ISSN 1392-3730/eISSN 1822-3605

VILNIUS TECH
Vilnius Gediminas Technical University

JOURNAL of CIVIL ENGINEERING and MANAGEMENT

2024
Volume 30
Issue 3
Pages 234–247
https://doi.org/10.3846/jcem.2024.20953

MIVES MULTI-CRITERIA FRAMEWORK TO SUSTAINABILITY INDEX OF DESIGN FOR MANUFACTURE AND ASSEMBLY

Tan TAN[1], Lang ZHENG[1], Fan XUE[1], Zhikang BAO[2],
Zigeng FANG[3], Xiaohu LIU[4]✉

[1] *Department Real Estate and Construction, The University of Hong Kong, Hong Kong SAR, China*
[2] *School of Energy, Geoscience, Infrastructure and Society, Heriot-Watt University, Edinburgh, United Kingdom*
[3] *Department of Civil Engineering, University of Nottingham, Nottingham, United Kingdom*
[4] *Department of Architecture, Huazhong University of Science and Technology, Wuhan, China*

Article History:

- received 10 November 2022
- accepted 24 November 2023

Abstract. Embracing sustainable strategies that consider Design for Manufacture and Assembly (DfMA) has become a rapidly growing trend in urban development. Continued uncertainty on the sustainability assessment of design could drive a series of indecisive decision-making among design alternatives, further disrupting the potential opportunities toward sustainable DfMA. However, there is a lack of research on sustainable design assessments for DfMA and establishing a sustainable index. This research establishes an integrated value model for the sustainability assessment framework and DfMA sustainability index to address this challenge. This model integrates Building Information Modelling (BIM) with MIVES, a customisable Multi-Criteria Decision Making (MCDM) tool. The pilot case of this framework is the retrofit of a commercial building's façade system, which demonstrated the capability of the proposed framework. Data collection and analysis include the comparisons between five design alternatives. This research furthers previous studies and has three-fold significance: 1) Establishing reasonable multi-criteria for the sustainable DfMA indices; 2) Adapting the MIVES approach for comparative analysis across three building phases to make it compatible with DfMA; 3) developing a quantitative analysis method for sustainable design assessment of DfMA in the construction industry.

Keywords: DfMA, sustainability index, sustainability assessment, MIVES, sustainable design.

✉Corresponding author. E-mail: *liuxiaohu@hust.edu.cn*

1. Introduction

Global sustainable construction faces several challenges. A primary concern is the growing demand for resources and energy, driven by rapid urbanisation and the increasing global population (Bao, 2023; Desa, 2018). Another challenge is the significant contribution of the Architectural Engineering and Construction (AEC) industry to greenhouse gas emissions, accounting for nearly 27% of global CO_2 emissions (Hamilton, 2023). Additionally, sustainable construction faces the complexities of balancing social, economic, and environmental factors to achieve long-term resilience and adaptability in architectural designs (Kibert, 2016). To achieve sustainability, it is significant for architects and engineers to evaluate and optimise design solutions by considering both sustainability performance and buildability. However, as sustainability is a multifaceted concept that cannot be fully captured by computer algorithms alone, it is necessary to involve human intelligence in comparing the sustainability of multiple design alternatives, particularly for the generation of parametric buildings with irregular shapes and non-standardised components.

As an emerging and promising design solution, Design for Manufacture and Assembly (DfMA) provides enormous opportunities for the AEC industry to embrace sustainability (Lu et al., 2021; Tan et al., 2020). DfMA aims to address some of the potential downstream manufacturing and assembly issues by evaluating and improving the early product's design process to achieve control over the total cost of ownership (Boothroyd, 2005; Dewhurst, 2010). Theoretically, DfMA consists of two core components, design for manufacture (DfM: which focuses on the manufacture of individual components) and design for assembly (DfA: an approach to the assembly of components) (Bogue, 2012). In the words of Luiten and Fischer (1998), DfMA transforms the traditional sequential process of construction into one, in which design and manufacture are interdependent. Although the body of research on DfMA has been growing across regions, how to integrate the concept of DfMA into sustainable design remains an unmatured area. Specifically, a knowledge gap is the decision analysis and making of opting for the best-fit sustainability design in the DfMA process.

The pressing need for a "Sustainability Index" in DfMA stems from the increasing global demand for environmentally conscious buildings and resource-efficient construction processes. A sustainability index is a tool used to measure and assess the environmental, social, and economic performance of building projects (Ariaratnam et al., 2013). It combines various sustainability indicators to create a comprehensive picture of a design's commitment to sustainable practices and long-term value creation. By evaluating diverse design factors, a sustainability index allows investors, stakeholders, and policymakers to make informed decisions and promote sustainable development in building design. Developing a comprehensive sustainability index would enhance DfMA by enabling the systematic evaluation and optimisation of building designs, ultimately promoting resource conservation, waste reduction, and environmental stewardship. However, current DfMA methodologies largely neglect the incorporation of quantifying sustainability metrics, thus presenting a significant research gap in developing the DfMA sustainability index.

Multi-Criteria Decision Making (MCDM) is a decision analysis and decision-making methodology that utilises available information, explores stakeholders' perceptions and demands, and evaluates the performances of various alternatives (Tan et al., 2021). In the AEC industry, MCDM has also been widely applied to supporting decision-making in building design due to its universality and capability for abstract concepts defined by a set of indicators, like "sustainability" (Fallahpour et al., 2020; Šaparauskas, 2003). Information acquisition is critical in facilitating strategic decisions, especially information about these indicators for sustainability assessment. In addition, MCDM and Building Information Modelling (BIM) technology are widely regarded as complementary systems. MCDM can thus be better stimulated to organise various decision-making criteria more efficiently and rigorously with the assistance of BIM. In turn, BIM capabilities can also be amplified with the synergy of MCDM when dealing with several uncertainties and risks in construction projects (Tan et al., 2021). In the initial design stage of a construction project, designers can benefit from BIM-enabled integration and dynamic information exchanges to make better evidence-based solutions (Al Hattab & Hamzeh, 2018).

MIVES (Spanish acronym: Modelo Integrado de Valor para una Evaluación Sostenible, in English: Integrated Value Model for Sustainability Assessment) is a customisable MCDM tool that allows decision-makers to evaluate and quantify the parameters (i.e. requirements, criteria and indicators) by using Analytic Hierarchy Process (AHP) and the value function (Cots et al., 2022). This concept enables the indirect measurement of the satisfaction grade of various stakeholders involved in the decision-making procedure. In addition, MIVES performs well in uncertainty analysis and calibration problems. It can be employed in different locations with varying characteristics without being constrained by the present conjuncture (Gilani et al., 2019, 2022). These main characteristics make MIVES unique among other competing methods for developing the DfMA sustainability index. However, MIVES usually only considers the "triple bottom line" sustainability (i.e., Economic, Environmental, Social) for the assessment dimensions. The factors that mutually exclude each other are incorporated into these three dimensions, making it difficult to compute complex situations where certain factors may influence multiple dimensions simultaneously. In addition, there are no specific MIVES frameworks for DfMA.

This research aims to establish a MIVES multi-criteria framework for the DfMA sustainability index by modifying and advancing the MIVES technique. The second section provides a literature review of sustainable assessment in DfMA and the development of MIVES in the construction industry. The third section explains the MIVES multi-criteria framework proposed in this research. The fourth section demonstrates the process and applicability of this approach by presenting a case study on developing the DfMA sustainability index. This research adopts an empirical case of a façade retrofit project in Wuhan, China, comparing five design alternatives. The fifth section discusses the research's main contributions, including the novelty of the proposed approach and how it fills the research gap in the field. Finally, the sixth section summarises the research. Overall, this research presents a valuable contribution to the field of sustainable assessment in DfMA, by proposing a novel approach that takes into account multiple criteria and offers a systematic process for evaluating the sustainability index.

