serve as the foundation for this selection. Although factors with loadings less than 0.5 are often eliminated because they are not expected to be good predictors of the core construct, a low loading factor could be kept if it has conceptual significance or improves our comprehension of the construct being assessed. Theoretical relevance, contribution to the overall factor structure, and cross-loading on several factors should all be carefully addressed before keeping or eliminating factors with loadings between 0.5 and 0.7. The results of the EFA provide important new insights into the underlying factor structure of the variables affecting the digitization of VE in building projects. The factor loadings are assessed from a theoretical and statistical standpoint to determine which elements are most pertinent to further study and hypothesis testing. The KMO and Bartlett's test findings confirm that the data is appropriate for factor analysis as shown in Table 5.

Table 5. KMO and Bartlett's test

KMO and Bartlett's Test		
Kaiser-Meyer-Olkin Measure of Sampling Adequacy		0.890
Bartlett's Test of Sphericity	Approx. Chi-Square	5211.909
	df	820
	Sig.	0.000

4.4.2. Measurement model

The measurement model for performing CFA was constructed based on the acquired data to test the model's reliability and validity. A factor loading of 0.7 is commonly regarded as adequate for latent value contribution, and anything less is normally removed from the CFA model. In this study, observed variables with factor loadings below 0.6 were eliminated, resulting in the final well-fitted measurement model as shown in Figure 6. Furthermore, some researchers have employed error correlations between variables to enhance model fit. The validity and reliability of the measuring model are used to demonstrate its dependability and usefulness. The high factor loadings above 0.8 for constructs like IP3, IP5, FAP1, OP3, OP4, OP5, EP1, EP3, IMPP1, and IMPP3 highlight the paramount significance of various aspects in digital VE implementation. Specifically, seamless information access, data validation, integration with existing workflows (e.g., Revit), operational scalability across project elements, regulatory compliance, efficient data handling, informed decision-making capabilities, long-term support, and maintenance, as well as user-friendly training are deemed critically important as discussed in Table 6. In contrast, lower loadings below 0.7 for constructs such as VECFA5, VE2, and OP1 suggest a relatively diminished emphasis on robust evaluation processes for alternatives, positioning VE as a cost reduction method, and return on investment considerations. The reliability of the model before assessing the predicted latent components is analyzed using Construct reliability (CR). The CR values exceeded the recommended threshold of 0.6, which indicates a high degree of reliability. The validity and suitability for future investigations were confirmed through this evaluation of measurement mode. The reliability of the constructs is assessed by reliable indicators of the underlying latent components using CR. CR value is 0.77 for the factor "Knowledge of VE" and for the construct "Evaluation of Critical Factors for VE Adoption" CR value is 0.78 both showing moderate reliability. The CR value is 0.83 for the "Digital Implementation" which effectively captures the essence of the hidden construct through associated observable variables. The "Operational Phase" construct having a CR value of 0.73 shows moderate reliability. The Convergent validity of the model and ability to measure the intended construct is determined and assessed using Average Variance Extracted (AVE). All constructs exceeded the recommended AVE threshold of 0.5 which indicates sufficient convergent validity. The Functional Analysis Phase construct exhibited the highest AVE value of 0.87 which suggests its observable factors described for a considerable proportion of variance in the underlying latent construct. The Digital Implementation of the VE construct was the lowest but acceptable, having an AVE value of 0.73. The overall fit of the data measurement model is evaluated using various goodness-of-fit (GOF) indices. Indices like the Goodness of Fit Index (GFI), Discrepancy Chi-square (Chisq), and Root Mean Square of Error (RMSEA) show the absolute fit of the model representing a good correlation with the observed data. The Chi-square score of 579.91 and p-value greater than 0.01 indicated an exceptional fit. The GFI score of 0.931, which exceeds the recommended 0.90 limit, demonstrated the ability of the model to explain a substantial amount of variation and covariance in the data. The RMSEA value of 0.064, which is within the acceptable range of 0.08, provides further evidence that the model is strongly fit. The Tucker-Lewis Index (TLI = 0.912) and Comparative Fit Index (CFI = 0.925) both exceeded the recommended 0.90 threshold indicate that the research model had a good enough fit compared to the baseline model. The Chi-square to degrees of freedom ratio (Chisq/df = 1.801) which is below the recommended criterion of 3 shows the model is appropriate and efficient. The CR and AVE results satisfy the criteria for validity and reliability resulting in the suitability of the CFA measurement approach for future research in this field. The various GOF indices that value within the recommended acceptance limits indicate that the model is a strong fit to the data. These findings increase the credibility of the model and support its use for further analysis in evaluating critical factors for the digitalization of VE.

