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Research Paper

Digital Value Engineering for Sustainable Commercial Buildings: A BIM and Life Cycle Cost-Based Decision-Making Framework

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Abstract

Sustainable commercial buildings require cost-effective and environmentally responsible design solutions. Traditional Value Engineering (VE) methods, while effective in cost reduction, often lack integration with digital tools, limiting their ability to optimize sustainability and performance. This study develops a Digital Value Engineering Model (DVEM) that aligns with Industry 4.0 principles, incorporating Building Information Modeling (BIM), Life Cycle Cost (LCC) analysis, and a weighted evaluation matrix to enhance decision-making transparency, cost efficiency, and environmental impact assessment. The model was implemented in Autodesk Revit and applied to a real-life commercial building project in Malaysia, systematically following six VE phases. The results demonstrate a 28% cost reduction while optimizing material selection, energy efficiency, and lifecycle performance. Unlike conventional VE, DVEM enables automated cost analysis, real-time sustainability assessment, and function-based decision modeling. By bridging traditional VE with modern digital workflows, this study provides a replicable, data-driven approach to optimizing commercial building design. The findings contribute to the construction industry by introducing a structured, scalable framework that enhances decision-making efficiency, resource utilization, and sustainability compliance in commercial building projects.

Keywords: *building information modelling; commercial buildings; , digital decision-making; life cycle costing; sustainability; value engineering.*

Introduction

The construction industry plays a vital role in economic and societal development, yet it continues to face persistent challenges related to cost overruns, inefficient resource utilization, and sustainability compliance (Abdelghany et al., 2015). Traditional project decision-making prioritizes cost and time, often neglecting the long-term environmental and economic impact of building projects (Zainul Abidin & Pasquire, 2005). This has led to unsustainable construction practices that contribute to excessive energy consumption, material wastage, and operational inefficiencies (Abidin & Pasquire, 2007; Zainul Abidin & Pasquire, 2005). Value Engineering (VE) is a structured methodology that enhances project performance by systematically optimizing costs without compromising functionality or quality (Aboelmaged, 2018). VE provides an effective framework for identifying cost-saving opportunities while maintaining or improving project value (Ahmed & Pandey, 2016). However, conventional VE practices are largely manual and lack integration with digital technologies, limiting their ability to support data-driven decision-making in complex construction projects (Al-Anzi et al., 2017).

In recent years, Building Information Modeling (BIM) and computational tools have emerged as key enablers of digital transformation in the construction industry . These technologies allow for real-time analysis of project alternatives, cost estimation, and sustainability assessment, making them ideal for integration into VE methodologies (Al-Yousefi & CVS-Life, 2007). Despite the potential of digital VE models, most existing approaches remain limited to infrastructure

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projects, with few applications in commercial building projects (Al-Yousefi, 2008). This gap highlights the need for an advanced, digitalized VE framework that leverages BIM and data analytics for improved decision-making in commercial construction (Aljerf & Choukaife, 2016). This study develops a Digital Value Engineering Framework (DVEF) that integrates BIM, Life Cycle Cost (LCC) analysis, and sustainability assessment to enhance cost efficiency, resource optimization, and environmental sustainability in commercial buildings (Arivazhagan et al., 2017; Atabay & Galipogullari, 2013).

The application of VE in commercial buildings has been relatively underexplored compared to infrastructure projects (Bowen et al., 2009). While VE is widely used in sectors such as transportation, water management, and industrial construction, its adoption in high-rise and multi-functional commercial buildings remains limited (Zheng et al., 2017). These buildings are characterized by complex design requirements, high energy demands, and significant lifecycle costs, making them ideal candidates for advanced VE applications (Kineber, Mohandes, et al., 2022). However, traditional VE methodologies are manual, time-consuming, and rely heavily on subjective expert judgment, leading to inconsistencies in decision-making (Kineber, Othman, Oke, Chileshe, & Alsolami, 2020). Integrating BIM-based cost analysis, automated sustainability assessments, and digital decision-support tools can enhance the efficiency and accuracy of VE in commercial construction (Kineber, Othman, Oke, Chileshe, & Buniya, 2020). This study addresses this gap by developing and applying a Digital VE Framework tailored specifically for commercial building projects (Kineber, Uddin, et al., 2022). A major limitation of existing VE models is their primary focus on cost reduction without adequate consideration of sustainability and long-term lifecycle performance (Chen et al., 2019). VE studies traditionally emphasize reducing initial construction costs, often overlooking the impact of material selection, energy efficiency, and long-term operational costs (Chan & Kumaraswamy, 1997). In contrast, sustainability-driven VE models incorporate environmental impact assessments, life cycle costing, and energy performance optimization, aligning with modern green building standards (Bocken et al., 2014). This study integrates sustainability principles into the VE process by using BIM-based energy analysis, material lifecycle assessments, and weighted evaluation matrices to enhance decision-making. By doing so, it offers a comprehensive approach that balances cost efficiency with long-term environmental sustainability (Erten et al., 2022). Recent research has explored the potential of Industry 4.0 in construction, emphasizing digitalization, automation, and real-time data analytics . However, most Industry 4.0 applications in VE remain theoretical, with few practical implementations in real-world projects. Many studies discuss theoretical frameworks for digital VE but fail to demonstrate how digital tools can be effectively integrated into construction workflows. This study clarifies the role of digital tools in VE by applying BIM-based decision-support systems to a commercial building project in Malaysia. While this study does not claim a full Industry 4.0 implementation, it represents a step towards digital transformation in VE by leveraging BIM, automated cost estimation, and sustainability metrics. By focusing on practical, data-driven applications, this research provides a more realistic and implementable approach to digital VE . One of the major research gaps in VE studies is the lack of a structured framework that integrates BIM, LCC analysis, and sustainability-driven decision-making. Conventional VE models are often criticized for their subjectivity and lack of quantitative assessment tools, leading to inconsistencies in project evaluations (Upadhyay & Punekar, 2023). Existing studies on VE and digital decision-making have primarily focused on infrastructure projects, neglecting the unique challenges of commercial buildings. Additionally, while previous research Kineber, Mohandes, et al. (2022) has proposed structured VE frameworks for sewer projects, there has been no significant adaptation of these models for commercial building applications. This study builds upon Kineber, Mohandes, et al. (2022) by adapting the VE methodology to commercial buildings, integrating BIM-based sustainability assessment and digital cost evaluation to enhance project outcomes. By applying this modified framework to a real commercial building project, this study provides empirical evidence of the benefits of digital VE in commercial construction (Kineber, Mohandes, et al., 2022). To address these research gaps, this study aims to develop and implement a Digital Value Engineering Framework (DVEF) that enhances cost efficiency and sustainability in commercial building projects (Menna et al., 2021).

This research aims to: (1) develop a Digital Value Engineering Framework (DVEF) integrating BIM and sustainability metrics to enhance cost optimization and environmental performance; (2) apply the framework to a real commercial building case study in Malaysia; and (3) compare digital VE with traditional VE in terms of cost savings, efficiency, and sustainability. BIM forms the foundation of the DVEF by enabling automated quantity take-offs, cost estimation, and sustainability assessment. The study incorporates Life Cycle Cost (LCC) analysis to evaluate long-term economic impacts of design alternatives, while a weighted evaluation matrix compares cost, environmental impact, and functional efficiency for data-driven decision-making. Unlike traditional VE, which relies on manual and qualitative methods, BIM-based tools improve accuracy and transparency. The study is particularly relevant in Malaysia, where construction faces cost overruns, inefficiencies, and environmental challenges, while digital VE adoption remains limited. The paper is structured into six sections: literature review, methodology, case study, analysis, discussion, and conclusion. The research advances sustainable construction by providing a practical, replicable, data-driven VE model that bridges conventional cost-focused approaches with sustainability-driven design strategies.

Literature Review

VE and sustainable construction operations

Value Engineering (VE) is a structured, function-based methodology aimed at maximizing a project's value by optimizing cost, performance, and sustainability (Francis & Thomas, 2020; Rathi et al., 2022). Initially developed in the manufacturing industry, VE has since been widely adopted in construction, infrastructure, and industrial projects to improve resource efficiency and cost-effectiveness (Kineber, Mohandes, et al., 2022; Kineber, Othman, Oke, Chileshe, & Buniya, 2020). VE methodologies follow a systematic six-phase process, including information gathering, functional analysis, creativity, evaluation, development, and implementation (Yanita & Mochtar, 2021). However, traditional VE approaches remain limited in their integration with digital tools and sustainability metrics, often focusing primarily on cost reduction rather than holistic performance optimization (Gatea et al., 2020; Karimi et al., 2023). Sustainability in construction has become an essential requirement due to increasing environmental concerns , resource depletion , and regulatory pressures . However, conventional VE methodologies have not fully adapted to the sustainability-driven decision-making paradigm (Pioppi et al., 2020). Traditionally, VE focuses on minimizing material costs and construction time, often overlooking factors such as life cycle performance, embodied carbon, and environmental impact . This limitation has led to growing interest in sustainability-driven VE models, which incorporate Life Cycle Costing (LCC), energy efficiency evaluations, and material sustainability assessment (Javaid et al., 2022). Several studies have explored the integration of VE with sustainability principles. For instance, Al-Yousefi (2007) emphasized the role of VE in sustainable construction by demonstrating how optimized material selection and functional design adjustments can reduce environmental impacts. Similarly, Ang and Marchal (2013) highlighted that VE practices in government-led infrastructure projects often fail to address long-term sustainability benefits, focusing primarily on upfront cost reductions (Elmousalami, 2020). This research gap underscores the need for a more comprehensive VE framework that integrates BIM-based modelling, sustainability assessments, and real-time decision-making tools . A critical limitation in existing VE models is their reliance on qualitative assessments and expert judgments, leading to subjectivity in decision-making. Traditional VE workshops typically involve manual cost estimation, paper-based function analysis, and ad-hoc decision matrices, which are time-consuming and prone to inconsistencies . In contrast, BIM-integrated VE models provide a data-driven, automated approach for optimizing construction decisions . By incorporating BIM, computational cost models, and sustainability performance metrics, digital VE frameworks allow for real-time scenario analysis and lifecycle assessments .

The Pareto Principle, also known as the 80/20 rule, has been widely applied in construction project management and cost optimization . It suggests that 80% of project expenses typically stem from just 20% of the project components . This principle is particularly relevant in VE, as it allows engineers to focus optimization efforts on the most cost-intensive elements . Several VE studies have demonstrated the effectiveness of applying Pareto analysis in construction. Nsiah et al. (2024) applied the Pareto approach to building materials selection, showing that a small subset of materials contributed disproportionately to overall project costs. However, despite mentioning the Pareto Principle, this study lacks a visual representation of its application in the case study. To enhance clarity, a Pareto chart should be developed for the commercial building case study to visually illustrate the distribution of costs across project components. This will help in identifying which key cost-driving elements should be prioritized in the VE process .