2. Literature review

Advancing assessment tools is a significant challenge in the construction industry. Ness et al. (2007) elevated the understanding of sustainability assessment to a broader interpretation of sustainability than just focusing on environmentally-focused areas. Early building assessment systems, such as Building Research Establishment Environmental Assessment Method (BREEAM), Leadership in Energy and Environmental Design (LEED) and Green Star, have been developed globally. These evaluation systems are usually only relevant to the site's environmental characteristics (Kaur & Garg, 2019; Retzlaff, 2008). However, the requirement for methods to assess building sustainability is now increasing. And it is not limited to the assessment of building components or the built environment (Berardi, 2011; Haapio, 2012). Building sustainability assessment requires quantitative and qualitative indicators at different spatial scales – from material selection, energy and indoor air quality analysis to whole building assessment. The integration of sustainability factors and knowledge at different building stages (e.g., manufacturing, assembly, operation and maintenance) also needs to be considered to reduce the adverse environmental impacts of building production processes (Ding, 2008; Tan et al., 2020; Wasim et al., 2022). Various sustainability issues are intertwined and involve conflicting aspects to assess. Hence, several life cycle assessment tools have been developed specifically to address the building as a whole, such as Eco-Quantum, EcoEffect, ENVEST, BEES, ATHENA and LCA House (Bragança et al., 2010). These systems vary in development history, strategic choices, assessment structures, assessment criteria and local benchmarking (Kaur & Garg, 2019). They all include a list of criteria organised into major categories, e.g., site planning, resource conservation, infrastructure optimisation, waste management, and recognised innovative technologies. Weighting or percentages are applied to score across the criteria. Building sustainability assessment methods and tools, whether performance-based, environmental or life-cycle-based, are constantly evolving to improve their capabilities. Current research is still aiming to find a suitable method to achieve the most appropriate balance between the variety of sustainability dimensions and the flexibility for different building types (Bragança et al., 2010). Most tools focus on projects involving traditional construction methods. However, specialised methods for assessing the sustainability of designs for off-site construction projects are still in their nascent stages.

Several sustainable assessments for DfMA have been developed, but they are predominantly focused on manufacturing rather than construction. For example, Suresh et al. (2016) proposed integrating DfMA and sustainability assessment to ensure sustainable product design for an automotive component, evaluating environmental impact using SolidWorks software and various inputs of CAD model, material, manufacturing process, manufacturing location, and distribution. Yang et al. (2017) proposed a sustainability analysis framework for DfMA that involves additive manufacturing-enabled part consolidation and applied it to evaluate a floor attachment component for an underground train. Peruzzini and Pellicciari (2018) developed a user experience model to estimate the manufacturing sustainability of DfMA, optimising product and process design for improved sustainable manufacturing. They applied the model to an industrial case study on redesigning a machine for automated drug management, resolving issues such as high costs and stressful assembly phases for workers. Han et al. (2021) developed a sustainability assessment framework for DfMA during the conceptual stage. The framework includes four metrics: material, production, use, and end of life, and was applied to evaluate the sustainability of two portable blender design concepts. It can be observed that there is a gap in that sustainability assessments of DfMA largely originate from the manufacturing sector, which fundamentally differs from the construction industry. The manufacturing sector focuses on the mass production of standardised products, whereas the construction industry is typically project-based (Lu et al., 2021). Therefore, existing manufacturing research on DfMA cannot be directly applied to the evaluation of architectural design in the construction industry. The sustainability assessment of DfMA within the construction sector remains an area that has not been thoroughly researched and discussed. Besides, DfMA sustainability assessment is a complex and multidimensional issue requiring a holistic approach. The review suggests that DfMA can provide significant sustainability benefits, such as reduced carbon footprint, improved safety performance, and enhanced cost-effectiveness. However, further research is needed to validate and refine the existing models and tools and to address the practical challenges of implementing DfMA in different settings and industries. The literature review highlights that one of the main challenges of DfMA sustainability assessment is the lack of a standardised methodology in the construction industry.

MIVES has been demonstrated to offer a significant and representative measurement of sustainability across various domains, though there is potential for further refinement. Some studies have explored the use of MIVES for sustainability assessment regarding building design (see Table 1). MIVES has been used frequently as a specialised and holistic sustainability assessment model for obtaining global sustainability indices (Pons et al., 2016). Compared with other MCDM techniques, Pons et al. (2016) argued that MIVES can define complete, objective and easy-to-apply sustainability assessment methods for most samples within the construction sector. However, utilising MIVES in these studies encounters some challenges when facing holistic sustainability considering various building stages. The determination of sets of multi-criteria in these studies might not be suitable for new scenarios, such as off-site construction and DfMA. The transformation of construction methods significantly impacts the determination of various indicators' weightings, which urges proposing emerging key sustainability indicators and removing unimportant ones. In addition, the "triple bottom line" (i.e., economic, environmental, social) was widely employed as the three dimensions' requirements (see Table 1). Thereafter, most studies categorised indicators into these three dimensions, although a few studies tried to involve some other dimensions, like the technological dimension (Pons-Valladares et al., 2023) and the functional dimension (Gilani et al., 2022). However, by dividing the indicators in this way, namely 3–4 dimensions to constructing sustainability, contradictions may arise. That is, certain indicators may have an impact in at least two dimensions. For example, waste may have economic and environmental impacts, while safety impacts both social and economic. The assessment may be imprecise when these factors are classified into only one dimension. In general, there is potential for MIVES to integrate with DfMA, thus providing a pathway for establishing a DfMA sustainability index, which is currently a research gap. In addition, an essential gap for

Table 1. MIVES-based sustainability assessment to building design

Authors	Requirements	Criteria (Indicators)	Case study
Gilani et al. (2017)	Economic; Environmental; Social.	Construction, Maintenance, End of life; Consumption, Waste, Reusability, Emission; Safety, Comfort, Aesthetics, Added value.	Façade alternatives – 3D sandwich panels
Gilani et al. (2019)	Economic; Environmental; Social.	Cost, Consumption, Waste, Emission, Safety, Comfort, Aesthetics.	Façade systems in contemporary residential buildings in Barcelona
Gilani (2020)	Economic; Environmental; Social.	Cost, Consumption, Emission, Waste, Safety, Labour availability, Added comfort, Aesthetics.	Five residential façade systems commonly used in Barcelona, two real buildings
Habibi et al. (2020)	Economic; Environmental; Social.	Cost, Fabrication & Assembling, Use, End of Life, Production & Assembling added value, User added value.	Five Intelligent Façade Layers alternatives and three case studies at schools in Barcelona
Egiluz et al. (2021)	Economic; Environmental; Social.	Costs, Return on investment, Material used, Emissions, Disturbance created, Inconvenience for owners, Comfort and health, Architectural heritage, Aesthetic.	A real residential building in Bilbao
Lozano et al. (2023)	Economic; Environmental; Social.	Cost, Time, Emissions, Resources, Social, Safety.	A bridge (Las Arenas Viaduct)
Pons-Valladares et al. (2023)	Economic; Environmental; Social; Technological.	Cost, Emissions, Resource consumption, Innovation, Working conditions, Third-party effects, Adaptability, Availability.	Castilla-La Mancha park footbridge in Alcobendas, Madrid
Maleki et al. (2023)	Economic; Environmental; Social.	Consumption, Waste, Emission, Cost, Safety, Sense of belonging to place, Comfort, Aesthetics.	Nine residential skyscrapers in Dubai
Gilani et al. (2022)	Functional; Economic; Environmental; Social.	Constructive solutions, Security, Condensation; Cost; Consumption, Emission, Waste; Safety, Constructability, User added comfort, Aesthetics.	Six most common residential façade systems in Barcelona

enhancement lies in advancing variants of the MIVES to account for mutually conflicting factors or influences across multiple dimensions, thereby yielding a MIVES framework that is more adept at accommodating a diverse array of requirements.

3. The proposed framework

The proposed framework, depicted in Figure 1, is composed of five distinct phases. The initial phase utilises BIM to define the various design alternatives. Subsequently, academic literature and the Delphi technique are employed in the second phase to establish the requirements tree. The remaining three phases (3–5) rely on the MIVES methodology to determine the weights for all parameters in the tree, create the value function for each parameter, and ultimately determine the DfMA SI for each alternative. The detailed implementation process for each phase is elaborated on in the subsequent sections.

3.1. Phase 1: Defining the design alternatives and the problem to be solved

Phase 1 of the proposed framework serves the purpose of identifying design alternatives that can be evaluated. During this phase, the design team undertakes the task of identifying and analysing various design alternatives that have the potential to address the sustainability challenges or goals at hand. Such challenges could be focused on minimising construction waste and energy consumption, or improving manufacturability and assemblability. These alternatives may include different materials, manufacturing processes, assembly methods, and other design considerations. The team then proceeds to evaluate each alternative against the established sustainability criteria for the project. By defining the problem at this early stage, the design process can remain focused on the project's sustainability goals, ensuring that the final design solution is effective and aligned with the intended objectives.