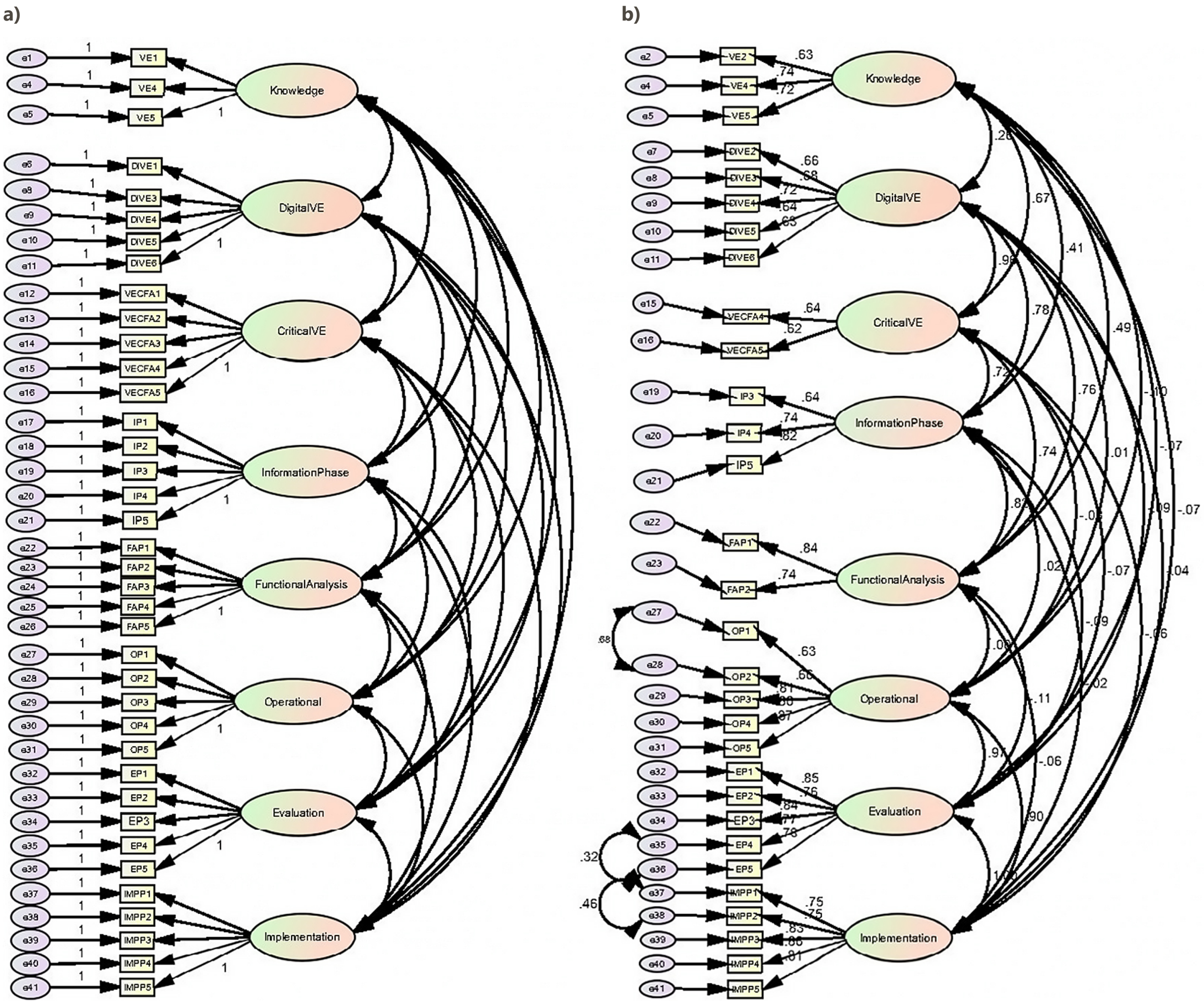

Figure 6. a – CFA-Input path diagram; b – CFA-Output standardized estimates path diagram

Table 6. Reliability and validity outcomes

Construct	AVE > 0.5	CR > 0.6
Knowledge of Value Engineering (VE)	0.74	0.77
Evaluation of Critical Factors for VE Adoption	0.83	0.78
Digital Implementation of VE	0.73	0.83
Information Phase	0.81	0.82
Functional Analysis Phase	0.87	0.85
Operational Phase	0.77	0.73
Evaluation Phase	0.86	0.79
Implementation Phase	0.81	0.88