Another major challenge in VE research is the lack of empirical validation of digital VE models in real-world projects . While many studies advocate for the adoption of BIM, LCC analysis, and computational decision-support tools, few provide actual case studies demonstrating their effectiveness. Kineber, Mohandes, et al. (2022) proposed a VE framework for sewer projects, integrating sustainability assessments and digital decision-making tools . However, this model was developed for linear infrastructure projects and lacks adaptation for commercial building applications . This study aims to address this gap by modifying the Kineber, Mohandes, et al. (2022) framework for commercial buildings, incorporating BIM-based life cycle cost analysis and multi-criteria decision matrices to improve cost efficiency and sustainability (Ershadi et al., 2021; Urton & Murray, 2021).

Use of VE in several engineering sectors

Value Engineering (VE) has been successfully implemented across various engineering disciplines, ranging from transportation and infrastructure projects to industrial and residential construction (Arenas & Shafique, 2023). Its primary objective remains consistent across sectors: to enhance project value by optimizing costs, improving functional efficiency, and ensuring sustainability . However, the extent of VE integration varies significantly between sectors, with some industries adopting digital tools and sustainability-driven assessments, while others continue to rely on traditional, cost-cutting approaches (Safari & AzariJafari, 2021). Transportation and infrastructure projects have been among the most prominent beneficiaries of VE methodologies, with applications spanning road networks, bridges, railways, and urban transit systems (Costa-Carrapiço et al., 2020). VE has been instrumental in optimizing material selection, reducing construction costs, and improving long-term maintenance strategies . Studies in this domain have shown that early-stage VE implementation can lead to cost savings of 10% to 25% without compromising performance or safety (Othman et al., 2021). For example, VE has been applied to road construction projects to evaluate alternative pavement materials and optimize geometric designs. A study by Lamptey et al. (2008) demonstrated how VE in highway maintenance planning reduced long-term operational costs by identifying cost-effective resurfacing strategies. Similarly, Kineber, Mohandes, et al. (2022) applied VE to sewer infrastructure projects, integrating sustainability assessments to enhance long-term performance. However, while these studies highlight the effectiveness of VE in linear infrastructure, the methodologies used remain heavily reliant on manual decision-making processes, lacking digital integration .

BIM-based VE models offer significant potential for optimizing transportation projects by integrating real-time cost analysis, traffic simulations, and lifecycle performance assessments (Olanrewaju et al., 2022). Unlike traditional methods that primarily focus on initial cost reductions, digital VE approaches allow for multi-criteria optimization, considering safety, durability, environmental impact, and maintenance costs simultaneously . Despite these advancements, the application of BIM-integrated VE in transportation projects remains limited, necessitating further research on digital VE adoption in large-scale infrastructure planning (Kineber et al., 2021). Marine construction projects, such as ports, offshore platforms, and shipbuilding, face unique challenges related to structural integrity, environmental impact, and harsh operating conditions . VE has been applied in this sector to reduce construction costs and improve the longevity of marine structures (Mohammadi et al., 2022; Subramanya et al., 2022). Tusar and Sarker (2022) highlighted how VE can be effectively used to optimize material selection in offshore oil platforms, reducing both initial construction expenses and long-term maintenance costs . However, one of the biggest challenges in marine construction is the lack of standardized VE practices, which makes decision-making highly project-specific and reliant on expert judgment rather than data-driven analysis (Kumar et al., 2020; Röck et al., 2020). Similarly, in the industrial construction sector, VE has been applied to enhance manufacturing facility layouts, optimize HVAC systems, and improve structural design efficiency . Studies have demonstrated that incorporating VE in the industrial sector can result in cost savings of up to 20% by optimizing workflow layouts, energy consumption, and material efficiency. However, most industrial VE applications still focus primarily on cost-cutting, with limited emphasis on sustainability and digital integration . Digital twins and AI-driven simulations present an opportunity for enhancing VE decision-making in industrial projects by providing real-time analytics and predictive modeling (Pontius & McIntosh, 2024).

In building construction, VE has been widely used to enhance architectural and structural designs, ensuring that projects meet functional requirements while minimizing costs . Residential and commercial buildings benefit from VE through optimized material selection, efficient space utilization, and improved energy performance . A multi-objective optimization model is developed for sustainable building retrofits, using BIM to evaluate cost, energy efficiency, and material durability (Ikudayisi et al., 2022). The study demonstrated how BIM-based VE frameworks improve sustainability compliance and enhance decision-making transparency . However, despite these advancements, most real-world applications of BIM-integrated VE in commercial and residential buildings remain limited (Aslam et al., 2021). One of the key challenges is the lack of industry-wide adoption of digital VE models, with many projects still relying on traditional, paper-based VE workshops . Additionally, most VE studies in the building sector focus solely on cost reduction, failing to incorporate life cycle cost (LCC) analysis, energy performance assessments, or carbon footprint evaluations (Abioye et al., 2021; Viles et al., 2020). This highlights the need for a more holistic, data-driven VE approach in the construction industry, integrating BIM, sustainability metrics, and real-time cost analysis (Bohra & Anvari‐Moghaddam, 2022). The application of VE in water management and irrigation projects has focused on enhancing efficiency, reducing waste, and improving sustainability . Studies have shown that VE can be used to optimize irrigation system layouts, reduce pipeline material costs, and improve water distribution efficiency (Li et al., 2022). In irrigation projects, VE has been used to evaluate alternative pipeline materials, optimize drainage designs, and reduce environmental impact (Alobaidi et al., 2020). For instance, Panagopoulos et al. (2014) applied VE to irrigation network design, identifying cost-effective solutions that improved water flow efficiency while minimizing resource consumption. Similarly, highlighted how VE-based decision-making led to significant cost savings in water reuse projects by evaluating alternative treatment technologies. However, a major limitation in VE applications in water management is the lack of integrated sustainability assessments, with most studies focusing solely on cost minimization rather than long-term environmental impact (Arena et al., 2020). BIM and digital tools present an opportunity to enhance VE in irrigation and water infrastructure projects by enabling real-time hydrological modeling, climate impact assessments, and automated material selection (Gong et al., 2023). Future research should focus on integrating digital VE models with hydrodynamic simulations, allowing for smarter, more sustainable water management strategies (Johnsson et al., 2020). Despite the proven benefits of VE across different engineering sectors, several challenges persist . One of the key issues is the lack of management support for VE implementation, particularly in developing countries, where decision-makers often prioritize upfront cost reductions over long-term value optimization (Shu et al., 2021). Studies have shown that senior management resistance is one of the biggest barriers to VE adoption, as stakeholders may not fully understand the long-term benefits of VE-based decision-making (Kim et al., 2020). Additionally, VE has been criticized for its over-reliance on cost-cutting measures rather than focusing on holistic project improvements . For example it is found that many VE studies neglect non-monetary factors such as safety, aesthetics, and environmental sustainability, leading to suboptimal design choices (Bastos Porsani et al., 2021). To address this, multi-criteria decision-making models should be incorporated into VE, ensuring that both quantitative and qualitative project factors are considered (Kiu et al., 2022). Another major challenge is the limited integration of digital tools in VE workflows. Although BIM-based VE frameworks have been proposed in several studies, real-world adoption remains slow due to the industry's reliance on traditional VE workshops (Güleroğlu et al., 2020).

The transition towards fully digitalized VE models requires widespread BIM adoption, improved stakeholder collaboration, and enhanced computational decision-support tools (Abioye et al., 2021). The comprehensive overview presented in Table 1 consolidates the findings from existing literature, spanning diverse applications and sectors (Delgado et al., 2020; Mathivathanan et al., 2021; Nilimaa, 2023; Umoh et al., 2024). The matrix delves into various factors, including sustainability, cost savings, quality and performance, time savings, stakeholder involvement, design optimization, risk mitigation, waste reduction, and life cycle cost considerations. However, certain applications, such as marine construction and government initiatives in developing countries, have encountered challenges or lack sufficient information regarding the effectiveness of VE implementation. Simultaneously, it highlights gaps or limitations in aspects like stakeholder involvement, risk mitigation, and life cycle cost considerations across various applications. VE has been successfully applied in transportation, marine, industrial, building, and water management projects, demonstrating its ability to enhance cost efficiency and optimize project performance. However, significant gaps remain in digital VE adoption, sustainability integration, and industry-wide implementation. By developing a Digital Value Engineering Framework (DVEF) and applying it to a commercial building case study in Malaysia, this research addresses some of these gaps by integrating BIM, LCC analysis, and sustainability-driven decision-making. Future studies should focus on scaling digital VE methodologies across different engineering disciplines, ensuring that value optimization extends beyond cost reduction to include long-term sustainability and operational efficiency.

Table 1 Comprehensive overview of VE applications and impacts across various factors and project types

Factors/ Application	Sustainability	Cost Savings	Quality/ Performance	Time Savings	Successful Implementation	Stakeholder Involvement	Design Optimization	Risk Mitigation	Waste Reduction	Life Cycle Cost	Environmental Impact	Social Impact	Economic Impact
Construction Projects	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Road Construction	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Marine Construction	✓	✓	✓	✓	×	✓	×	×	×	✓	✓	✓	✓
Building Projects	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓	✓
Irrigation Projects	✓	✓	✓	✓	✓	✓	×	✓	×	×	✓	✓	✓
Transportation Sector	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Industrial Sector	×	✓	✓	×	×	✓	✓	✓	×	×	✓	✓	✓
Residential Construction	✓	✓	✓	✓	✓	✓	✓	×	✓	✓	✓	✓	✓
Pipeline Transmission	×	✓	✓	×	×	✓	✓	✓	×	×	×	✓	✓
Government Initiatives (Developing Countries)	×	×	×	×	×	×	×	×	×	×	×	×	×
New Construction Techniques	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Retrofit/Renovation Projects	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Research Methodology

The research follows a mixed-method approach, integrating qualitative and quantitative methodologies. The qualitative approach involves FAST (Function Analysis System Technique) and brainstorming to identify areas for value improvement. The quantitative approach includes mathematical models and digital plugin-based analysis, incorporating decision matrix analysis, life cycle cost analysis (LCCA), and benefit-cost ratio analysis. The methodology aligns with SAVE (2008) standards, covering pre-study, main study, and post-study phases. The pre-study phase involves the Information and Functional phases, where project objectives are defined, and key areas for improvement are identified. The main study phase includes the Creativity, Evaluation, and Development phases, generating and assessing alternatives using digital tools. The post-study phase focuses on the Output phase, finalizing VE recommendations. This structured approach ensures systematic value enhancement, integrating BIM-based VE for optimized decision-making while addressing sustainability, cost efficiency, and functional performance. The study design used in Figure 1 was taken from SAVE (2008) (Kelly et al., 2014).