3.2. Establishing the requirement tree

The procedure for establishing the requirements tree involved several steps. Initially, a preliminary list of parameters was compiled based on the available literature. For example, this research builds on the work by Tan et al. (2020) in which we have reviewed and discussed relevant DfMA guidelines. Thereafter, the Delphi technique was employed, involving two questionnaire iterations, to solicit responses from an expert panel regarding two specific questions in this research. The first question pertained to identifying the most critical parameters contributing to refining the DfMA concept when assessing sustainability. The second question sought pairwise comparisons of the importance of parameters at the same hierarchy.

To ensure a panel of highly qualified experts for this research, potential candidates were required to meet at least one of the following criteria: 1) senior practitioners in sustainable architectural design or 2) experts in building sustainability assessment. Following the first questionnaire iteration, a set of final responses from six experts was used to construct an authoritative requirements tree (as shown in Table 2) that only included the most significant parameters for DfMA sustainability assessment.

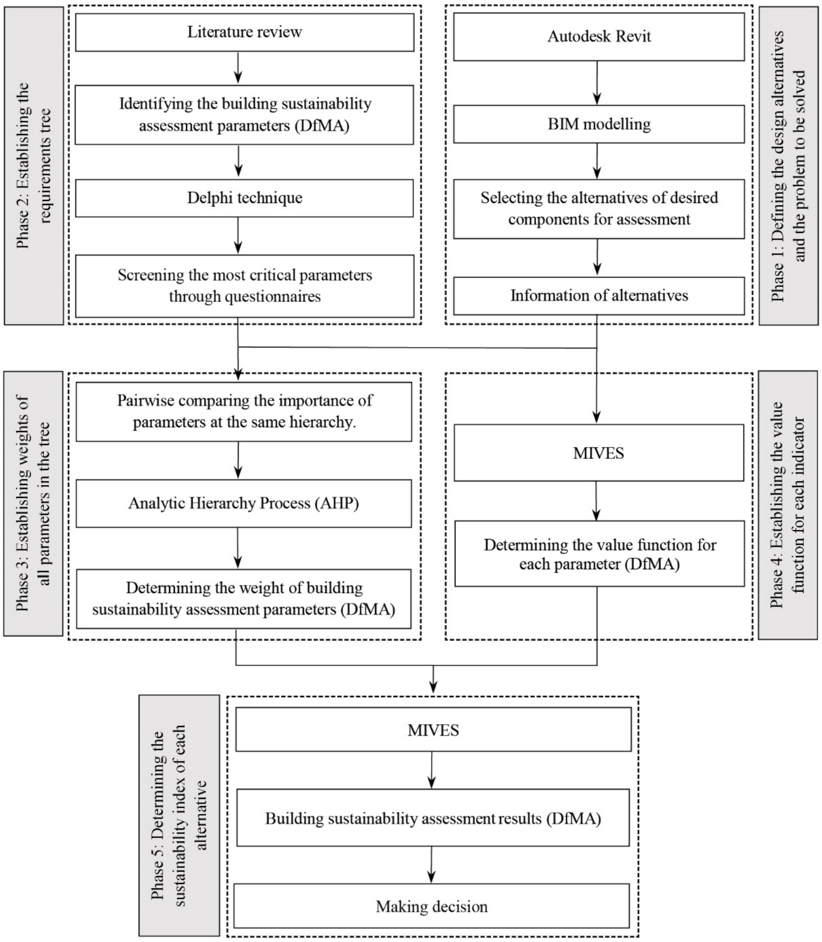


Figure 1. Proposed framework for DfMA sustainability index

Table 2. Requirements tree

Requirements	Criteria	Indicators	Sustainability aspects		
			T_1. Economic	T_2. Environmental	T_3. Social
R_1. Manufacture	C_1. Manufacturing quantity	I_1. Reduced number of molds	√	√	
		I_2. Reduced number of part counts	√	√	
		I_3. Use off-the shelf components	√	√	
	C_2. Manufacturing difficulty	I_4. Standardised parts	√	√	
		I_5. Simplified parts	√	√	
R_2. Assembly	C_3. Assembly quantity	I_6. Reduced connections and connectors	√	√	
	C_4. Assembly difficulty	I_7. lightened material and components	√	√	
		I_8. Standardised connectors	√	√	
		I_9. Assembly error tolerance	√	√	
		I_{10}. Multifunctional and multi-use parts	√	√	
R_3. Operation & Maintenance	C_5. Performance	I_{11}. Environmentally friendly building forms		√	√
		I_{12}. Environmentally friendly indoor space		√	√
		I_{13}. Environmentally friendly materials		√	√
		I_{14}. Low operation energy consumption		√	
		I_{15}. Contextual compatibility			√
		I_{16}. Visual quality			√
	C_6. Maintainability	I_{17}. Reduced fragile parts	√	√	
		I_{18}. Easy replacement of building components and materials	√	√	
		I_{19}. Safety and resilience	√		
		I_{20}. Reduced cleaning requirements	√	√	

This requirements tree comprises three main sustainability requirements, namely R_1 Manufacture, R_2 Assembly, and R_3 Operation & Maintenance. These three requirements are further subdivided into six criteria and 20 indicators. The parameters were evaluated based on their impact on the "triple bottom line", ensuring that the sustainability assessment of the DfMA concept was comprehensive and well-rounded.

3.3. Establishing weights of all parameters in the tree

Once the requirements tree has been defined, the next step involves calculating the weights of the requirements, followed by the calculation of the weights of the criteria included in each requirement, and finally the weights of the indicators included in each criterion. These weights reflect the relative importance and strength of each parameter. In the MIVES methodology, experts use the AHP to determine the weights.

To determine the weights of the parameters in this research, parameter comparison matrices and a scale of relative importance were developed (as shown in Table 3). These were used in conjunction with the Delphi technique to address research question 2 and eliminate the subjectivity of the AHP method. By conducting a second iteration of the questionnaire, the expert panel was able to provide their most consistent judgment on the pairwise importance of the parameters. This approach ensured that the weights were based on a rigorous and reliable process, ultimately contributing to the robustness of the framework.

Table 3. Parameter comparison matrices (Left) and scale of relative importance (Right)

	Intensity of importance	Definition
$A = \begin{bmatrix} 1 & I_{12} & \cdots & I_{1n} \\ I_{21} & 1 & \cdots & I_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ I_{n1} & I_{n2} & \cdots & 1 \end{bmatrix}$	1	Equal importance
	3	Moderate importance
	5	Strong importance
	7	Very strong or demonstrated importance
	9	Extreme importance
	2,4,6,8	Intermediate values

The parameter comparison results obtained by the Delphi technique may still be logically inconsistent. Therefore, to quantitatively evaluate the magnitude of this inconsistency, a consistency index (*CI*) should be calculated prior to the weights calculation:

$$CI = (\lambda_{\max} - n) / (n - 1), \tag{1}$$

where $\lambda_{\max}$ is the parameter comparison matrix's largest eigenvalue and the size. The larger the *CI*, the more inconsistent the entire matrix is, and when the *CI* is 0 it is the ideal consistent matrix. To judge whether the calculated consistency index is acceptable for the study, the ratio of the *CI* to the random index (*RI*) needs to be calculated to obtain the consistency ratio (*CR*) (Table 4). If $CR < 0.1$, then the consistency of the parameter comparison matrix can be accepted; otherwise, the expert panel needs to revise the parameter comparison matrix again.

Table 4. The Random Index (*RI*)

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.46	1.49

$$CR = CI / RI. \tag{2}$$

After $CR < 0.1$ is met, the parameter comparison matrices data can be input to AHP and calculated for the weights for each requirement, criterion and indicator.