4.4.3. Structural model (SM)

The Structural Model Output Standardized Estimates Path Diagram is a visual representation of the relationships between the latent constructs (factors) in the structural model, along with the factor loadings (standardized estimates) of the observed variables on their respective latent constructs. This diagram provides insights into the structural relationships among the constructs and the strength of these relationships, which are typically represented as standardized regression coefficients. In the context of this study, the diagram depicts the latent constructs, such as Knowledge of Value Engineering, Evaluation of Critical Factors for VE Adoption, Digital Implementation of VE, Information Phase, Functional Analysis Phase, Operational Phase, Evaluation Phase, and Implementation Phase, as circles or ellipses. The observed variables (e.g., VECFA4, VECFA5, FAP3, FAP4, FAP5, OP1, IP1, IP2) are represented as rectangles. The structural connections between the latent constructs are represented by the connecting arrows, and the strength of these interactions is indicated by the associated values. Figure 7 also shows error correlations, which are shown as curving bi-directional arrows joining the error terms (shown as "e") connected to certain observed variables. The correlated measurement errors of the associated observable variables are identified by these error correlations, and taking related measurement errors with it can enhance the model fit. Three specific error correlations are mentioned: e27–e28, which indicates a moderate positive correlation between the error terms associated with the observed variables represented by e27 and e28; e35–e36, which indicates a less strong positive correlation between the error terms associated with the observed variables represented by e35 and e36; and e37–e38, which indicates a moderate positive correlation between the error terms associated with the observed variables represented by e37 and e38, with a value of 0.50. The inclusion of these error correlations in the model usually occurs when there is proof of associated measurement mistakes, which can arise from several diverse sources, including duplication in item content, item phrasing, or other systematic measurement error causes. As shown in Table 7, it was evaluated the GOF indices for the structural model in addition to the Structural Model Output Standardized Estimates Path Diagram. These indices evaluate the model's overall fit to the data, ensuring an accurate evaluation of the model's applicability. The GFI, RMSEA, and Chisq Absolute Fit Indices, among others, all came within acceptable bounds, suggesting a satisfactory fit between the model and the data. The Incremental Fit Indices, such as the TLI and the CFI, which are both above the recommended values, also showed an appropriate fit with respect to the baseline model. The Parsimonious Fit Index, or Chi-square/Degrees of Freedom, or Chisq/df ratio, eventually fell below the recommended cutoff, indicating a modest and well-fitting model. The Structural Model suited the data well and fell under the recommended acceptability level, as shown by the several GOF indices displayed in Table 8. The inclusion of error correlations (e27–e28, e35–e36, and e37–e38) in the model likely contributed to improving the model fit by accounting for related measurement errors among the observed variables, further enhancing the model's cred-

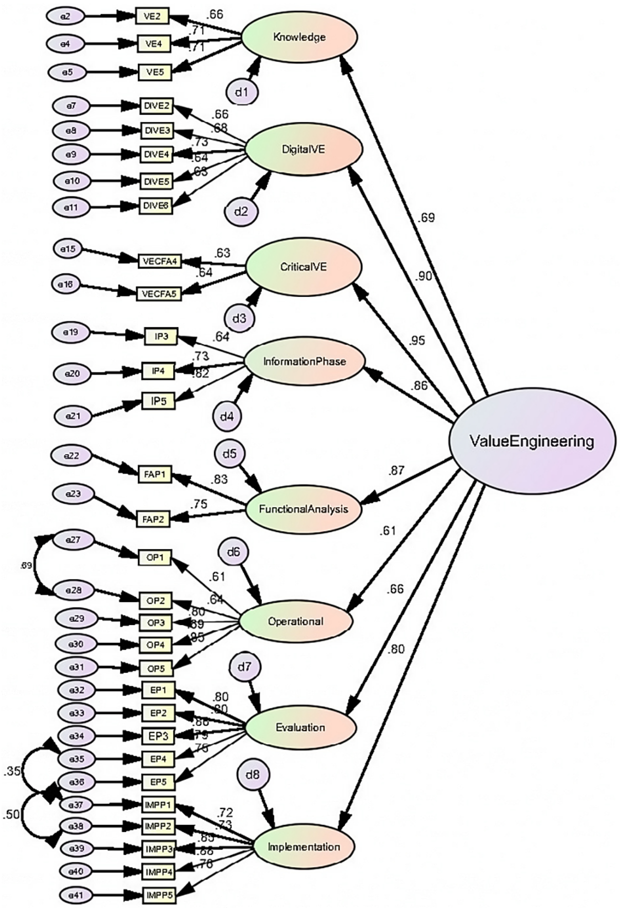

Figure 7. Structural model – Output standardized estimates path diagram

Table 7. GOF indices for the CFA model

Category	Index Name	Index	Attained Values	Acceptance criteria
Absolute Fit Indices	Discrepancy Chi square	Chisq	579.91	p > 0.01
	Goodness of Fit Index	GFI	0.931	>0.90
	Root Mean Square of Error	RMSEA	0.064	<0.08
Incremental Fit	Comparative Fit Index	CFI	0.925	>0.90
Indices	Tucker-Lewis Index	TLI	0.912	>0.90
Parsimonious Fit	Chi Square/Degree of freedom	Chisq/df	1.801	<3

Table 8. GOF indices for the SM model

Category	Index Name	Index	Attained Values	Acceptance criteria
Absolute Fit Indices	Discrepancy Chi-square	Chisq	1219.07	p > 0.01
	Goodness of Fit Index	GFI	0.964	>0.90
	Root Mean Square of Error	RMSEA	0.078	<0.08
Incremental Fit	Comparative Fit Index	CFI	0.948	>0.90
Indices	Tucker-Lewis Index	TLI	0.913	>0.90
Parsimonious Fit	Chi-Square/Degree of freedom	Chisq/df	2.441	<3

ibility and suitability for the analysis of critical factors for digitalization of value engineering in construction projects towards automation using SEM/AMOS Modelling.