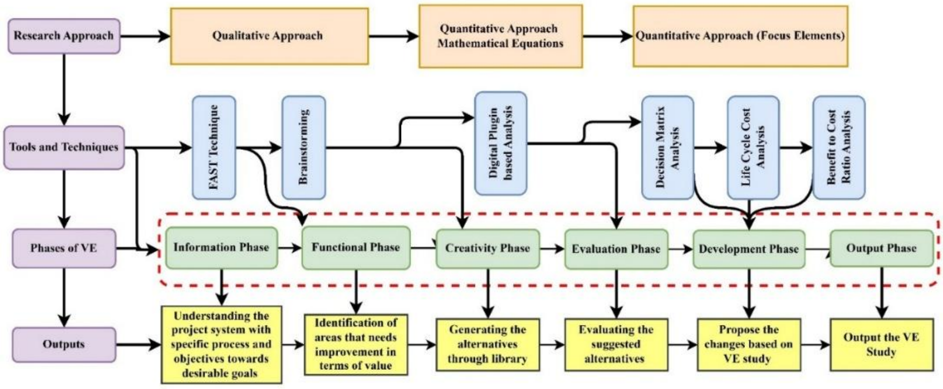


Figure 1 Flow chart of research methodology.

Information Phase

This stage involves gathering important data about the proposed commercial construction project in a structured and systematic way. Every document pertaining to the project is carefully reviewed, including specifications, customer needs, bills of quantities, design bases and standards, drawings, and estimated project costs. The purpose of this phase is to help customers and end users clearly and concisely communicate the objectives, scope, expectations, and needs for their planned commercial building projects. This phase involves a thorough assessment and analysis of the study's purpose as well as the present project conditions (El-Nashar & Elyamany, 2018).

3.2. Functional Phase

Functional analysis is carried out to discover the fundamental purposes of commercial building once a sufficient level of project comprehension has been attained. This process aids in identifying and determining the function of each component utilized in the project. It is crucial to understand how these roles relate to one another and how they help the building accomplish its main purpose. A function analysis system technique should be used to link the functions to one another after they have been identified and categorized. This will help to explain their relationships and provide a more comprehensive picture of the required task scope (Mosey, 2009). The objective of this effort is to choose the functions for continued analysis and assessment at the function stage. Every ownership cost for every element is provided by the function cost. The cost-to-worth ratio can be computed by using the function worth, which VE professionals can use to appraise each item's worth. This ratio is then employed to determine the possibility of value enhancement. A ratio less than one indicates good value; a ratio more than one suggests a prospect for value improvement; and Eq. (1) indicates that further value study is necessary for this item (Bailey & Prange, 2023).

$$\text{Value index} = \text{Cost}/\text{worth} \tag{1}$$

Creativity Phase

The Creativity Phase in Value Engineering (VE) aims to generate innovative, cost-effective alternatives that enhance project value without compromising functionality. In this study, a digital plugin-based analysis is integrated into the Creativity Phase to systematically explore design alternatives. Instead of relying solely on brainstorming, a BIM-based library of design options is utilized to assess material, structural, and energy efficiency improvements. This data-driven approach enhances decision-making by automating alternative generation and ensuring feasibility. The proposed alternatives are then evaluated against predefined performance criteria, ensuring alignment with project objectives and sustainability goals (Buniya et al., 2021).

Evaluation Phase

The idea appraisal phase of VE research is regarded as the most crucial. Every concept and option presented in the earlier stage will be assessed in this stage. Every concept is assessed according to predetermined standards and may be aided by digital tools and BIM software plugins. The VE team consists of multidisciplinary professionals, including architects, engineers, cost analysts, and sustainability experts. The team leader is a Certified Value Specialist (CVS) with expertise in VE methodologies, ensuring structured decision-making. Team members are selected based on experience in BIM, cost estimation, and sustainable design, with a minimum of five years of industry experience. The workshop duration is three to five days, depending on project complexity. The VE team operates as a third-party advisory body, providing recommendations, while the final decisions are made by the project's decision-making stakeholders to ensure alignment with strategic goals.

Development Phase

The aim of this stage is to create a workable substitute that isn't totally reliant on cost and performance. Since the weighted evaluation approach considers both monetary and non-monetary characteristics, it is the method of choice for analyzing and comparing the alternatives created during the creation phase (Mahdi et al., 2015). The following steps are included in this phase:

Phase 1: Calculating the overall life cycle cost of each alternative

For comparing design choices, the present and projected costs for each option should be computed and brought to a common moment. This methodology uses the present worth approach. All current and future expenses are converted to their present value using this method. Present value is commonly used to express current (present) expenses. Both recurrent and non-recurring expenses can be converted to present value estimates using the following formulas as shown in equations (Thiry, 1997):

Recurring expenses:

$$P = A\,[(1 - (1 + i)^\wedge - n) / i] \tag{2}$$

where: minimum desirable rate of return (n) is the number of interest periods; interest rate per interest period (i) is the interest rate (in decimals). P = current total amount of money (current value) As stated in Eq. (2), For the next n periods, A reflects the end-of-period payment or acknowledgment in a consistent series. At interest rate i, the entire series equals P (Thiry, 1997).

Non-recurring expenses:

$$P = F\,(1 + i)^\wedge - n \tag{3}$$

In Eq. (3), P represents the present value, the amount of money that will equal P at the end of n interest periods, with an interest rate of i, is denoted by F, and the total amount of interest periods is n (Thiry, 1997).

Phase 2: Choosing and establishing the weightings for the criteria

In this step engineers or VE experts in design of commercial building choose the evaluation criteria for the choices. The paired comparison technique is used to establish the relative weights or degrees of importance of certain criteria. The suggested designs and the original design are thoroughly compared using paired comparisons and an evaluation matrix. Each criterion is then compared to the other to ascertain the weight of the criteria. A crucial query is posed first: "A or B?" The response is then assigned to one, two, or three points based on whether it is classified as small, medium, or major. Until all criteria are compared and their relative relevance is assessed, as seen in Figure 2, this procedure is repeated by comparing A with C and then with D (Choo & Wedley, 2004; Yin et al., 2017).

Phase 3: Listing and ranking alternatives

Commercial building professionals in Malaysia compile a list of the effective alternatives and rank them according to each set of criteria. For each possibility, a rating scale (for example, good = 5, poor = 1) is indicated.

Phase 4: Calculating the value index for each alternative

The option with the most points in the value index is the best option that has been selected and is suggested for implementation once the total function points for each alternative have been calculated.

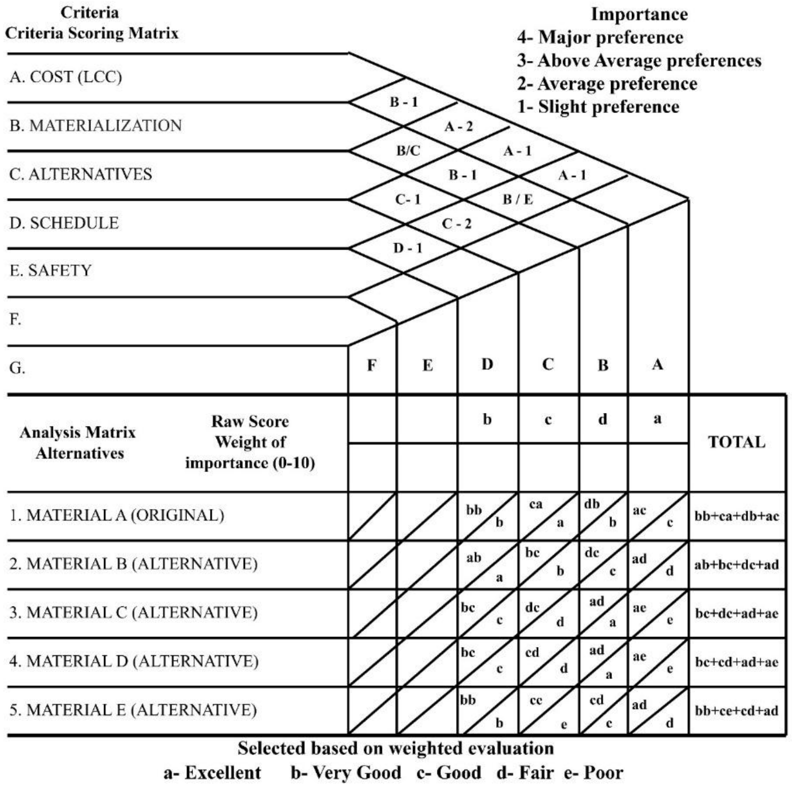


Figure 2 Paired Comparison and Evaluation Matrix.

Output Phase

The last phase of the VE Job plan consists of compiling the suggestions and findings drawn from the full investigation. The Development Phase is very important since it involves a detailed assessment and examination of all the different designs that were created in the Creativity Phase. The weighted evaluation approach considers both qualitative and quantitative aspects, such as cost, sustainability, and aesthetics, making it a valuable tool for performing thorough studies (Mousa et al., 2022). To ensure that the weightings and criteria accurately reflect the demands and objectives of the commercial construction project, experts are involved in the process. It is necessary to compute the life cycle cost of each alternative since this metric takes into consideration both the initial building expenditures as well as continuing operations and maintenance costs throughout the course of the structure's existence (Li, 2015). This strategy promotes the selection of durable, sustainable options. During the output phase, stakeholders are provided with an extensive synopsis of the VE study together with the optimal choice for the commercial construction project (Norton & McElligott, 1995). The study also includes recommendations and results.

Digital value engineering model (DVEM)

The developed scheme supports Value Engineering studies for commercial buildings in Malaysia using spreadsheet tools and BIM plugins. The Digital Value Engineering Model integrates computational techniques to improve decision making, moving beyond traditional spreadsheet methods. A MATLAB based model applies multi criteria decision analysis to evaluate alternatives using key indicators such as initial cost, sustainability, performance efficiency, life cycle cost, and cost worth ratio. The model uses weighted scoring and normalization for objective evaluation. Results are visualized through charts including alternative rankings, decision matrices, cost worth analysis, and life cycle cost distribution. This approach improves transparency, enables automated analysis, and supports scenario based simulations.