3.4. Establishing the value function for each indicator

As depicted in Figure 2, the MIVES methodology involves calculating the score of the value function for each indicator related to each alternative using Eqn (3):

$$V_i = A + B[1 - \exp(-K_i \times (|X_{\text{ind}} - X_{\min}|/C_i)^{P_i}], \tag{3}$$

where A is the response value to $X_{\min}$, generally $A = 0$; Variable B is the factor that ensures the score of the value function falls within the range 0 to 1, obtained with Equations (4); X_{ind} is the abscissa value of alternative being evaluated with respect to the indicator i under consideration; $X_{\min}$ and $X_{\max}$ are the value of the indicator i at the minimum and maximum satisfaction, respectively; P_i is the shape factor that dictates whether the value function curve for the indicator i is concave ($P_i < 1$), straight ($P_i \approx 1$), convex or S-shaped ($P_i > 1$) (Figure 2); C_i is the abscissa value for the inflexion point in curves with $P_i > 1$; K_i is the ordinate value to the point C_i:

$$B = [1 - \exp(-K_i \times (|X_{\max} - X_{\min}|/C_i)^{P_i}]^{-1}. \tag{4}$$

To simplify the calculation of the value function, the specific data of objective indicators in this research were remapped to a range from 1 to 10. The data of subjective indicators were also on a scale of 1 to 10, and the value function shapes for each indicator were generated by a group of diverse stakeholders. In cases where stakeholders

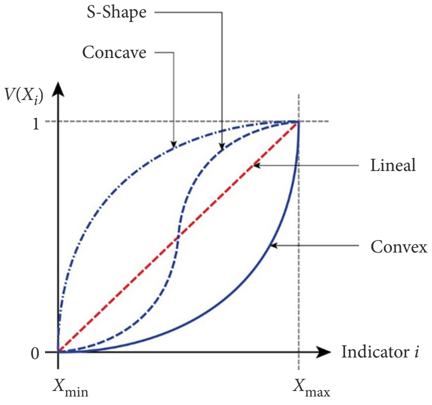


Figure 2. Different value function shapes

held differing views, the minimum squares approach was used to reconcile the differing perspectives and arrive at a consensus. This ensured that the value functions accurately reflected the stakeholders' perspectives and contributed to a more comprehensive evaluation of the alternatives.

3.5. Determining the sustainability index of each alternative

The final phase of the proposed MIVES-based method involves evaluating the sustainability index of each alternative using Eqn (5):

$$SI = \sum_{i=1}^{i=N} \alpha_i \cdot \beta_i \cdot \gamma_i \cdot V_i\left(S_{i \cdot x}\right), \qquad (5)$$

where α_i, β_i, and γ_i are the weights of each requirement, criterion, and indicator, respectively; $V_i(S_{i \times x})$ is the value function score of the alternative x with respect to the indicator i under consideration; N is the total number of indicators. To determine the most sustainable alternative, the index of T_1 Economic, T_2 Environmental, and T_3 Social can be calculated based on the sum of corresponding indicators' results (i.e., VIi). This index provides a comprehensive evaluation of each alternative's performance across economic, environmental, and social parameters, highlighting areas of strength and weakness. Ultimately, the stakeholders involved in the decision-making process can use the sustainability index to select the most suitable design alternative. This can be identified as the alternative with the highest SI, or the one that achieves a balanced performance across all parameters. By considering the sustainability index, stakeholders can make well-informed decisions, ensuring that the final design solution is aligned with the project's sustainability goals and objectives.

4. Case study

4.1. Context and background

A façade retrofit project was used to test the proposed framework. Embracing sustainable retrofit strategies for existing buildings has been a rapidly growing trend in the age of urban regeneration. Retrofitting existing buildings, such as their façade systems, can bring enormous benefits for the achievement of sustainable cities and society (Moghtadernejad et al., 2021). The case is a façade retrofit project located in Wuhan, China. There are eight design alternatives completed in December 2019. All design alternatives have the same building floors, which decreases the negative impacts from other factors and contributes to the focus of the façade retrofit design. There are some drawbacks to the existing old façade system. For example, the design style is outdated, has poor visual quality, and has low visual identification (see Figure 3). In addition, some site conditions, such as nearby transportation systems, parking systems and site landscape, impact the new design. This case represents a typical practice in China's building retrofit projects. A significant problem is evaluating these design alternatives, especially regarding sustainability. This research adopted five design alternatives with a rich data set selected for the sustainability assessment, as shown in Figure 4. The alternatives involved different building materials and structural forms, where all the façade systems were manufactured off-site and assembled on-site. Thus, the project is an appropriate empirical setting to test the proposed framework and establish the DfMA indices. The parameterised special-shaped façade in some design schemes had brought significant challenges to manufacturing and assembly, especially in terms of sustainability assessment. BIM Level 3 models were then used for data collection and analysis by following the framework proposed in Section 3.

4.2. Case study results

In the second phase, the weights of each parameter were generated through the Delphi technique and AHP (see Table 5). Both R_1 Manufacture and R_2 Assembly hold the same 0.20 weights, while R_3 Operation & Maintenance dominants 0.60 weights. In off-site construction, both these two stages share the same importance rather than solely the construction stage. It can be observed C_5 Performance accounts for the most ratio among all criteria, as it has long-standing effects on building sustainability.