Table 9 also presents the SEM outcomes, including the correlation coefficients, p-values, and the SEM outcomes ("Maintained" or "Deleted") for various factors related to the digitalization of value engineering in construction projects. These factors are categorized under different constructs, such as Knowledge of VE, Evaluation of Critical Factors for VE Adoption, Digital Implementation of VE, Information Phase, Functional Analysis Phase, Operational Phase, Evaluation Phase, and Implementation Phase. The correlation coefficients indicate the strength and direction of the relationship between each factor and the respective construct, while the p-values determine the statistical significance of these relationships. Factors with higher correlation coefficients and statistically significant p-values (typically < 0.05) were maintained in the final SEM model, whereas those with lower correlation coefficients or insignificant p-values were deleted.

Table 9. SEM outcomes based on correlation coefficient and P-value in SM model

Construct	Code	Factors	Correlation Coefficient	P-Value	SEM Outcomes
Knowledge of Value Engineering (VE)	VE1	Knowledge of VE or similar terms	0.461	<0.001	Maintained
	VE2	VE is an enhanced tool rather than a method of cost reduction	0.573	<0.001	Deleted
	VE3	VE reduces costs by creative alternative design	0.765	<0.001	Deleted
	VE4	Clients can achieve better value for money if VE is implemented	0.505	<0.001	Maintained
	VE5	Expertise must cover engineering principles, costs, and product functions across disciplines	0.525	<0.001	Maintained
Evaluation of Critical Factors for VE Adoption	VECFA1	The VE team uses an accurate cost model to evaluate the current project	0.401	<0.001	Deleted
	VECFA2	The VE team conducts a comprehensive functional analysis to identify the essential and non-essential functions of the product or service	0.646	<0.001	Deleted
	VECFA3	The VE team uses a systematic process to select the most promising alternatives for further evaluation.	0.766	<0.001	Deleted
	VECFA4	VE team considers the lifecycle cost of the current project in its evaluation	0.588	<0.001	Maintained
	VECFA5	The VE team uses a robust evaluation process to identify the best alternative for the current project	0.638	<0.001	Maintained
Digital Implementation of VE	DIVE1	It can improve the speed and efficiency of the VE process	0.346	0.014	Deleted
	DIVE2	It can increase the accuracy and reliability of VE results	0.151	0.295	Maintained
	DIVE3	It can enable a more comprehensive and creative VE process	0.395	0.005	Maintained
	DIVE4	It can improve the communication and collaboration of VE teams	0.323	0.022	Maintained
	DIVE5	Utilization of digital platforms and tools contributes to making VE more accessible to a wider audience or users	0.472	0.001	Maintained
	DIVE6	Digital implementation can make VE more accessible and affordable	0.548	<0.001	Maintained
Information Phase	IP1	It is important for digital VE to meet the primary needs and requirements of users	0.481	<0.001	Deleted
	IP2	It is important for digital VE facilitation in collaboration and communication within the project team	0.417	0.003	Deleted
	IP3	It is important in digital VE for users to easily access and retrieve relevant information during VE study	0.486	<0.001	Maintained
	IP4	It is important in digital VE to provide transparent information about the sources and methodology used in VE analyses	0.537	<0.001	Maintained
	IP5	It is important in digital VE capability to validate and ensure the accuracy of data input during the information phase	0.729	<0.001	Maintained
Functional Analysis Phase	FAP1	It is crucial to integrate digital VE with the existing Revit environment for your workflow	0.702	<0.001	Maintained
	FAP2	The ability for users to customize and tailor digital VE to meet specific project requirements	0.656	<0.001	Maintained
	FAP3	Complete documentation for digital VE features and functionalities is required	0.707	<0.001	Deleted
	FAP4	Robust error handling and reporting functionality within digital VE to ensure data accuracy	0.612	<0.001	Deleted
	FAP5	Version control functionality is essential for managing changes made through the plugin in a collaborative project environment	0.674	<0.001	Deleted

End of Table 9

Construct	Code	Factors	Correlation Coefficient	P-Value	SEM Outcomes
Operational Phase	OP1	Cost-effectiveness and potential return on investment when considering digital VE adoption	0.491	<0.001	Maintained
	OP2	It will easily gather user input in the digital VE process and features during its usage	0.552	<0.001	Maintained
	OP3	It is critical for the digitalization of VE to assist in ensuring regulatory compliance related to VE practices	0.362	0.010	Maintained
	OP4	Digitalization of VE can scale effectively across several types and sizes of elements	0.396	0.004	Maintained
	OP5	Digitalization of VE can seamlessly integrate with other calculations commonly used in the VE study	0.537	<0.001	Maintained
Evaluation Phase	EP1	Efficient handling of data input and output for digital VE analysis is important	0.729	<0.001	Maintained
	EP2	Digitalization of VE can effectively generate reports and visualizations for alternative assessments	0.702	<0.001	Maintained
	EP3	Digitalization of VE can empower users to make informed decisions during the VE study	0.656	<0.001	Maintained
	EP4	Digitalization of VE can integrate diverse sources of information to enhance the analysis process	0.707	<0.001	Maintained
	EP5	The ability of digital VE can handle information at various levels of granularity, accommodating both detailed and summary data for comprehensive analysis	0.612	<0.001	Maintained
Implementation Phase	IMPP1	It is critical for satisfactory support and maintenance for the long-term use of digital VE in projects	0.674	<0.001	Maintained
	IMPP2	It is critical for user-friendliness for both novice and experienced Revit users when considering a digital VE process	0.491	<0.001	Maintained
	IMPP3	It is important for digital VE to provide user-friendly training materials and onboarding processes	0.552	<0.001	Maintained
	IMPP4	It is critical for digital VE to adhere to security and privacy standards in handling project data	0.362	0.010	Maintained
	IMPP5	The ability of digital VE can automate routine tasks and processes during the VE implementation, reducing manual effort	0.396	0.004	Maintained