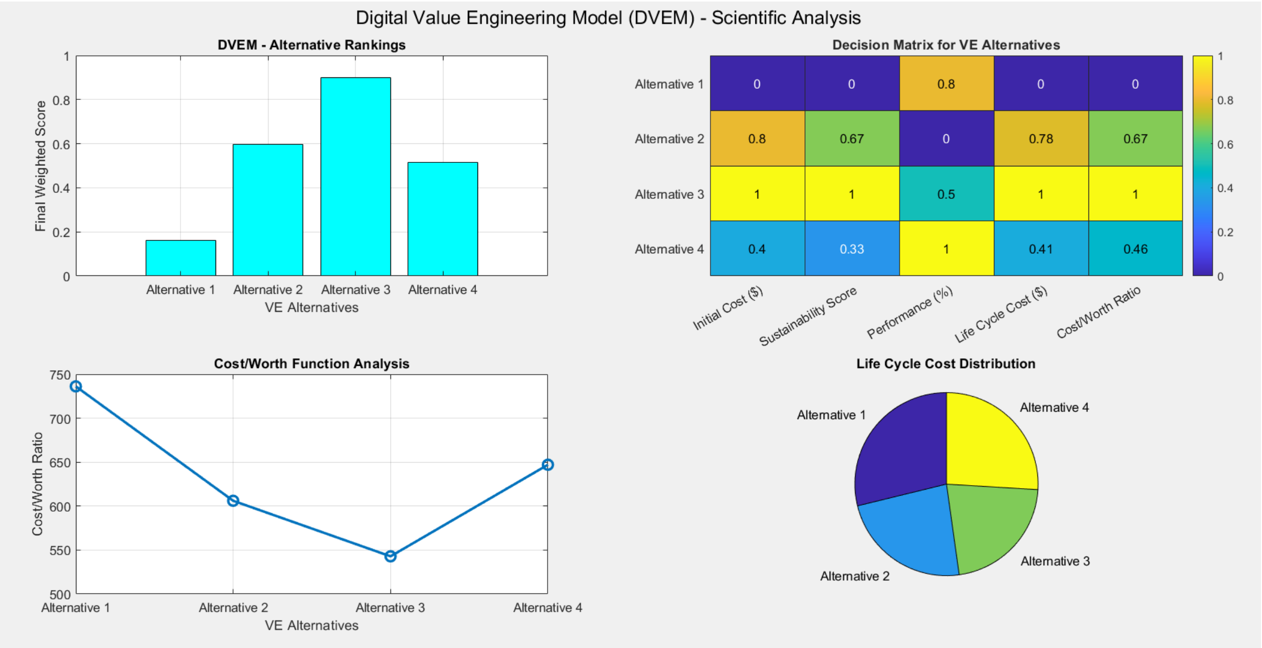


Figure 3 Digital value engineering model (DVEM).

Input data

The information table is displayed when the user employs the information phase interface to enter data into DVEM. This table is linked to the detailed data of the various project components for which a VE study is to be generated.

Processing

The following steps are taken when processing the input data in DVEM with the intent of finding the best options at the lowest possible cost:

1. Phase 1: Function: In this phase, the building components are functionally analyzed to gain an understanding of the project. The components can be categorized by the user into three groups: Secondary Function (SF), and Basic Function (BF). A baseline feature (BF) is the critical performance attribute that the selected technological solution needs to meet. As seen in Figure 4, the SF stands for the value study's overarching goal, while the SF backs the BF.
2. The second and most important stage of the DVEM process is the evaluation phase, during which the suggestions made during the creativity phase are assessed using data from a survey and the advice of experts. This can be achieved by using the weighted assessment matrix technique.
3. The FAST Method (Function Analysis System) Diagram: This diagram makes it easier to comprehend the project and identify its primary goal. It is made up of putting the crucial functions (BF and SF) that, on the essential route of functions, connect the low-order functions (LOF). The setting of the secondary functions, all-time functions, and design objectives on either end of the critical path.
4. Cost/Worth Analysis: The components that need a value analysis are identified by automatically calculating the cost/worth value for each component using the cost/worth table.
5. The creativity phase involves identifying the components whose cost/worth value is larger than "one" and coming up with alternatives for each one in the table of creativity, as illustrated in Figure 5.
6. The Present Worth approach is utilized to determine the overall life cycle cost of each option. Figure 6 shows this process, which considers several elements such the initial cost, the rate of discount, salvage value, project life cycle, and yearly operating and maintenance expenses.

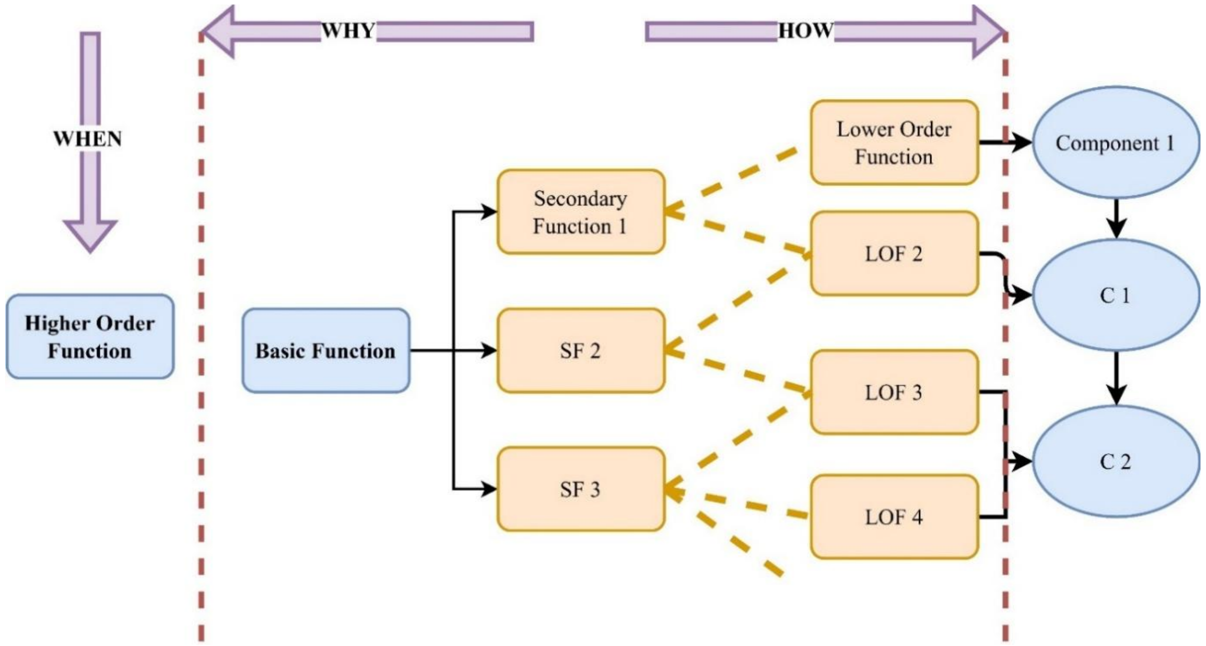
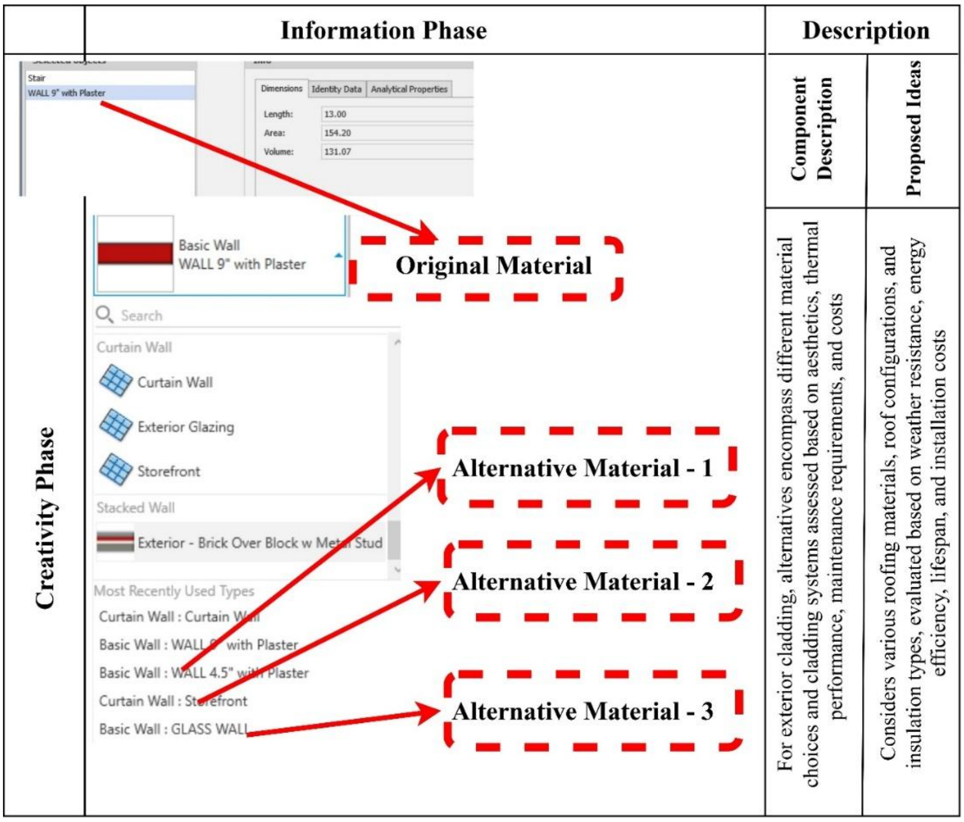


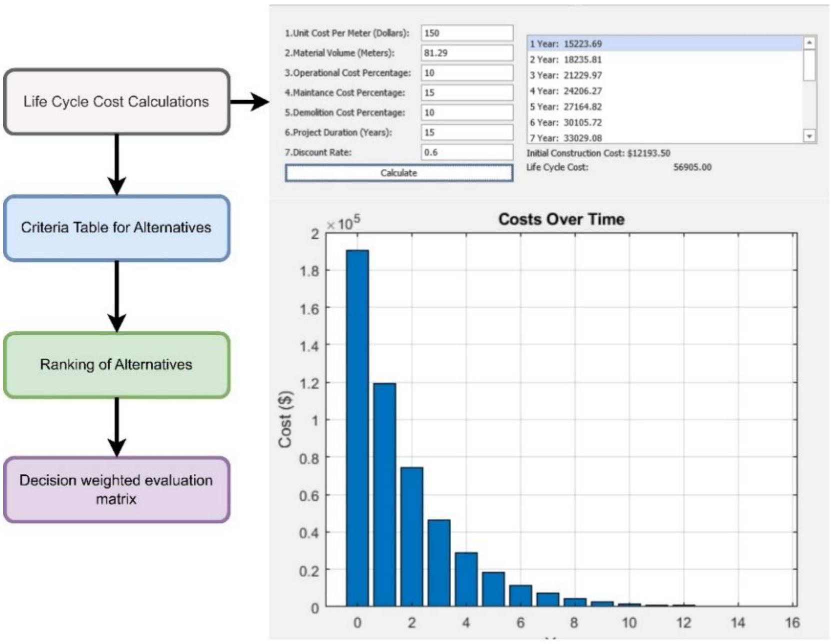
Figure 4 Fast Diagram flow for selected alternatives.



For exterior cladding, alternatives encompass different material choices and cladding systems assessed based on aesthetics, thermal performance, maintenance requirements, and costs

Considers various roofing materials, roof configurations, and insulation types, evaluated based on weather resistance, energy efficiency, lifespan, and installation costs

Figure 5 Creativity table for cost/worth value.