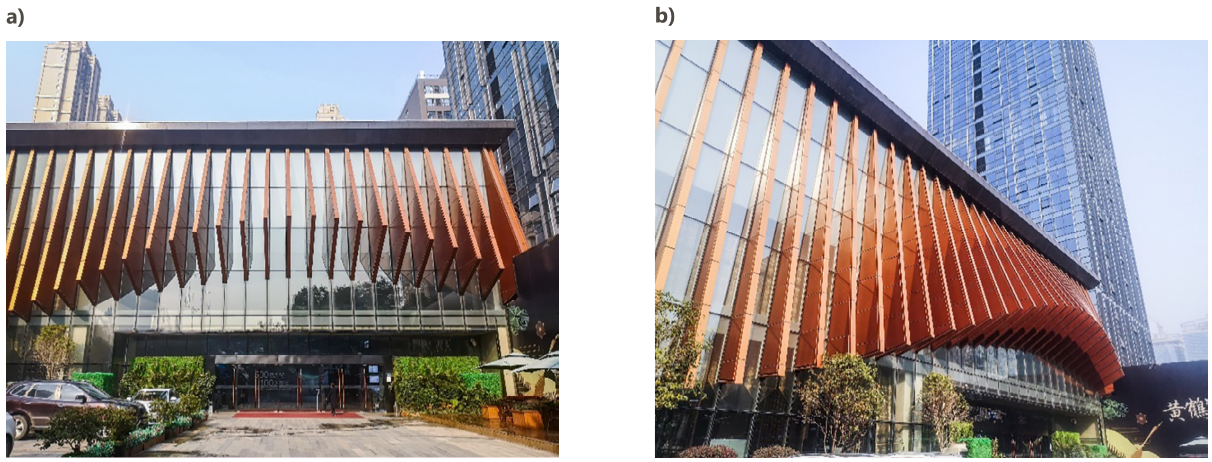


Figure 3. Existing façade system

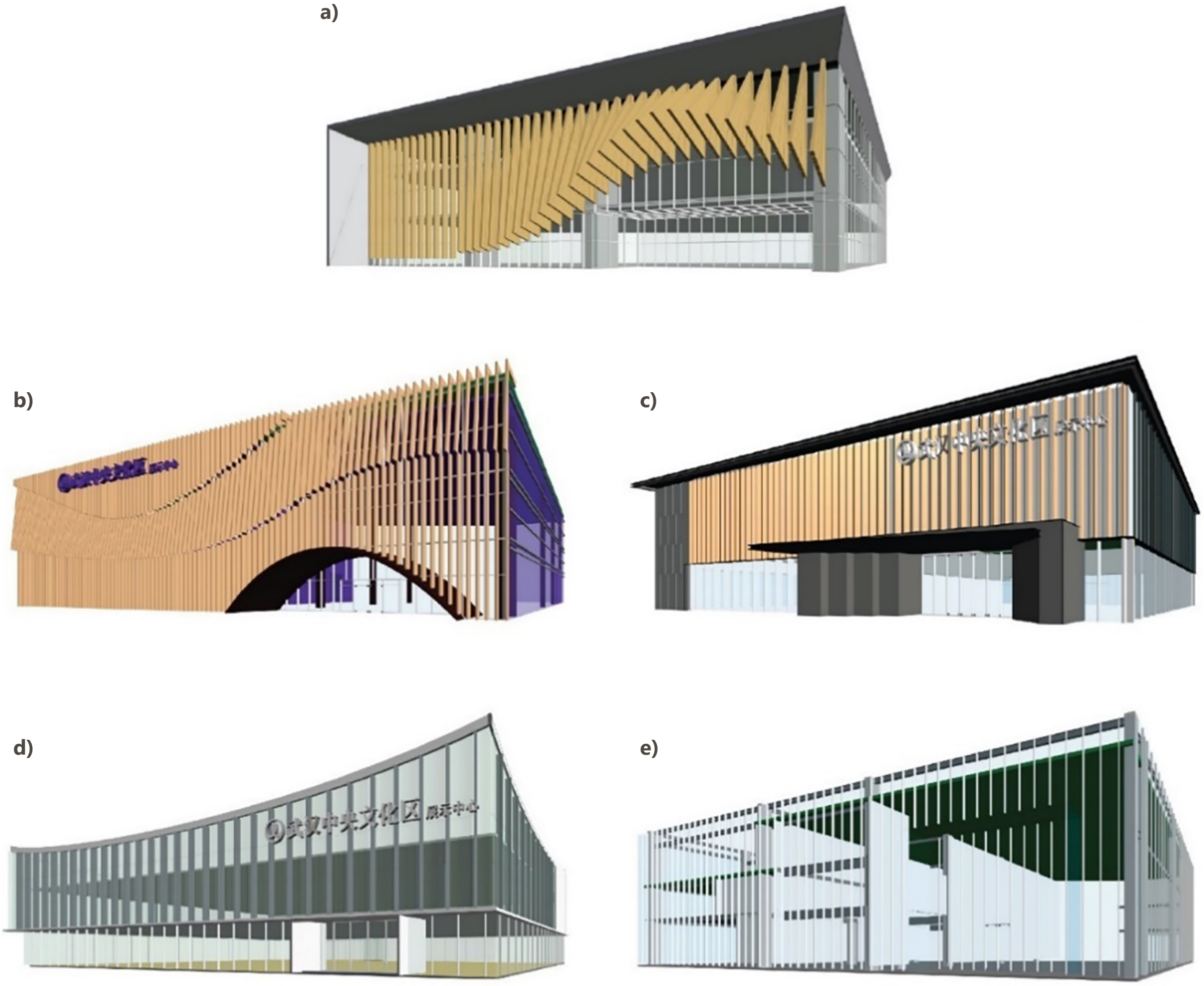


Figure 4. Alternative façade designs

Table 5. Requirements tree with calculated weights

Requirements	Criteria	Indicators
R_1. Manufacture (0.20)	C_1. Manufacturing quantity (0.25)	I_1. Reduced number of moulds (0.26)
		I_2. Reduced number of part counts (0.10)
		I_3. Use off-the shelf components (0.64)
	C_2. Manufacturing difficulty (0.75)	I_4. Standardised parts (0.75)
		I_5. Simplified parts (0.25)
R_2. Assembly (0.20)	C_3. Assembly quantity (0.25)	I_6. Reduced connections and connectors (1.00)
	C_4. Assembly difficulty (0.75)	I_7. lightened material and components (0.10)
		I_8. Standardised connectors (0.37)
		I_9. Assembly error tolerance (0.16)
		I_{10}. Multifunctional and multi-use parts (0.37)
R_3. Operation& Maintenance (0.60)	C_5. Performance (0.75)	I_{11}. Environmentally friendly building forms (0.13)
		I_{12}. Environmentally friendly indoor space (0.08)
		I_{13}. Environmentally friendly materials (0.05)
		I_{14}. Low operation energy consumption (0.32)
		I_{15}. Contextual compatibility (0.20)
		I_{16}. Visual quality (0.22)
	C_6. Maintainability (0.25)	I_{17}. Reduced fragile parts (0.26)
		I_{18}. Easy replacement of building components and materials (0.06)
		I_{19}. Safety and resilience (0.17)
		I_{20}. Reduced cleaning requirements (0.51)

In the next phase, the value function for each indicator was defined. The specific data of objective indicators were obtained directly from the BIM (see Figure 5). Data of I_1, I_3–I_8, I_{10}, I_{14} and I_{17} can be observed or calculated through the schedules and quantities function in Revit, which provides statistics on the various available fields (e.g., function, type, count, supplier, manufacturer, assembly code and description, material density, volume, operation and cost, etc.) of each part. The data of I_2 is directly displayed on the user interface (see Figure 5). Afterwards, the obtained data of each objective indicator from experts' ratings were remapped. For example, the common divisor of I_2 data is taken as 330, so the remainder of I_2 data divided by the common divisor is minimised to reduce the error of subsequent calculations. The result of the division operation is rounded to obtain the remapped value of I_2 data, see Table 7. The finalised data for each indicator value function was obtained by combining the opinions of the different experts, which are presented in Table 7. Then, the value function for each indicator related to each alternative was calculated. The SI, the values of requirement (V_{Ri}), criterion (V_{Ci}), and indicator (V_{Ii}) related to each alternative are presented in Table 8.

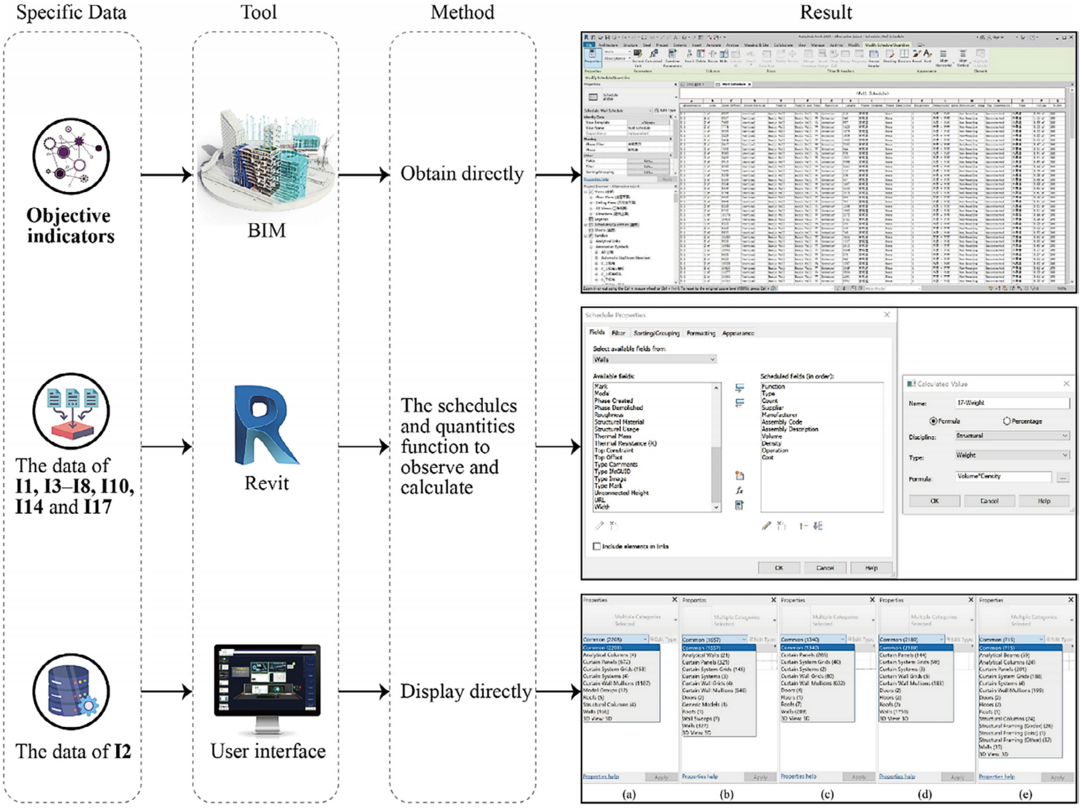
Table 6. Remapped the specific data of I2 into the range from 1 to 10

(a)	(b)	(c)	(d)	(e)
2208	1657	1340	2189	715
7	5	4	7	2

Table 7. Data of each indicator value function related to each alternative

Indicators	Alternatives					Types of value function curves			
	(a)	(b)	(c)	(d)	(e)	Types	C	K	P
I_1	8	9	6	7	4	DL	10	0.01	1
I_2	7	5	4	7	2	DL	10	0.01	1
I_3	3	3	7	4	8	IC_{VX}	5.5	0.2	1.5
I_4	1	1	5	3	9	IL	1	0.01	1
I_5	3	4	4	4	9	IL	1	0.01	1
I_6	3	8	5	5	4	DL	10	0.01	1
I_7	9	9	8	5	2	DC_{CV}	7.25	0.65	0.85
I_8	3	3	6	5	7	IL	1	0.01	1
I_9	4	3	5	6	8	IC_{CV}	4.25	0.8	0.85
I_{10}	5	3	4	3	4	IL	1	0.01	1
I_{11}	7	9	4	4	8	IS	6.5	0.8	3.1
I_{12}	5	5	5	5	5	IS	5	0.8	3
I_{13}	9	9	6	4	3	IC_{CV}	4.5	0.95	0.75
I_{14}	6	7	6	5	4	DC_{CV}	6.25	0.6	0.93
I_{15}	8	8	5	4	6	IC_{VX}	6	0.2	1.7
I_{16}	8	9	2	2	3	IC_{VX}	5.5	0.01	2.3
I_{17}	4	4	6	5	5	DC_{VX}	4.5	0.01	3
I_{18}	9	6	6	5	6	IL	1	0.01	1
I_{19}	8	8	7	7	9	IC_{CV}	7.5	0.6	0.35
I_{20}	4	4	6	9	9	DC_{CV}	7.75	0.7	0.65

Note: DL – Decreasing Lineal; IC_{VX} – Increasing Convexly; IL – Increasing Lineal; DC_{CV} – Decreasing Concavely; IC_{CV} – Increasing Concavely; IS – Increasing Convexly to Concavely; DC_{VX} – Decreasing Convexly.