4.5. Conceptual framework development

The digital framework as shown in Figure 8 for VE in construction projects is a six-phase approach that combines traditional VE methods with automation and modern digital technology. The phases are Information, Functional Analysis, Creative, Evaluation, Development, and Presentation. The Information phase collects and analyses project data, its specifications and the requirements of the stakeholders. The Functional Analysis phase analyses the functions in detail of the whole project by separating necessary from unnecessary components. The Creative phase encourages brainstorming and innovation to achieve the specified functions while increasing the value of the project. The Evaluation phase assesses the solutions of the alternatives against criteria which is predetermined. The constructability, timing, and resource allocation are considered as selected alternatives during the development phase. The proposed solutions and benefits to stakeholders are presented in the presentation phase. This framework aims to transform VE into construction projects by integrating digital technology for automation by improving efficiency and cost-effectiveness.

The Digital VE framework automates the manual VE process in construction projects by integrating modern digital tools and technologies. Three essential inputs such as project details, an alternative library, and expert opinions are used in this framework. The requirements and specifications of drawings are included in project details for considering the alternative library for continuous improvement in the evaluation phase. Throughout the VE process, expert opinions provide valuable insights and guidance while considering project-specific constraints such as time, budget, schedule, and material availability. It generates measurable outcomes like financial savings, reduced CO_2 emissions, optimized energy usage, and Life Cycle Cost (LCC) analysis. The objective of the framework is to reduce costs and automate to improve the value of the project. In the Information phase, precise cost modelling facilitates information collection, and in the Creative phase, comprehensive functional analysis finds chances to create value. During the adaptation phase, the best solutions are chosen using a methodical process that takes cost, performance, and stakeholder demands into account. Within the VE Job Plan, digital technology facilitates easy information exchange and decision-making, which leads