1.Unit Cost Per Meter (Dollars): 150
2.Material Volume (Meters): 81.29
3.Operational Cost Percentage: 10
4.Maintance Cost Percentage: 15
5.Demolition Cost Percentage: 10
6.Project Duration (Years): 15
7.Discount Rate: 0.6

1 Year: 15223.69
2 Year: 18235.81
3 Year: 21229.97
4 Year: 24206.27
5 Year: 27164.82
6 Year: 30105.72
7 Year: 33029.08

Initial Construction Cost: $12193.50
Life Cycle Cost: 56905.00

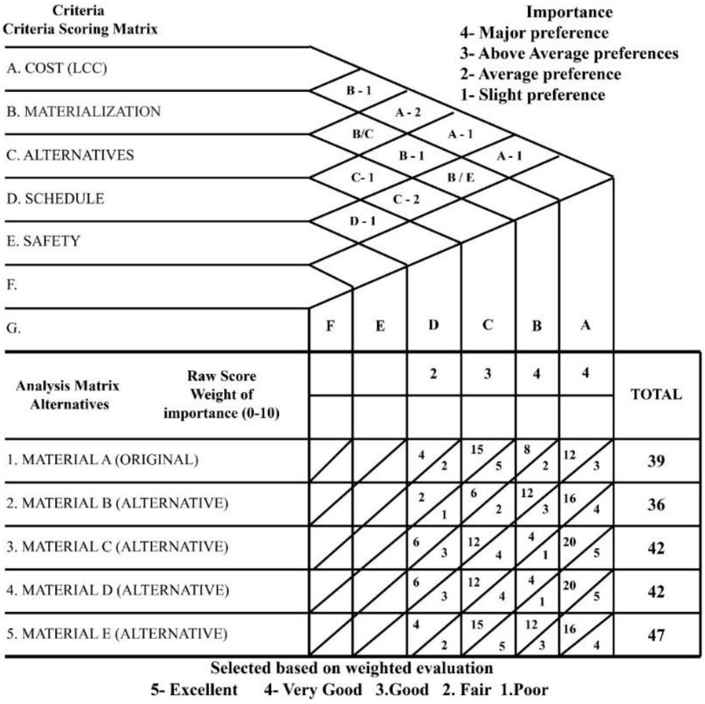
Figure 6 Evaluation of alternatives based on LCC calculations.

7. Criteria Evaluation: As seen in Table 2, criteria are defined for evaluating the alternatives, and a comparison of the suggested alternatives is carried out using these criteria (Mahdi et al., 2015).

Table 2 Criteria table for selection of alternatives

Item Name	Criteria-1	Criteria-2	Criteria-3
Original Material	AA	AB	AC
Alternative 1	BA	BB	BC
Alternative 2	CA	CB	CC
Alternative 3	DA	DB	DC
Alternative 4	EA	EB	EC
Alternative 5	FA	FB	FC

8. Matrix of Decisions: Creating the evaluation matrix is the last stage in the evaluation process. The alternatives are ordered according to the criteria, which are weighed using a paired comparison. For every alternative, the total function points, and the value index (function points divided by cost) are computed (Jaapar et al., 2012). As seen by Figure 7, the option deemed most favorable is the one with the highest value index.



Analysis Matrix Alternatives	F	E	D	C	B	A	TOTAL
Raw Score Weight of importance (0-10)			2	3	4	4	
1. MATERIAL A (ORIGINAL)			4 / 2	15 / 5	8 / 2	12 / 3	39
2. MATERIAL B (ALTERNATIVE)			2 / 1	6 / 2	12 / 3	16 / 4	36
3. MATERIAL C (ALTERNATIVE)			6 / 3	12 / 4	4 / 1	20 / 5	42
4. MATERIAL D (ALTERNATIVE)			6 / 3	12 / 4	4 / 1	20 / 5	42
5. MATERIAL E (ALTERNATIVE)			4 / 2	15 / 5	12 / 3	16 / 4	47

Figure 7 Decision matrix for alternative selection.

9. Value Savings Calculation: The original design and the suggested alternative are compared to calculate the worth of savings for the component that is being evaluated.

Output data

The findings are automatically generated after completing the evaluation matrix in the final phase. Key comparison criteria include alternative name, initial cost, maintenance cost, life cycle cost, function points, and value index. DVEM streamlines Value Engineering in Malaysian commercial projects through stages such as functional analysis, evaluation, life cycle costing, and value optimization. It integrates stakeholder input to ensure alignment with project goals, regulations, sustainability, and user comfort. The model combines qualitative and quantitative criteria using a weighted matrix to assess cost, performance, environmental impact, and user satisfaction. Life cycle cost analysis supports long term, sustainable decisions. DVEM outputs improve transparency, enabling better communication among stakeholders and facilitating faster approvals and implementation (Kineber et al., 2021). The novelty of the DVEM lies in its systematic incorporation of weighted evaluation matrices, which consider both monetary and non-monetary criteria. Furthermore, its integration with BIM-based tools allows for precise simulation and visualization of cost, energy performance, and sustainability impacts, enabling stakeholders to make data-driven decisions. This approach has not been previously explored for Malaysian commercial building projects, making it a pioneering application of digital VE for this context.

Results: Commercial building case study analysis

This section presents a case study of a Malaysian commercial building, demonstrating the effectiveness of the Digital Value Engineering Model in optimizing design, cost, and sustainability. The model achieved a 28% cost reduction compared to traditional Value Engineering by integrating BIM, Industry 4.0 principles, and digital decision tools. Unlike conventional approaches focused mainly on cost, this study emphasizes sustainability and digital transformation. The case examines a multi story office building using a 3D Autodesk Revit model that integrates architectural, structural, and mechanical systems. This enables real time simulations, automated quantity take offs, and lifecycle analysis. The model supports cost evaluation, performance assessment, and clash detection, reducing rework and improving efficiency. Integration of IoT, data analytics, and machine learning allows predictive energy analysis and refined decision making, ensuring accurate, sustainable, and compliant project outcomes.

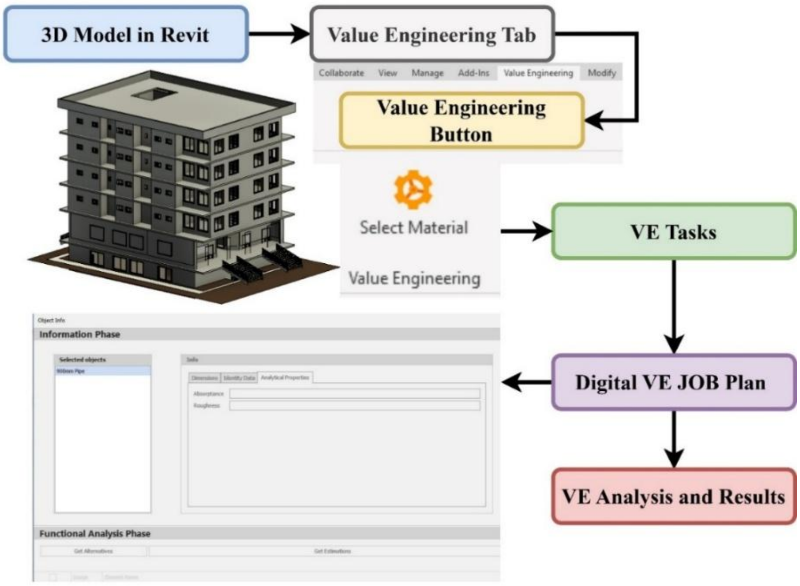


Figure 8 Digital value engineering model for selected case study.

Information Analysis

The Information Phase involved the systematic collection and analysis of project specifications, design documents, material quantities, and cost estimates. This phase is essential for identifying high-cost project components and establishing the foundation for the Value Engineering (VE) study.

Key Data Sources

To understand project cost distribution, data were gathered from BIM based drawings, the Bill of Quantities, lifecycle cost estimates, and environmental impact assessments. Key cost intensive components identified include the structural system, MEP systems, finishing, facade, foundation, and landscaping. A Pareto chart was used to visualize cost distribution, applying the 80 20 principle. Results show that structure, MEP, and finishing contribute about 83.9% of total cost, making them the main targets for Value Engineering. Other elements have lower impact on overall savings. This analysis helped prioritize areas for optimization without compromising quality or performance. These components were further examined in Functional and Creativity phases. Additionally, a Quality Model was developed to evaluate cost efficiency, functionality, and sustainability, ensuring focused and effective VE interventions.

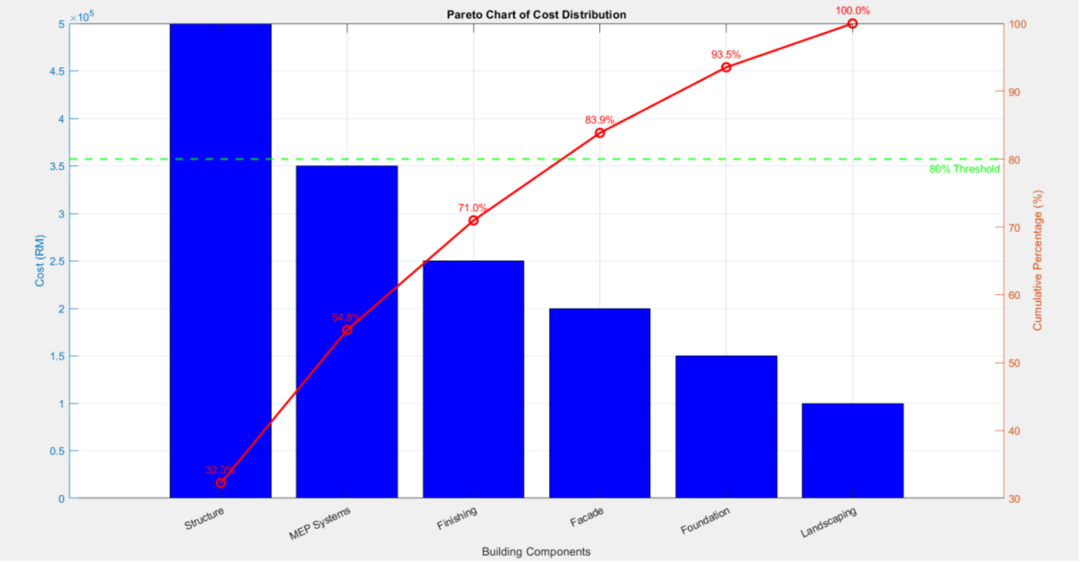


Figure 9 Pareto Chart of Cost Distribution in the Case Study.

Functional Analysis

The Functional Phase defines project objectives and classifies building elements based on their functions. A FAST diagram was developed to map relationships between functions, ensuring all components align with overall goals. The Function Table categorizes elements using Level of Function classifications, including Higher Order, Basic, and Secondary functions, improving earlier versions of the study. The BOQ was also expanded beyond the initial items to include systems such as fire suppression, plumbing, and façade elements. Functions are described using active verb and measurable noun formats for clarity. A cost worth table evaluates key components like structure and HVAC, while cost to worth ratios identify areas needing further value improvement and optimization.