Name: I7-Weight
● Formula ○ Percentage
Discipline: Structural
Type: Weight
Formula: Volume*Density

Figure 5. Exported data of from BIM

Table 8. Values of SI, VRi, VCi, and VIi for each of the five alternatives

Alternatives	SI	V_{R1}	V_{R2}	V_{R3}	V_{C1}	V_{C2}	V_{C3}	V_{C4}	V_{C5}	V_{C6}
(a)	0.48	0.09	0.47	0.62	0.17	0.06	0.78	0.37	0.59	0.71
(b)	0.47	0.11	0.25	0.66	0.17	0.09	0.22	0.26	0.65	0.70
(c)	0.42	0.46	0.50	0.38	0.57	0.43	0.56	0.48	0.32	0.56
(d)	0.35	0.26	0.48	0.34	0.27	0.26	0.56	0.45	0.32	0.39
(e)	0.57	0.85	0.63	0.46	0.73	0.89	0.67	0.61	0.48	0.40

Alternatives	VI1	VI2	VI3	VI4	VI5	VI6	VI7	VI8	VI9	VI10
(a)	0.22	0.33	0.13	0.00	0.23	0.78	0.21	0.23	0.57	0.46
(b)	0.11	0.56	0.13	0.00	0.34	0.22	0.21	0.23	0.44	0.23
(c)	0.45	0.67	0.60	0.46	0.34	0.56	0.36	0.57	0.68	0.34
(d)	0.33	0.33	0.23	0.23	0.34	0.56	0.70	0.46	0.77	0.23
(e)	0.67	0.89	0.73	0.89	0.89	0.67	0.93	0.68	0.90	0.34

Alternatives	VI11	VI12	VI13	VI14	VI15	VI16	VI17	VI18	VI19	VI20
(a)	0.52	0.34	0.96	0.57	0.70	0.56	0.30	0.89	0.94	0.83
(b)	0.88	0.34	0.96	0.46	0.70	0.77	0.30	0.57	0.94	0.83
(c)	0.08	0.34	0.81	0.57	0.29	0.01	0.09	0.57	0.90	0.68
(d)	0.08	0.34	0.63	0.68	0.18	0.01	0.18	0.46	0.90	0.31
(e)	0.71	0.34	0.51	0.77	0.42	0.03	0.18	0.57	0.97	0.31

The results of the evaluation are presented in Figure 6 and Figure 7, indicating that alternative (e) has the highest SI, while alternative (c) achieves the most balanced performance across all parameters. Additionally, alternatives (a) and (b) stand out in terms of their performance in operation. To compare the "triple bottom line" performance, which includes economic, environmental, and social performance, Figure 8 presents the performance index for each alternative. The data indicates that alternative (e) performs the best in terms of both the economy and the environment, while alternative (b) has the highest performance index on the social level. Based on these findings, stakeholders can select the design alternative that best aligns with their sustainability goals and priorities.

5. Discussion

MIVES has been used in several studies to conduct sustainability assessments of buildings, especially façade design (Egiluz et al., 2021; Gilani et al., 2017, 2019, 2022; Habibi et al., 2020). Several studies have adopted the MIVES technique in the AEC industry. They have demonstrated the merits of this model for sustainability assessment, especially in terms of application agility, user-friendliness, and flexibility and customisation provided by the value functions (Lizarralde et al., 2022). However, none of these MIVES approaches focuses on DfMA. This research proposes a MIVES multi-criteria framework for the DfMA sustainability index involving five phases: defining the design alternatives and problem to be solved, establishing the requirements tree, establishing weights for all parameters in the tree, establishing the value function for each indicator, and determining the sustainability index of each alternative.

The framework also captures the complexity of the design process by using a multi-level structure to evaluate the sustainability of design alternatives, from requirements to criteria to indicators. This structure allows for a comprehensive evaluation of design alternatives, considering multiple factors that contribute to sustainability. The framework involves human intelligence for the assessment and quantification of the parameters. Stakeholders can use the data obtained to select the design alternative with which they are most satisfied. The pilot results confirm that the MIVES framework can provide a comprehensive and integrated approach to evaluating the sustainability of DfMA. Like the two sides of a coin, the drawbacks of this approach are that it relies on expert judgment and input to determine parameter weights, which can introduce subjectivity and potential biases into the assessment. Additionally, the framework may not encompass all aspects of sustainability relevant to a particular project, necessitating customisation to ensure a comprehensive evaluation.

Compared with other DfMA sustainability tools, those approaches only focus on the manufacturing industry, such as the work developed by Yang et al. (2017) and Eastwood and Haapala (2015), while there are no such DfMA tools in the construction industry. This research presents a method that integrates the concepts of MIVES and DfMA in the construction industry context. In contrast to most MIVES approaches in construction, such as the tool developed by Pons et al. (2016) and Sánchez-Garrido et al. (2022), which only focuses on the comparison of the "Triple Bottom Line", this research modified MIVES for shifting to a comparison across six dimensions of DfMA, including manufacturing quantity, manufacturing difficulty, assembly quantity, assembly difficulty, performance, and maintainability.

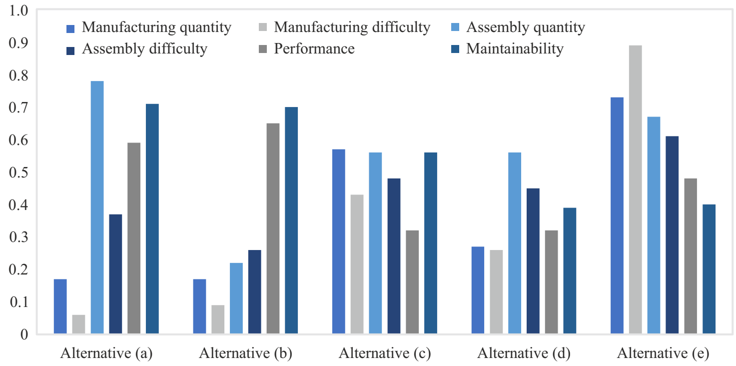


Figure 6. Criteria performance for each alternative

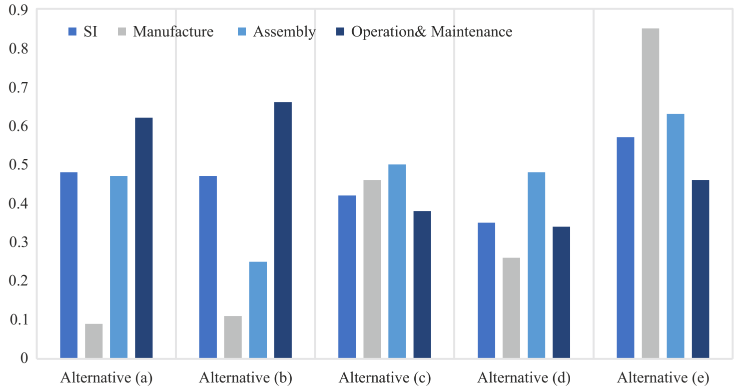


Figure 7. Sustainability and requirements performance for each alternative

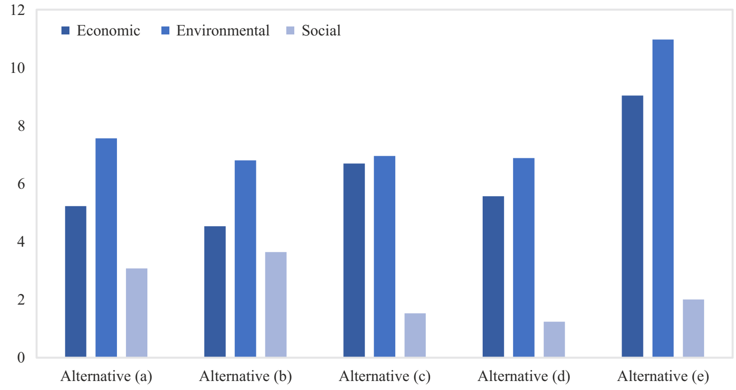


Figure 8. Triple bottom line performance for each alternative

Based on the performance in these six aspects, design alternatives can further be compared from economic, environmental, and social perspectives. Consequently, this method offers a more building design technical-focus approach specifically to DfMA for conducting sustainable comparisons. When sufficient and accessible objective data are available, the data influencing these six indicators can be obtained from BIM models. Simultaneously, this method allows the establishment of input data for the evaluation system through expert subjective scoring when objective data are lacking. This flexible operability lays the foundation for the widespread application of this method.