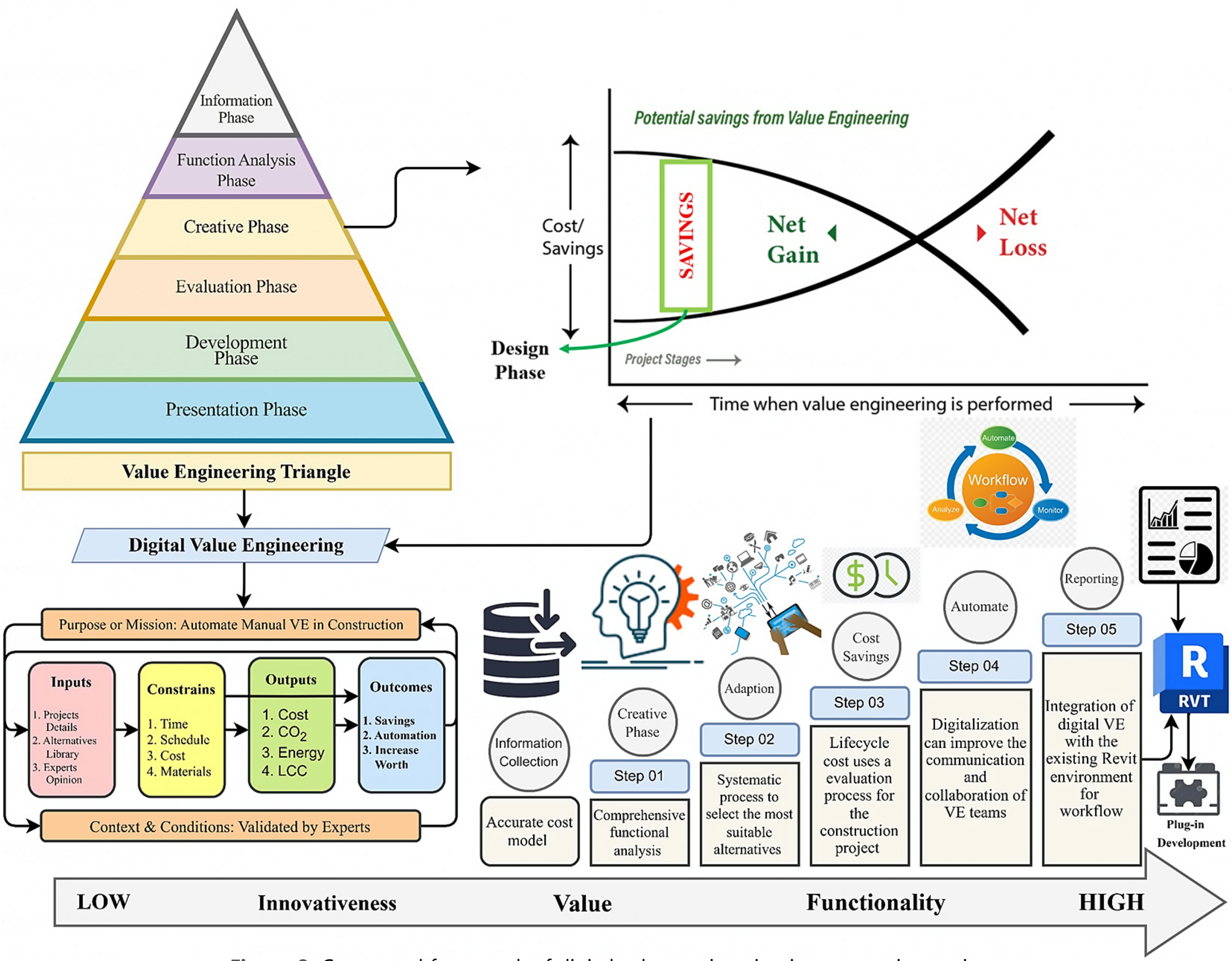

Figure 8. Conceptual framework of digital value engineering in construction projects

to automation. It also improves cooperation and communication. Digital VE solutions are integrated with current processes, including Revit environments, to allow smooth and efficient deployment throughout the reporting phase. This framework provides an integrated approach to project value optimization by preserving the essential ideas and practices of the conventional VE process while using the possibilities of automation and digitization. Using digital technology and encouraging active stakeholder engagement propels innovation, economic efficiency, and sustainability in the construction sector.

5. Discussion

This study set out to investigate and model the critical factors that influence the digitalization of Value Engineering (VE) in construction projects, particularly in the Malaysian context. Using a Structural Equation Modelling (SEM) approach with AMOS, it identified and validated a multi-phase conceptual framework that integrates digital technologies with traditional VE methodologies. The key objective was to bridge the gap between theoretical understanding and practical application of VE digitalization, offering construction stakeholders a robust, data-driven strategy to enhance cost-effectiveness, project value, and decision-making capabilities through digital integration. The discussion below reflects on the research findings, synthesizes them with prior literature, and highlights their implications for theory and practice.

A primary contribution of this study is the development and validation of a holistic framework that models the digital transformation of VE across eight key constructs: Knowledge of VE, Evaluation of Critical Factors for VE Adoption, Digital Implementation of VE, Information Phase, Functional Analysis Phase, Operational Phase, Evaluation Phase, and Implementation Phase. This sequence aligns with the conventional VE job plan but extends it by embedding digital tools and practices within each stage. The conceptual model was tested using empirical data from 199 professionals in the Malaysian construction industry, with results showing high internal consistency (Cronbach's alpha = 0.915) and strong model fit indices (GFI = 0.964, RMSEA = 0.078, CFI = 0.948), reinforcing the reliability and robustness of the findings. Among the most significant insights is the strong performance of constructs such as the Information Phase, Functional Analysis Phase, and Implementation Phase, which registered high factor loadings above 0.8. These phases represent foundational components of the digital VE process, and their importance aligns with existing research emphasizing the central role of structured information management and collaborative design in modern construction. For instance, the high loading of indicators such as IP3 (easy access to relevant information), IP5 (validation of data accuracy), and FAP1 (integration with Revit workflows) confirms that successful digital VE begins with accessible, transparent, and validated project information. This supports the argument by (El Mokhtari et al., 2022; Gonçalves et al., 2022) that digital tools must first address informational gaps before any higher-order optimization can occur.

Furthermore, the Functional Analysis Phase demonstrated strong performance through factors such as FAP2 (customizability for project-specific needs) and FAP3 (comprehensive documentation). These suggest that digital VE must not only digitize existing processes but also allow for adaptability and flexibility in applying those processes to varied project conditions. This resonates with the findings of Bakhshi et al. (2024) who emphasize that the value outcomes of VE are highly dependent on the ability to customize tools to meet project-specific constraints, such as design complexity, stakeholder priorities, and regulatory demands.

Equally important is the study's validation of the Implementation Phase, which emerged as a critical area for ensuring long-term sustainability of digital VE initiatives. Indicators such as IMPP1 (long-term support and maintenance), IMPP3 (user-friendly training), and IMPP5 (automation of routine tasks) were shown to have high explanatory power. These findings highlight the necessity of not only deploying digital VE systems but also sustaining them through institutional support, adequate training, and automated processes that reduce manual labor. Prior literature has often noted that the biggest challenges in construction digitalization lie not in tool availability but in change management and end-user adoption. This is reflected in Langseth et al. (2023) study, which notes that successful digital transformation depends heavily on training and long-term support mechanisms.