Table 3 Function analysis table for each element

Element	Explanation	Verb	Noun	Kind	Level of Function (LOF)
Structural System					
Hot-Rolled Steel Sections	Conventional structure	Support	Structure	HOF	Basic Function (BF)
Cold-Formed Steel Framing	Lighter, flexible design	Frame	Structure	HOF	Basic Function (BF)
Steel-Concrete Composite	Hybrid for enhanced performance	Combine	Materials	HOF	Higher Order Function (HOF)
External Cladding					
Terracotta Rainscreen	Aesthetic and protective	Protect	Building	HOF	Secondary Function (SF)
Precast Concrete Panels	Robust, long-lasting	Insulate	Façade	HOF	Basic Function (BF)
Aluminum Curtain Wall	Lightweight and modern	Enclose	Building	HOF	Secondary Function (SF)
Roofing System					
Standing Seam Metal Roofing	Durable and weather-resistant	Cover	Roof	HOF	Basic Function (BF)
Built-Up Bituminous Roofing	Traditional multi-layer roof	Seal	Roof	HOF	Basic Function (BF)
Green Roof System	Eco-friendly, insulating	Insulate	Roof	HOF	Higher Order Function (HOF)
Flooring					
Engineered Wood Flooring	Aesthetic, practical	Surface	Floor	HOF	Secondary Function (SF)
Elevated Access Flooring	Flexible for cable management	Support	Technology	HOF	Higher Order Function (HOF)
Concrete Slabs with VCT	Durable and economical	Finish	Floor	HOF	Basic Function (BF)
HVAC System					
Chilled Beam System	Energy-efficient, low maintenance	Cool	Air	HOF	Basic Function (BF)
Radiant Heating/Cooling	Comfortable, efficient distribution	Heat/Cool	Space	HOF	Higher Order Function (HOF)
Traditional VAV System	Customizable airflow control	Ventilate	Air	HOF	Secondary Function (SF)

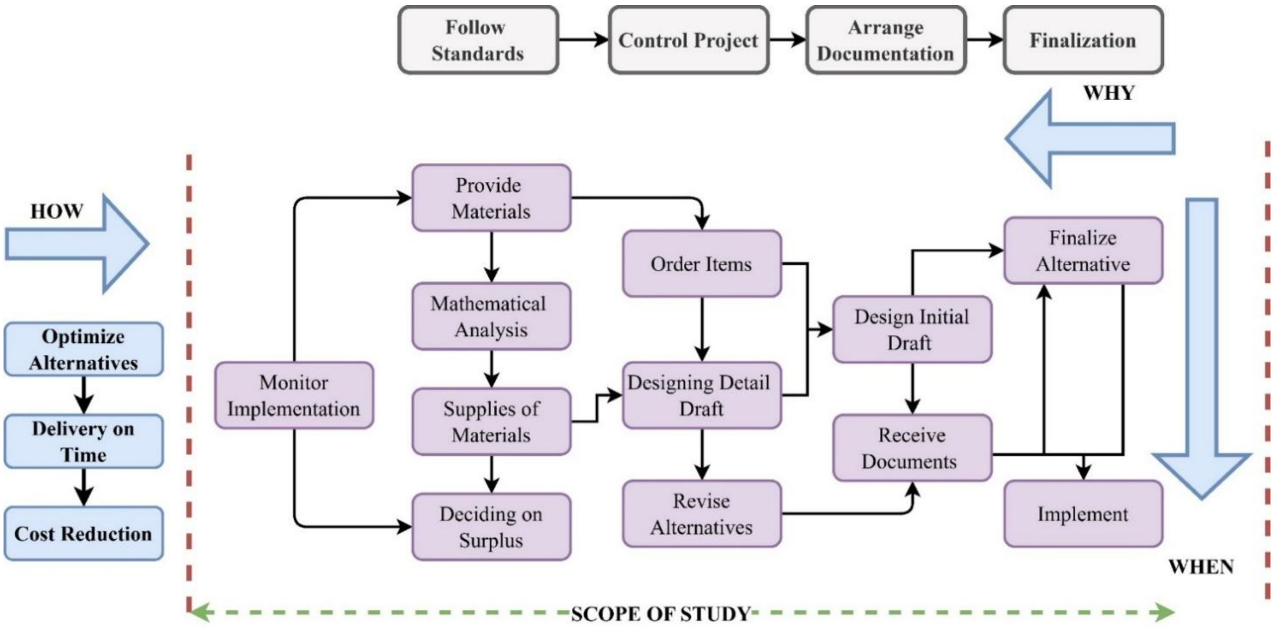


Figure 10 FAST Diagram for selection criteria of Alternatives.

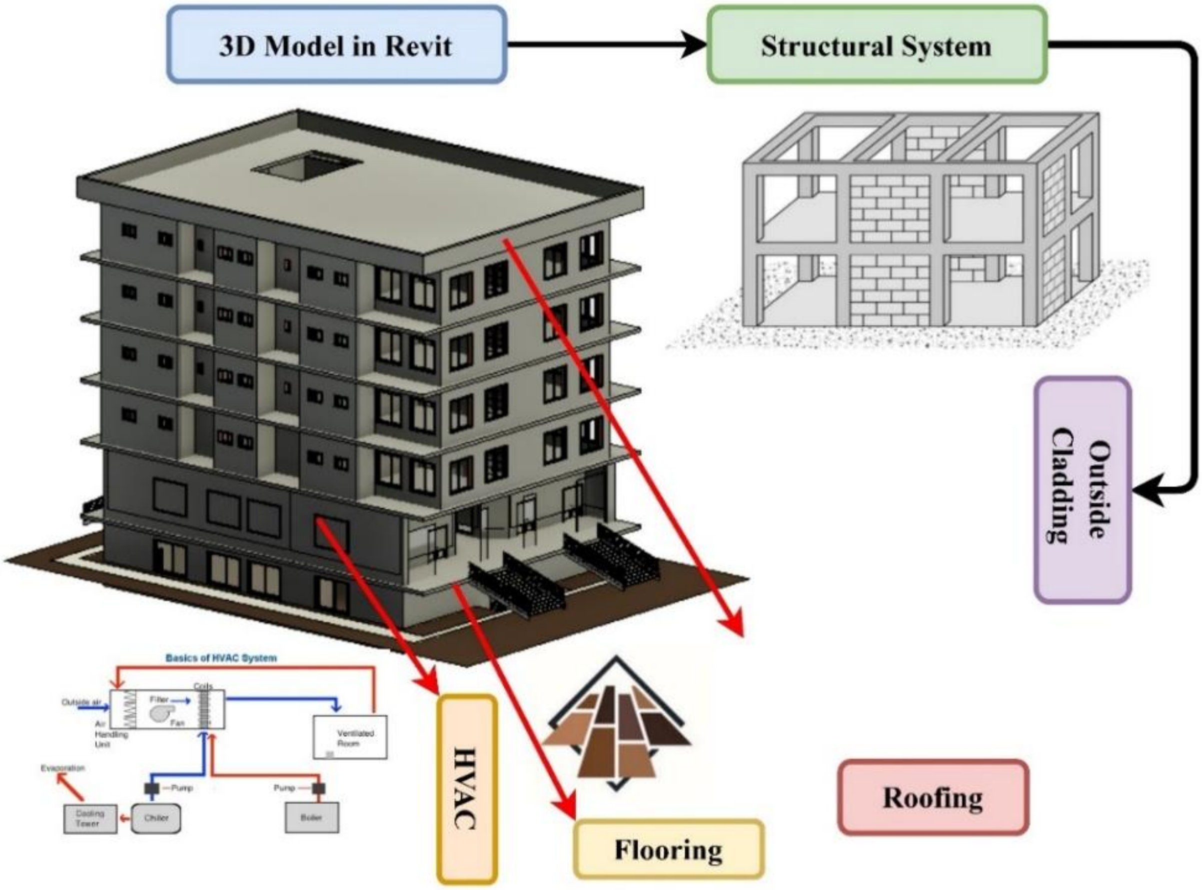


Figure 11 Function analysis of selected materials in commercial buildings.

Creativity Analysis

The Creativity Phase explores alternative design solutions to improve cost efficiency and sustainability through a structured brainstorming process. Key structural options include hot rolled steel, cold formed steel framing, and steel concrete composite construction, each with distinct cost and performance benefits. Cladding alternatives such as terracotta rainscreens, precast panels, and aluminum curtain walls are evaluated based on thermal performance, maintenance, and aesthetics. Additional options include roofing systems like metal, bituminous, and green roofs, flooring types such as engineered wood, access flooring, and VCT, and HVAC systems including chilled beam, radiant systems, and VAV. Each alternative is assessed for cost, durability, energy efficiency, and environmental impact. The revised Creativity Table documents cost worth analysis, supporting comparison and selection. This phase promotes innovative, sustainable, and cost effective solutions aligned with project goals.

Regarding material costs, building methods, and structural performance, each alternative has specific benefits and trade-offs. Regarding the external cladding, some options are terracotta rainscreen cladding, precast concrete panels, and an aluminum curtain wall system. These choices affect both initial and ongoing expenses by providing differing levels of thermal insulation, visual attractiveness, and complexity. The group may suggest standing seam metal roofing, built-up bituminous roofing, or a green roof system for the roofing system. The material composition, longevity, and energy efficiency of these alternatives vary which affects the overall environmental impact and operating expenses of building. The flooring options include engineered wood flooring, elevated access flooring, and concrete slabs finished with vinyl composite tile (VCT). There are certain factors to consider with each alternative in terms of installation costs, upkeep needs, and tenant comfort. The team may recommend a chilled beam system, radiant heating/cooling, or a traditional VAV (Variable Air Volume) system for the HVAC system. The solutions differ in terms of energy usage, upfront costs, and suitability for achieving the best possible interior environmental quality.

Table 4 Cost/worth analysis table for selected alternatives

Element	Explanation	Function (LOF-Based)	Primary Cost (RM)	Worth (RM)	Cost/ Worth	Remarks (Function-Based)
Structural System						
1. Hot-Rolled Steel Sections	Conventional structure	Support Structure (BF)	10,000,000	9,000,000	1.11	High strength, faster construction time
2. Cold-Formed Steel Framing	Lighter, flexible design	Frame Structure (BF)	8,500,000	7,800,000	1.09	Cost-effective, versatile applications
3. Steel-Concrete Composite	Hybrid for enhanced performance	Combine Materials (HOF)	11,000,000	10,000,000	1.10	Improved durability, fire resistance
External Cladding						
1. Terracotta Rainscreen	Aesthetic and protective	Protect Building (SF)	5,000,000	4,500,000	1.11	Enhances building appearance
2. Precast Concrete Panels	Robust, long-lasting	Insulate Façade (BF)	4,200,000	4,000,000	1.05	High thermal mass, energy efficient
3. Aluminum Curtain Wall	Lightweight and modern	Enclose Building (SF)	6,500,000	5,800,000	1.12	Expensive but high aesthetic value
Roofing System						
1. Standing Seam Metal Roofing	Durable and weather-resistant	Cover Roof (BF)	3,000,000	2,800,000	1.07	Long lifespan, minimal maintenance
2. Built-Up Bituminous Roofing	Traditional multi-layer roof	Seal Roof (BF)	2,700,000	2,500,000	1.08	Cost-effective, reliable
3. Green Roof System	Eco-friendly, insulating	Insulated Roof (HOF)	4,000,000	3,600,000	1.11	Reduces urban heat, water runoff
Flooring						
1. Engineered Wood Flooring	Aesthetic, practical	Surface Floor (SF)	1,800,000	1,700,000	1.06	Warmth and style, moderate durability
2. Elevated Access Flooring	Flexible for cable management	Support Technology (HOF)	2,200,000	2,000,000	1.10	Suitable for tech-heavy environments
3. Concrete Slabs with VCT	Durable and economical	Finish Floor (BF)	1,500,000	1,400,000	1.07	High traffic areas, easy to maintain
HVAC System						
1. Chilled Beam System	Energy-efficient, low maintenance	Cool Air (BF)	7,500,000	7,000,000	1.07	Quiet operation, reduces space usage
2. Radiant Heating/Cooling	Comfortable, efficient distribution	Heat/Cool Space (HOF)	8,000,000	7,500,000	1.07	Consistent temperatures, energy savings
3. Traditional VAV System	Customizable airflow control	Ventilate Air (SF)	6,000,000	5,500,000	1.09	Flexible, well-understood technology

Table 5 presents the comparative scoring of each alternative, providing a quantitative justification for selecting the most cost-effective and sustainable solutions. The Weighted Evaluation Matrix (WEM) systematically assesses design alternatives based on cost, performance, sustainability, durability, and lifecycle efficiency.