For theoretical implications, this research furthers previous studies in DfMA. By proposing a MIVES multi-criteria framework, the way to establish DfMA sustainability index is developed. Design evaluation is an essential aspect of the concept of DfMA (Gao et al., 2020), and the research fills the gap of the lack of DfMA sustainability index by adapting the MIVES approach with the considerations from the manufacturing, assembly, and operations & maintenance phases. This research furthers previous research about DfMA guidelines (Bao et al., 2022; Tan et al., 2020) and constructability assessment (Qi et al., 2021) to an overall index. A feasible approach to quantify DfMA qualitative guidelines is established. In addition, this research broadens the scope of DfMA application cases, as previous studies mainly focus more on new buildings (Tan et al., 2020) or interior projects (Bao et al., 2022). The 20 indicators proposed in this research can help practitioners start from these aspects to improve retrofit projects' capabilities and sustainable development using DfMA.

As for the implications for the industry, the retrofit of existing buildings is an important part of urban regeneration in the use case. How to continue the style and culture of the city through retrofit design and achieve the ultimate goal of sustainable development is one of the problems faced by the practitioners. The demolition of existing buildings, the transportation of waste materials and the input equipment are all consumption of resources. At the same time, the dust generated during the demolition of buildings can also cause environmental pollution problems, which is even more contradictory to sustainable development. The DfMA and MIVES methods can be used together to deal with these challenges. In general, the MIVES framework can be used by architects, engineers, and other stakeholders to evaluate the sustainability of DfMA in different building projects. The weights assigned to these indicators do not represent a one-size-fits-all setting; instead, users can adjust the relevant weights according to their specific needs. This flexibility enables targeted evaluation of projects using these indicators, making it a valuable tool for identifying and addressing sustainability issues in a range of contexts. This research contributes to the theoretical aspect of DfMA as a design strategy and philosophy and the practical aspect of DfMA as a design evaluation tool.

6. Conclusions

The MIVES multi-criteria framework demonstrates the ability to assess the DfMA sustainability index by comparing five design alternatives for a façade retrofit project. Specifically, this research contributes to the adoption of the multi-criteria MIVES approach. This research furthers previous studies and has three-fold significance: 1) Establishing reasonable multi-criteria for the sustainable DfMA indices; 2) Adapting the MIVES approach for comparative analysis across three building phases to make it compatible with DfMA; 3) developing a quantitative analysis method for sustainable design assessment of DfMA in the construction industry. Specifically, this research goes beyond previous MIVES-based studies for the "triple bottom line"-informed requirements setting. During the assessment, various life cycles can be considered by replacing the "triple bottom line" through R_1 Manufacture, R_2 Assembly, and R_3 Operation & Maintenance. Especially with the transformation of off-site construction, the new scenario challenges brought by the manufacture and assembly stages induce essential changes for the requirements of design evaluation, especially in terms of sustainability.

Another implication is that after this replacement, the previous indicators classified under the "triple bottom line" and had to do an either-or-choice would no longer be the only option. Therefore, indicators affecting two or three aspects of the "triple bottom line" can be included in the evaluation, making the assessment more accurate. In addition, this research sheds light on the application of BIM for approach development and bridges the synergy approaches between MCDM and BIM. The expert-based rating system is established using objective BIM data and BIM functionalities, combining subjective and objective data advantages. The framework can evaluate the façade system retrofit mentioned in the case and can be applied to various other types of building projects after corresponding adjustment of the indicators and weightings based on project requirements.

This research also has limitations. In the phase of scheme design, professionals frequently encounter difficulties in executing high-precision BIM modelling for all possible design alternatives. As a result, variations in the depth of data between various design options frequently occur, which may affect the evaluation and results. In addition, the weighting and scoring system among the indicators of the proposed method is based on the expert team. The advantage is that scoring based on experts can provide more flexibility and enforceability in practice, but it may lack data objectivity, which, however, requires higher accuracy of the BIM model data. The quantitative data obtained through BIM in the methodology of this research merely serves as a foundation for the expert evaluators to assign scores and does not assume an overarching, deterministic role in determining the final outcome.

Subsequent research can take three divergent paths. Firstly, it can create specific metrics tailored to different building types, such as new design projects, retrofit projects, and interior projects, to derive their corresponding DfMA indices. Secondly, future research can develop more advanced value function models that can better capture the complexity of sustainability criteria and indicators. Thirdly, it can strive to establish an automated scoring calculation process based on BIM techniques for select indicators, thus enhancing the method's objectivity. Overall, this research represents a valuable contribution to the field of sustainability assessment and DfMA, as it has expanded the horizons of DfMA-based design evaluation development and advanced the discourse surrounding the DfMA sustainability index.

Funding

This study is supported by the National Natural Science Foundation of China (51978295), and Hong Kong Research Grants Council Collaborative Research Fund (C7080-22GF).

Author contributions

T. T. conceived the study and was responsible for the design and development of the data analysis. T. T. L. Z. and X. L. were responsible for data collection and analysis. T. T. were responsible for data interpretation. L. Z. Z. B. Z. F. wrote the first draft of the article. F. X. reviewed and edited the final draft. X. L. was responsible for the funding.

Disclosure statement

Authors of this article declare no competing financial, professional, or personal interests from other parties.

References

Al Hattab, M., & Hamzeh, F. (2018). Simulating the dynamics of social agents and information flows in BIM-based design. *Automation in Construction*, *92*, 1–22. https://doi.org/10.1016/j.autcon.2018.03.024

Ariaratnam, S. T., Piratla, K., Cohen, A., & Olson, M. (2013). Quantification of sustainability index for underground utility infrastructure projects. *Journal of Construction Engineering and Management*, *139*(12), Article A4013002. https://doi.org/10.1061/(ASCE)CO.1943-7862.0000763

Bao, Z. (2023). Developing circularity of construction waste for a sustainable built environment in emerging economies: New insights from China. *Developments in the Built Environment*, *13*, Article 100107. https://doi.org/10.1016/j.dibe.2022.100107

Bao, Z., Laovisutthichai, V., Tan, T., Wang, Q., & Lu, W. (2022). Design for manufacture and assembly (DfMA) enablers for offsite interior design and construction. *Building Research* & *Information*, *50*(3), 325–338. https://doi.org/10.1080/09613218.2021.1966734

Berardi, U. (2011). Beyond sustainability assessment systems: Upgrading topics by enlarging the scale of assessment. *International Journal of Sustainable Building Technology and Urban Development*, *2*(4), 276–282. https://doi.org/10.5390/SUSB.2011.2.4.276

Bogue, R. (2012). Design for manufacture and assembly: background, capabilities and applications. *Assembly Automation*, *32*(2), 112–118. https://doi.org/10.1108/01445151211212262

Boothroyd, G. (2005). *Assembly automation and product design*. CRC Press. https://doi.org/10.1201/9781420027358

Bragança, L., Mateus, R., & Koukkari, H. (2010). Building sustainability assessment. *Sustainability*, *2*(7), 2010–2023. https://doi.org/10.3390/su2072010

Cots, D. B., Pardo-Bosch, F., Blanco, A., Aguado, A., & Pujadas, P. (2022). A systematic review on MIVES: A sustainability-oriented multi-criteria decision-making method. *Building and Environment*, *223*, Article 109515. https://doi.org/10.1016/j.buildenv.2022.109515

Desa, U. (2018). *Revision of world urbanization prospects*. UN Department of Economic and Social Affairs.

Dewhurst, N. P. (2010). DFMA the product, then lean the process. In *Proceedings of International Forum on Design for Manufacture and Assembly*.