On the other hand, constructs such as VE2 (VE as a cost-cutting tool) and OP1 (return on investment considerations) displayed lower factor loadings, indicating a shift in perception regarding VE's role. Historically, VE has been associated with minimizing cost without compromising quality. However, the findings suggest that this narrow view is being replaced with a broader understanding of VE as a mechanism for value optimization rather than just cost reduction. This trend is supported by Askar et al. (2021) who emphasize that the modern role of VE should include considerations of sustainability, lifecycle value, user satisfaction, and adaptability to future needs. Therefore, while cost is still an important metric, the contemporary construction environment values holistic performance metrics, and digital VE tools are instrumental in facilitating such comprehensive evaluations. Another important finding is the empirical confirmation of the Digital Implementation of VE construct, which encompasses factors such as enhanced communication (DIVE4), broader accessibility (DIVE5), and affordability (DIVE6). These elements were shown to have significant effects on the overall VE process, confirming that the integration of digital tools like Building Information Modelling (BIM), cloud platforms, and decision-support systems enhances not only technical performance but also collaboration, stakeholder engagement, and inclusiveness. These results affirm the conclusions of Vemuri et al. (2024) who emphasized that immersive technologies like VR and cloud-based platforms not only improve visualization but also foster shared understanding among multidisciplinary teams.

The study also highlights the crucial role of operational scalability and regulatory compliance in digital VE. Operational factors such as OP4 (scalability across project types) and OP5 (integration with other calculations) underscore the importance of interoperability and adaptability of digital VE tools. Compliance-related factors (OP3) suggest that regulatory alignment is a key enabler of digital transformation, particularly in public-sector projects. This is consistent with the findings of Fateh and Aziz (2021) who noted that government-mandated VE requirements play a significant role in accelerating adoption across Malaysian construction projects. Beyond theoretical contributions, this research provides practical implications for multiple stakeholders. For construction managers and engineers, the findings provide a data-driven guide to prioritize investments in digital VE enablers, such as structured data platforms, stakeholder communication tools, and integrated cost-value assessment systems. The validation of constructs related to user-friendliness and automation indicates that system design must consider both technical and human dimensions. Moreover, training and onboarding remain essential to build competency in digital VE practices, ensuring these systems are used to their full potential.

For policymakers and industry regulators, the study offers evidence-based insights into where policy support and institutional investment are most needed. For example, government mandates that tie VE compliance to funding approval, or that incentivize the use of BIM-integrated VE tools, can significantly boost adoption rates. In emerging markets like Malaysia, where VE awareness remains low, public-private partnerships may be instrumental in creating the digital infrastructure, training programs, and certification schemes necessary for widespread VE transformation. Despite these contributions, the study is not without limitations. While the sample of 199 respondents provided statistically valid results, it was geographically limited to Malaysia, which may affect the generalizability of the findings. Future research could expand the model across other Southeast Asian or developing countries to compare contextual differences in digital VE adoption. Additionally, while SEM provides strong statistical validation, a mixed-method approach incorporating qualitative case studies would enrich the understanding of how digital VE frameworks are implemented in practice. Observations of real-time VE workshops or interviews with VE facilitators could uncover nuanced barriers and success factors that are not easily captured through surveys. This study presents a comprehensive, empirically validated framework that models the digitalization of Value Engineering in construction projects. It addresses a significant research gap by aligning theoretical constructs with practical realities through SEM and offering a structured roadmap for stakeholders seeking to improve value outcomes through digital transformation. The results confirm that effective digital VE is not only about technological tools but also about structured information flow, collaborative processes, regulatory alignment, and sustained institutional support. As the construction industry continues to evolve, such integrated models will be crucial for achieving sustainable, high-value outcomes in increasingly complex project environments.

6. Conclusions

The digital transformation of the construction sector demands innovative approaches to enhance project value, efficiency, and stakeholder collaboration. VE, traditionally applied as a cost-saving methodology, is now being reimagined as a data-driven, digitally enabled framework capable of supporting complex decision-making across the project lifecycle. This study explored the critical factors influencing the digitalization of VE in construction projects through a conceptual model validated by SEM using data collected from 199 Malaysian construction professionals. The integration of both quantitative analysis (SEM and descriptive statistics) and qualitative insights (literature synthesis and expert validation) forms the basis of this comprehensive assessment. The research identified 41 significant indicators and grouped them under eight latent constructs, aligning with the phases of the VE job plan and enriched by digital technology considerations. The SEM analysis validated the proposed framework, revealing that constructs such as the Information Phase, Functional Analysis Phase, and Implementation Phase hold the highest significance in successful digital VE integration. These results quantitatively confirm the centrality of seamless data access, workflow integration with tools like BIM, stakeholder coordination, and sustainable support mechanisms as key enablers for digital VE. Qualitatively, the research highlights a paradigm shift in how VE is perceived and applied within construction. No longer viewed as merely a cost-reduction exercise, digital VE is now recognized for its ability to enhance lifecycle value, support regulatory compliance, drive innovation, and improve stakeholder satisfaction. The findings support an emerging body of literature advocating for VE's broader role in value optimization, sustainability, and cross-functional collaboration. This study concludes that successful digital VE implementation depends on a careful orchestration of organizational culture, technological readiness, and project-level adaptability. The proposed conceptual framework provides a practical roadmap for stakeholders aiming to enhance VE performance through digitalization, offering measurable benefits in terms of project efficiency, quality, and value delivery.