Table 5 Weighted Evaluation Matrix for Alternative Solutions

Criteria	Weight (%)	Alternative 1: Hot-Rolled Steel (Conventional Structure)	Alternative 2: Cold-Formed Steel Framing	Alternative 3: Steel-Concrete Composite Construction	Best Alternative
Initial Construction Cost (RM/m^2)	20%	RM 1,500/m^2 (Score: 5)	RM 1,200/m^2 (Score: 7)	RM 1,400/m^2 (Score: 6)	Cold-Formed Steel
Lifecycle Cost (LCC) (20 years)	20%	RM 2,000,000 (Score: 4)	RM 1,500,000 (Score: 7)	RM 1,300,000 (Score: 8)	Steel-Concrete Composite
Energy Performance (kWh/m^2/year)	15%	140 kWh/m^2 (Score: 6)	130 kWh/m^2 (Score: 7)	110 kWh/m^2 (Score: 9)	Steel-Concrete Composite
Material Durability & Maintenance	15%	Moderate (Score: 5)	Low Maintenance (Score: 7)	High Durability, Low Maintenance (Score: 9)	Steel-Concrete Composite
Sustainability (Carbon Footprint, kg CO_2/m^2)	10%	500 kg CO_2/m^2 (Score: 4)	400 kg CO_2/m^2 (Score: 6)	350 kg CO_2/m^2 (Score: 8)	Steel-Concrete Composite
Fire Resistance (hrs)	10%	2 Hours (Score: 6)	1.5 Hours (Score: 5)	4 Hours (Score: 9)	Steel-Concrete Composite
Seismic Performance	5%	Moderate (Score: 6)	Weak (Score: 4)	High (Score: 9)	Steel-Concrete Composite
Constructability (Ease of Installation)	5%	Moderate (Score: 6)	High (Score: 8)	High (Score: 8)	Cold-Formed Steel / Steel-Concrete Composite

The evaluation criteria have been weighted according to their relative importance, ensuring a comprehensive decision-making framework aligned with SAVE (2008) principles. A weighted evaluation matrix technique is used to thoroughly assess the suggested alternatives during the evaluation analysis phase. This matrix considers several factors, such as the original cost of construction, ongoing operating costs, energy efficiency, the impact on the environment, occupant comfort, and adherence to Malaysian sustainability requirements and building rules. The LCC analysis, and it takes into consideration both the recurring and non-recurring costs over lifecycle building in addition to the initial construction costs, is an essential part of this phase. Using a discount rate, all future expenses are converted to their present value via the Present Worth (PW) approach, which is frequently employed in LCC computations.

Evaluation Analysis

The Evaluation Phase involves a Weighted Evaluation Matrix (WEM) to systematically comparing the generated alternatives. Previous iterations incorrectly positioned the WEM in the Development Phase; it has now been correctly structured within the Evaluation Phase, in accordance with SAVE (2008) guidelines.

The evaluation criteria include:

1. Initial Construction Costs
2. Lifecycle Costs (LCC)
3. Energy Performance
4. Material Durability and Maintenance
5. Sustainability Compliance

Total Weighted Scores:

1. Hot-Rolled Steel: (5×20%) + (4×20%) + (6×15%) + (5×15%) + (4×10%) + (6×10%) + (6×5%) + (6×5%) = 5.1
2. Cold-Formed Steel: (7×20%) + (7×20%) + (7×15%) + (7×15%) + (6×10%) + (5×10%) + (4×5%) + (8×5%) = 6.4
3. Steel-Concrete Composite: (6×20%) + (8×20%) + (9×15%) + (9×15%) + (8×10%) + (9×10%) + (9×5%) + (8×5%) = 7.9

Final Selection:

Steel-Concrete Composite Construction emerges as the most optimal alternative, scoring the highest (7.9) due to its superior lifecycle cost savings, energy performance, durability, fire resistance, and seismic performance. Although Cold-Formed Steel has a lower initial cost and higher ease of installation, it lacks durability and seismic resilience. Therefore, Steel-Concrete Composite is recommended for implementation. This structured decision-making approach ensures that the selected alternative maximizes long-term value, balancing cost, performance, and sustainability. For instance, consider the LCC estimates for the structural steel alternatives also shown in Figure 12:

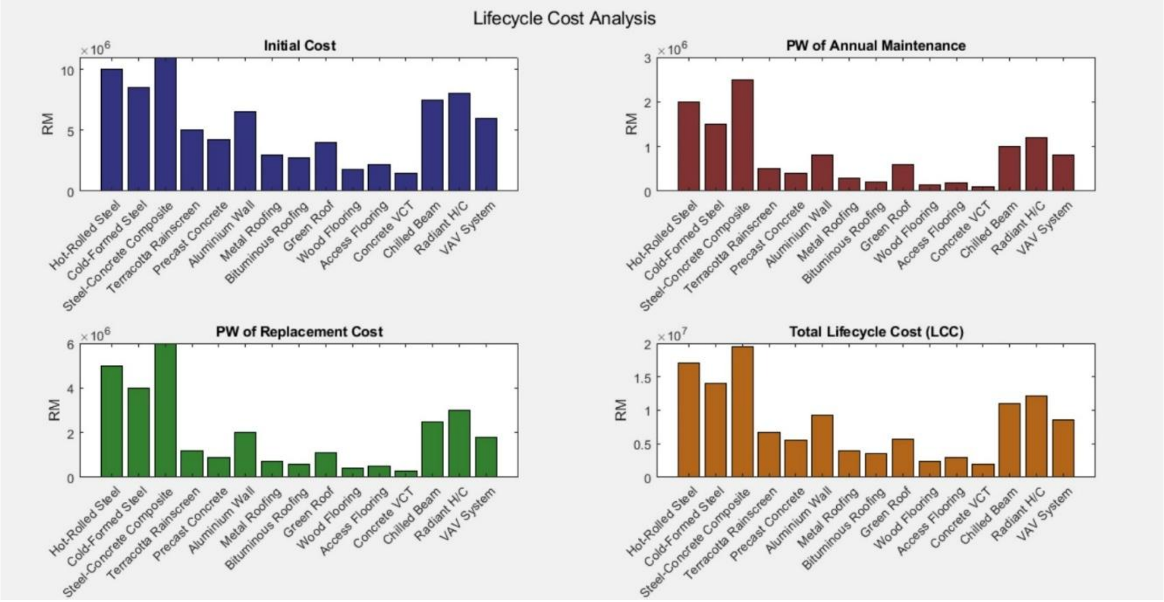


Figure 12 Lifecycle cost analysis of selected alternatives for commercial buildings.

Alternative 1: Traditional hot-rolled steel sections LCC = Initial Cost + Present Worth of Recurring Costs + Present Worth of Non-recurring Costs = RM 2,500,000 + PW (Annual Maintenance Cost) + PW (Replacement Cost after 30 years).
Alternative 2: Cold-formed steel framing LCC = Initial Cost + Present Worth of Recurring Costs + Present Worth of Non-recurring Costs = RM 2,200,000 + PW (Annual Maintenance Cost) + PW (Replacement Cost after 25 years).
Alternative 3: Composite steel-concrete construction LCC = Initial Cost + Present Worth of Recurring Costs + Present Worth of Non-recurring Costs = RM 2,800,000 + PW (Annual Maintenance Cost) + PW (Replacement Cost after 40 years).
The Present Worth (PW) of recurring costs, such as annual maintenance, is calculated using the formula as shown in Eq. (4):

$$PW = A\,[(1 - (1 + i)^\wedge - n) \,/\, i] \tag{4}$$

where A is the recurring cost, i is the discount rate, and n is the number of periods.

Similarly, the PW of non-recurring costs, like replacement costs, is calculated using the formula as shown in Eq. (5):

$$PW = F\,(1 + i)^\wedge - n \tag{5}$$

Where F is the future cost, i is the discount rate, and n is the number of periods until the future cost occurs. For the structural steel element and other building components, the project team will be able to ascertain which options are most value-optimized by doing these LCC calculations and allowing for the weighted assessment criteria.

Development Analysis

The Development Phase refines two final proposals, one technical and one financial, based on Evaluation Phase results. The selected structural system is steel concrete composite construction due to better lifecycle performance and lower maintenance, supported by a technical report on constructability, fire resistance, and seismic behavior. For HVAC, the chilled beam system was chosen for energy efficiency, comfort, and cost savings, with a financial report showing return on investment over 20 years. The VE team collaborates with architects, engineers, and sustainability experts to ensure feasibility, compliance, and performance. Design specifications, materials, and construction methods are optimized to meet project requirements while maximizing value and sustainability.

Presentation Analysis

The final phase involved documenting and presenting findings to stakeholders using visual aids such as cost benefit charts, lifecycle graphs, and 3D renderings. The study shows that digital tools and Industry 4.0 integration enhance Value Engineering by enabling real time decision making and predictive analysis. Aligned with SAVE best practices, the framework ensures cost savings, sustainability, and efficiency. A comprehensive cost worth analysis includes cost versus worth comparison, ratio evaluation, and function level distribution. These identify inefficiencies, highlight elements needing reassessment, and classify functions into basic, secondary, and higher order categories. The dominance of core functions reflects strong structural and operational focus.

The presentation should provide a detailed explanation of the selected options, emphasizing how they maximize value by balancing several factors, including construction costs, continuing expenses, energy efficiency, sustainable development, and occupant comfort. The group might offer a thorough analysis of the LCC estimates for every option, highlighting the long-term financial effects and supporting their suggestions with value optimization over the course of the building's life. The VE team ensures that the commercial building project in Malaysia maximizes value while satisfying the client's requirements and adhering to local regulations and sustainability goals by providing a thorough and well-substantiated analysis that empowers the project stakeholders to make informed decisions.