Ding, G. K. (2008). Sustainable construction – The role of environmental assessment tools. *Journal of Environmental Management*, *86*(3), 451–464. https://doi.org/10.1016/j.jenvman.2006.12.025

Eastwood, M. D., & Haapala, K. R. (2015). A unit process model based methodology to assist product sustainability assessment during design for manufacturing. *Journal of Cleaner Production*, *108*, 54–64. https://doi.org/10.1016/j.jclepro.2015.08.105

Egiluz, Z., Cuadrado, J., Kortazar, A., & Marcos, I. (2021). Multicriteria decision-making method for sustainable energy-saving retrofit facade solutions. *Sustainability*, *13*(23), Article 13168. https://doi.org/10.3390/su132313168

Fallahpour, A., Wong, K. Y., Rajoo, S., Olugu, E. U., Nilashi, M., & Turskis, Z. (2020). A fuzzy decision support system for sustainable construction project selection: an integrated FPP-FIS model. *Journal of Civil Engineering and Management*, *26*(3), 247–258. https://doi.org/10.3846/jcem.2020.12183

Gao, S., Jin, R., & Lu, W. (2020). Design for manufacture and assembly in construction: a review. *Building Research* & *Information*, *48*(5), 538–550. https://doi.org/10.1080/09613218.2019.1660608

Gilani, G. (2020). *MCDM approach for assessing the sustainability of buildings' facades* [PhD thesis]. Polytechnic University of Catalonia.

Gilani, G., Blanco, A., & de la Fuente, A. (2017). A new sustainability assessment approach based on stakeholder's satisfaction for building facades. *Energy Procedia*, *115*, 50–58. https://doi.org/10.1016/j.egypro.2017.05.006

Gilani, G., Pons, O., & de la Fuente, A. (2019). Towards the façades of the future: A new sustainability assessment approach. *IOP Conference Series: Earth and Environmental Science*, *290*, Article 012075. https://doi.org/10.1088/1755-1315/290/1/012075

Gilani, G., Pons, O., & de la Fuente, A. (2022). Sustainability-oriented approach to assist decision makers in building facade management. *Journal of Construction Engineering and Management*, *148*(1), Article 04021182. https://doi.org/10.1061/(ASCE)CO.1943-7862.0002194

Haapio, A. (2012). Towards sustainable urban communities. *Environmental Impact Assessment Review*, *32*(1), 165–169. https://doi.org/10.1016/j.eiar.2011.08.002

Habibi, S., Valladares, O. P., & Pena, D. (2020). New sustainability assessment model for Intelligent Facade Layers when applied to refurbish school buildings skins. *Sustainable Energy Technologies and Assessments*, *42*, Article 100839. https://doi.org/10.1016/j.seta.2020.100839

Hamilton, I. (2023). *Decarbonizing the global buildings sector: Efficiency*, *Electrification*, *and Equity*. Center on Global Energy Policy.

Han, J., Jiang, P., & Childs, P. R. (2021). Metrics for measuring sustainable product design concepts. *Energies*, *14*(12), Article 3469. https://doi.org/10.3390/en14123469

Kaur, H., & Garg, P. (2019, Feb). Urban sustainability assessment tools: A review. *Journal of Cleaner Production*, *210*, 146–158. https://doi.org/10.1016/j.jclepro.2018.11.009

Kibert, C. J. (2016). *Sustainable construction: Green building design and delivery*. John Wiley & Sons.

Lizarralde, R., Ganzarain, J., & Zubizarreta, M. (2022). Adaptation of the MIVES method for the strategic selection of new technologies at an R&D centre. Focus on the manufacturing sector. *Technovation*, *115*, Article 102462. https://doi.org/10.1016/j.technovation.2022.102462

Lozano, F., Jurado, J., Lozano-Galant, J., de la Fuente, A., & Turmo, J. (2023). Integration of BIM and Value model for sustainability assessment for application in bridge projects. *Automation in Construction*, *152*, Article 104935. https://doi.org/10.1016/j.autcon.2023.104935

Lu, W., Tan, T., Xu, J., Wang, J., Chen, K., Gao, S., & Xue, F. (2021). Design for manufacture and assembly (DfMA) in construction: The old and the new. *Architectural Engineering and Design Management*, *17*(1–2), 77–91. https://doi.org/10.1080/17452007.2020.1768505

Luiten, G. T., & Fischer, M. A. (1998). Opportunities for computer-aided design for construction. *Engineering*, *Construction and Architectural Management*, *5*(2), 127–136. https://doi.org/10.1108/eb021067

Maleki, B., del Mar Casanovas-Rubio, M., Daniel Tsavdaridis, K., & de la Fuente Antequera, A. (2023). An assessment of sustainability for residential skyscrapers in accordance with a multicriteria decision-making method: Nine Dubai case studies. *Journal of Architectural Engineering*, *29*(4), Article 04023038. https://doi.org/10.1061/JAEIED.AEENG-1559

Moghtadernejad, S., Chouinard, L. E., & Mirza, M. S. (2021). Enhanced façade design: A data-driven approach for decision analysis based on past experiences. *Developments in the Built Environment*, *5*, Article 100038. https://doi.org/10.1016/j.dibe.2020.100038

Ness, B., Urbel-Piirsalu, E., Anderberg, S., & Olsson, L. (2007). Categorising tools for sustainability assessment. *Ecological Economics*, *60*(3), 498–508. https://doi.org/10.1016/j.ecolecon.2006.07.023

Peruzzini, M., & Pellicciari, M. (2018). User experience evaluation model for sustainable manufacturing. *International Journal of Computer Integrated Manufacturing*, *31*(6), 494–512. https://doi.org/10.1080/0951192X.2017.1305502

Pons-Valladares, O., del Mar Casanovas-Rubio, M., Armengou, J., & de la Fuente, A. (2023). Approach for sustainability assessment for footbridge construction technologies: Application to the first world D-shape 3D-Printed fiber-reinforced mortar footbridge in Madrid. *Journal of Cleaner Production*, *394*, Article 136369. https://doi.org/10.1016/j.jclepro.2023.136369

Pons, O., De la Fuente, A., & Aguado, A. (2016). The use of MIVES as a sustainability assessment MCDM method for architecture and civil engineering applications. *Sustainability*, *8*(5), Article 460. https://doi.org/10.3390/su8050460

Qi, B., Costin, A., & Razkenari, M. (2021). An ontology for manufacturability and constructability of prefabricated component. In *ASCE International Conference on Computing in Civil Engineering 2021* (pp. 745–752). https://doi.org/10.1061/9780784483893.092

Retzlaff, R. (2008). Green building assessment systems: A framework and comparison for planners. *Journal of the American Planning Association*, *74*(4), 505–519. https://doi.org/10.1080/01944360802380290

Sánchez-Garrido, A. J., Navarro, I. J., & Yepes, V. (2022). Multi-criteria decision-making applied to the sustainability of building structures based on modern methods of construction. *Journal of Cleaner Production*, *330*, Article 129724. https://doi.org/10.1016/j.jclepro.2021.129724

Šaparauskas, J. (2003). Multiple criteria evaluation of buildings with emphasis on sustainability. *Journal of Civil Engineering and Management*, *9*(4), 234–240. https://doi.org/10.3846/13923730.2003.10531334

Suresh, P., Ramabalan, S., & Natarajan, U. (2016). Integration of DFE and DFMA for the sustainable development of an automotive component. *International Journal of Sustainable Engineering*, *9*(2), 107–118. https://doi.org/10.1080/19397038.2015.1096313

Tan, T., Lu, W. S., Tan, G. Y., Xue, F., Chen, K., Xu, J. Y., Wang, J., & Gao, S. (2020). Construction-oriented design for manufacture and assembly guidelines. *Journal of Construction Engineering and Management*, *146*(8), Article 04020085. https://doi.org/10.1061/(ASCE)CO.1943-7862.0001877

Tan, T., Mills, G., Papadonikolaki, E., & Liu, Z. N. (2021, Jan). Combining multi-criteria decision making (MCDM) methods with building information modelling (BIM): A review. *Automation in Construction*, *121*, Article 103451. https://doi.org/10.1016/j.autcon.2020.103451

Wasim, M., Vaz Serra, P., & Ngo, T. D. (2022). Design for manufacturing and assembly for sustainable, quick and cost-effective prefabricated construction – a review. *International Journal of Construction Management*, *22*(15), 3014–3022. https://doi.org/10.1080/15623599.2020.1837720

Yang, S., Talekar, T., Sulthan, M. A., & Zhao, Y. F. (2017). A generic sustainability assessment model towards consolidated parts fabricated by additive manufacturing process. *Procedia Manufacturing*, *10*, 831–844. https://doi.org/10.1016/j.promfg.2017.07.086