6.1. Practical and theoretical implications

This research contributes to VE and construction management literature in several significant ways. First, it advances theoretical understanding by developing a holistic, phase-based conceptual model that maps the relationships between digital technologies and VE practices. While previous studies have explored digital tools in isolation (e.g., BIM, VR), this study connects them within a structured VE framework, offering a unified model that mirrors real-world workflows. This model integrates digital enablers, organizational dynamics, and operational contexts, bridging a gap in prior research that often considered these elements in silos. Second, the use of SEM offers quantitative validation for constructs that were previously only theorized or qualitatively described. By statistically testing relationships among key success factors, the study reinforces the causal pathways that underlie effective digital VE implementation. This strengthens the empirical foundation of VE scholarship and invites future researchers to test or expand this model in other contexts or regions. Third, the research reframes the role of VE knowledge and evaluation as foundational rather than supplementary. The findings show that initial awareness and comprehension of VE concepts significantly influence later phases of digital adoption, suggesting that theoretical models must account for knowledge dissemination and capacity-building as core elements.

From a practical standpoint, this study provides several important takeaways for construction professionals, managers, policymakers, and technology providers. Project managers can use the validated framework to guide strategic planning and implementation of digital VE systems. The findings recommend that stakeholders prioritize investments in information access systems, collaborative platforms, scalable digital solutions, and user-centered training programs. In particular, the results emphasize the importance of interoperability and integration digital VE tools must align with existing project management systems, regulatory requirements, and functional design processes. Stakeholders should not merely adopt digital tools but embed them into a lifecycle-oriented VE strategy that begins at the conceptual design phase and continues through implementation and post-occupancy evaluation. For policymakers and regulatory agencies, the results underscore the need to institutionalize digital VE practices through public guidelines, industry incentives, and capacity-building programs. Given the relative underdevelopment of VE practices in Malaysia, there is a clear opportunity to accelerate industry-wide transformation through regulatory support and public-private partnerships. Technology developers and digital platform providers can also benefit from this study by aligning their tools with the critical constructs identified particularly focusing on features that enhance data accuracy, functional analysis, regulatory tracking, and automation.

6.2. Limitations of the study

While this study offers valuable insights, certain limitations must be acknowledged. First, the research is geographically limited to Malaysia. Though the sample was diverse in terms of roles, experience, and project types, the findings may not be entirely generalized to other national contexts where construction practices, digital maturity, and VE adoption levels differ. Second, while SEM is a powerful statistical tool, it is primarily based on self-reported survey data, which may carry biases related to perception and experience. Third, the study did not include detailed case studies or direct field observations, which could have added greater depth to the interpretation of how digital VE tools are applied in real-world settings. Fourth, the fast pace of technological advancement in construction means that some tools and platforms evaluated in this study may evolve rapidly, potentially altering their impact or relevance. Lastly, this research focuses on VE from a project-level perspective and does not fully explore the organizational transformation and change management aspects that may be required for digital VE to thrive at scale.

6.3. Methodological limitations

One limitation of this study is the use of the same dataset for both EFA and CFA. While necessary due to sample size constraints, this approach may lead to overestimated model fit statistics. Although the sequence of EFA followed by CFA on the same data is common in studies with similar constraints, best practice recommends separate datasets or validation methods to ensure the robustness of the factor structure. Future research should address this by employing hold-out samples, cross-validation, or independent datasets to enhance generalizability and mitigate the potential inflation of fit indices.

6.4. Future recommendations

To build on the findings of this study, future research should explore cross-country comparative studies to understand how cultural, regulatory, and economic factors influence digital VE adoption across diverse regions. Such research could offer a more globalized model of digital VE and help refine implementation strategies in various socio-economic contexts. Incorporating qualitative methods, such as in-depth interviews, field observations, and longitudinal case studies, can complement the quantitative findings and provide richer insight into real-world application challenges and success stories. For instance, future research could follow VE project teams over time to examine how digital tools are integrated into their workflows, how resistance is managed, and how outcomes evolve. Future studies should evaluate the effectiveness of specific technologies such as digital twins, AI-powered design optimization tools, or blockchain-based VE tracking systems on improving VE outcomes. Assessing how these tools interact with the constructs identified in this study could offer actionable insights for tool developers and adopters alike. Further exploration of Return on Investment (ROI) and life-cycle cost modeling in digital VE projects is also recommended. While this study identified these factors, future research could quantify their economic and sustainability impacts more explicitly. Lastly, there is a need for industry-wide best practices and standards for digital VE. Professional bodies and academic institutions can collaborate to create training modules, certification programs, and implementation toolkits to accelerate adoption and build digital literacy in VE practices.

Author contributions

All the authors contributed equally to this study.

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Conflicts of interests

The authors declare that they have no conflict of interest.

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