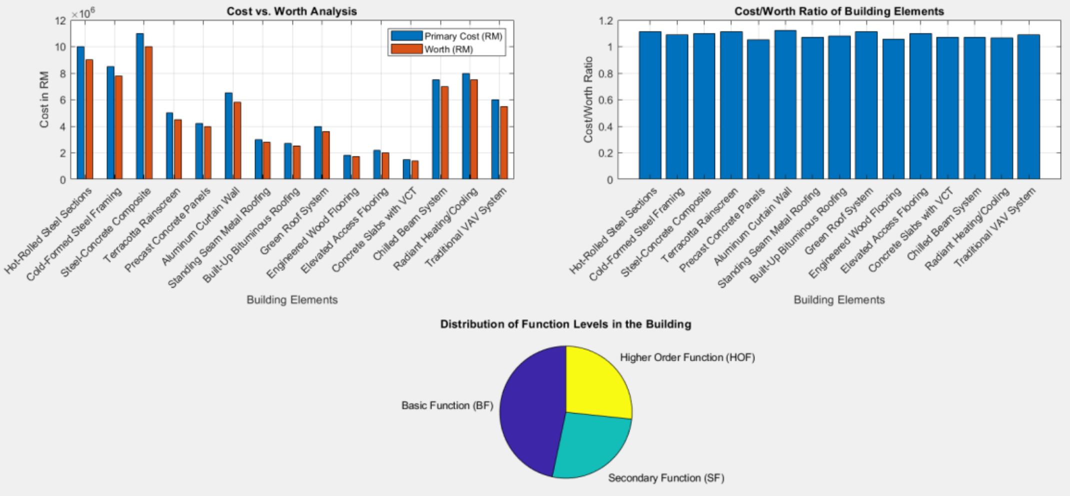


Figure 13 Cost/Worth Analysis Based on Function Phase.

Discussion

This study integrates the Digital Value Engineering Model with BIM, life cycle cost analysis, and sustainability driven tools to improve efficiency, cost optimization, and environmental performance in commercial construction. Results show 28% cost savings over traditional VE, confirming the value of data driven decision making. However, further work is needed to better quantify sustainability benefits, compare DVEM with other digital VE tools, address adoption challenges in developing countries, and incorporate evolving Industry 4.0 technologies.

Information Phase: Data Acquisition and Sustainability Integration

The information phase serves as the foundation for the VE Job Plan, ensuring that all relevant project details, objectives, and constraints are clearly identified before proceeding to functional analysis and alternative development (Mansour & Abueusef, 2015). This phase involves extensive data collection, stakeholder engagement, and sustainability goal setting, providing the groundwork for an informed decision-making process. In this study, end-users and clients defined the scope, expectations, and strategic goals of the project through an information-sharing workshop, allowing stakeholders to align their priorities before the implementation of VE (Gu & London, 2010). However, a major limitation of this phase is the lack of quantitative sustainability assessments, as the study primarily relies on qualitative descriptions of green alternatives without providing empirical evidence of their environmental benefits. While sustainability considerations were embedded into the early project stages, measurable factors such as carbon emission reductions, energy efficiency improvements, and material life cycle performance were not systematically analyzed. To strengthen the sustainability claims of DVEM, future research should integrate BIM-based energy simulation tools, such as EnergyPlus, IES-VE, or OpenStudio, to provide precise estimations of operational energy savings and greenhouse gas emissions reduction. Additionally, Life Cycle Assessment (LCA) methodologies, following ISO 14040/14044 standards, should be embedded into DVEM to assess the long-term environmental impact of different material choices and design configurations (Zhang et al., 2009).

Another limitation of the information phase is the inconsistency of sustainability priorities among stakeholders, which can result in conflicts when balancing cost reduction and environmental considerations. Clients and VE facilitators often have differing views on the trade-offs between short-term cost savings and long-term sustainability benefits, which may influence the selection of alternatives during VE implementation. To address this issue, future applications of DVEM should incorporate Multi-Criteria Decision Analysis (MCDA), allowing stakeholders to systematically evaluate and balance these competing objectives through a structured weighting system. Furthermore, sensitivity analysis of sustainability parameters should be conducted to assess how variations in material efficiency, energy costs, and lifecycle performance impact overall project outcomes. By implementing such methodologies, DVEM can evolve into a more robust and adaptable decision-support tool, improving the objectivity of sustainability evaluations and ensuring greater alignment among project stakeholders(Fellows & Liu, 2012).

Functional Phase: Enhancing Performance Evaluation and Decision-Support

In the functional phase, the study utilized the Functional Analysis System Technique (FAST) to establish a clear hierarchy of core and secondary functions within the commercial building project, ensuring that cost-optimization does not compromise functional performance (Chen et al., 2010). This phase plays a critical role in understanding the interdependencies between various project functions, helping decision-makers identify where cost reductions can be achieved without negatively affecting quality and user requirements (Abdelghany et al., 2015).. However, a key limitation in this study is the absence of AI-driven function optimization tools (Assaf et al., 2000).. While traditional VE frameworks rely on manual expert-driven function classification, recent research suggests that machine learning (ML) algorithms can analyze historical VE data to predict cost-effective function hierarchies and improve decision accuracy (Janani et al., 2018). Future research should explore how AI-assisted function analysis tools can be integrated into DVEM to automate function classification, reduce subjectivity, and improve decision efficiency. Moreover, this phase does not include a structured sensitivity analysis of function parameters such as cost-weighting criteria, energy consumption factors, and lifecycle performance indicators (Dell'Isola, 1997). Future iterations of DVEM should incorporate Monte Carlo simulations to assess how variations in function priorities affect overall project performance, ensuring that the model remains adaptable to different project conditions and sustainability goals.

Evaluation Phase: Life Cycle Cost Analysis and Quantitative Benchmarking

The evaluation phase represents one of the most critical components of VE, as it involves the systematic assessment of design alternatives through a weighted evaluation matrix (WEM) and LCCA calculations. Unlike conventional VE models that often rely on qualitative assessments, this study integrates a data-driven evaluation framework, enabling more precise quantification of trade-offs between cost, sustainability, and performance metrics (Kanapeckiene et al., 2011). However, a major limitation of this phase is the lack of comparative benchmarking analysis against other digital VE methodologies, particularly AI-driven optimization tools. While DVEM demonstrates efficiency improvements and cost savings, it has not been directly compared with alternative decision-support frameworks such as blockchain-enabled VE models, predictive AI-based VE tools, or real-time digital twin systems. Future research should conduct control group experiments, where identical projects undergo traditional manual VE, digital VE (DVEM), and AI-assisted VE, allowing researchers to quantify differences in decision-making efficiency, cost-effectiveness, and sustainability performance. Additionally, real-time energy simulations should be integrated into the evaluation phase to validate sustainability claims by measuring the actual performance of optimized design solutions under varying operational conditions. By embedding IoT-enabled energy monitoring systems, future iterations of DVEM can provide dynamic, real-world data on building performance, ensuring that the selected VE alternatives achieve their projected sustainability targets (Bhosekar & Vyas, 2012).

Creativity Phase: AI-Driven Alternative Generation and Parametric Design

The creativity phase involves the generation of alternative design solutions to improve cost efficiency, functional performance, and environmental sustainability. Traditionally, this process relies on brainstorming and expert-driven assessments, which may introduce biases and suboptimal solutions due to cognitive limitations and limited access to large datasets. A significant advancement in VE research is the use of AI-driven generative design algorithms, which can autonomously generate and evaluate multiple design configurations using multi-objective optimization techniques. Future implementations of DVEM should integrate AI-assisted generative design tools, allowing for the automatic generation of cost-optimal, high-performance design alternatives (Yu et al., 2018). Furthermore, blockchain-enabled supplier evaluation tools could be incorporated into DVEM to improve material selection by ensuring transparency and traceability in procurement processes. By leveraging blockchain-based smart contracts, the procurement and evaluation of VE alternatives can be streamlined, reducing inefficiencies and enhancing trust among stakeholders (Oke & Aigbavboa, 2017).

Presentation Phase: Communicating Digital VE Outcomes

The presentation phase ensures that VE outcomes are effectively communicated to stakeholders. This study utilized BIM-based 3D models, cost-benefit analyses, and LCCA visualizations to support data-driven decision-making. However, this phase can be further enhanced by integrating immersive visualization tools, such as Augmented Reality (AR) and Virtual Reality (VR). These technologies allow stakeholders to interact with VE-optimized designs, improving decision clarity and engagement. Additionally, real-time dashboard analytics should be incorporated into DVEM to provide ongoing updates on cost-performance trade-offs, allowing stakeholders to monitor VE outcomes dynamically (Kelly & Male, 2002).

Conclusion

This study developed and applied a Digital Value Engineering Model (DVEM) integrating BIM, life cycle cost analysis, and a weighted evaluation matrix to improve decision making in commercial construction. Tested on a Malaysian case study, the model demonstrated strong potential to optimize costs, enhance sustainability, and streamline VE processes. It bridges traditional and digital VE through a structured, data driven approach aligned with Industry 4.0. Notably, DVEM achieved a 28% cost reduction compared to conventional methods, confirming its effectiveness. The framework also provides a replicable tool for industry professionals to support smarter and more sustainable decisions.However, the study is limited to a single case study, affecting generalizability.

Theoretical and Practical Implications

This study advances construction engineering management by integrating digital VE with sustainability in commercial building projects. It addresses gaps in research by introducing a structured framework combining BIM, LCC, and data driven decision making, tailored to the Malaysian context. The integration of qualitative expert input, quantitative LCC, and technological BIM approaches, along with tools such as FAST and WEM, provides a systematic method for function analysis, value assessment, and sustainability evaluation. It also highlights that VE is not limited to large projects but can enhance efficiency, reduce costs, and improve timelines even in smaller developments, aligning with Industry 4.0 principles. Practically, the study offers actionable insights for stakeholders, showing that digital VE can reduce cost overruns, improve sustainability compliance, and enhance project transparency. The proposed framework supports better forecasting, resource efficiency, and long term value creation, encouraging wider adoption of sustainable, data driven VE practices in Malaysia’s construction industry.

Limitations and future research

Although this study offers valuable insights into digital Value Engineering (VE) in commercial buildings, several limitations remain. A key challenge is the shortage of trained VE professionals with both technical and managerial expertise. Future research should enhance certification programs and industry training to expand VE knowledge in Malaysia. Broader adoption also requires collaborative models that promote knowledge-sharing, innovation, and cross-sector partnerships. Research should further explore integrating VE into large-scale and mega-infrastructure projects, while fostering a culture of innovation by encouraging employee-driven VE recommendations. The private sector should play a stronger role through investment in research, technology, and sustainability-focused practices. Future studies should extend VE applications to residential, industrial, and public infrastructure projects, tailoring strategies to diverse requirements. Integrating lean maintenance, cost efficiency, quality improvement, and Industry 4.0 principles is essential. Additionally, AI-driven decision models, digital twins, predictive analytics, and automated VE tools can enhance accuracy and adoption. Expanding sustainability compliance indicators, including LCA-based material selection and carbon assessments, will strengthen decision-making and align projects with global sustainability standards.

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The authors declare they have no conflict of interest or financial conflicts to disclose.

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