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Optimizing Cost Management in Construction Projects: A Sustainability Assessment Model Using Fuzzy Inference Systems (Case Study of the Apadana Project in the Persian Gulf Petrochemical Industries Company)

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ABSTRACT

Objective: The construction industry has been increasingly criticized for its poor sustainability performance in recent decades, creating a chance for the sector to play a key role in global sustainability efforts. Rapid technological advancements and increasing construction project complexities have driven the need for flexible, sustainability-focused project management frameworks. This study introduces a fuzzy inference system designed to evaluate construction project sustainability, built on insights from extensive literature and expert input.

Methods: To design the proposed model, the system inputs—criteria for evaluating the sustainability level of construction projects at various layers—were first identified. Next, the necessary if-then rules were developed based on expert opinions. The system output was determined in alignment with the research's final objective. By offering a comprehensive assessment of construction project sustainability, the model enables organizations to identify their strengths and weaknesses, assess their current position, and make informed decisions to enhance their sustainable performance.

Results: The output of the research includes a detailed analysis of the sustainability performance of construction projects. The designed model, along with its measurement tools, provides an opportunity for leaders and managers in the construction industry who are concerned about sustainability to gradually enhance their sustainability status and advance the sustainability level of projects. This model consists of three subsystems named the Direction, Execution, and Results subsystems. The aforementioned subsystems are the result of a literature review and are considered inputs to the final level of the model.

Conclusion: The designed model serves as a tool to identify and implement improvement methods and potential areas for project advancement from a sustainability perspective. By utilizing this model, the quality of project execution in line with sustainability indicators, while addressing all three dimensions—economic, social, and environmental—improves continuously and proportionately.

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Introduction

Of all industrial sectors, the construction industry has the most significant environmental impact (Marrero et al., 2024). Construction projects require substantial capital investment and, as such, play a critical role in both promoting and potentially undermining sustainable development. According to global estimates, the construction industry ecosystem contributes approximately 13% to the world's Gross Domestic Product (GDP). However, the sector is also responsible for significant environmental impacts, with buildings and construction collectively accounting for 36% of global energy consumption and 39% of energy-related carbon dioxide (CO_2) emissions. Construction projects entail allocating significant financial resources and consequently serve as a critical leverage point that can either advance or undermine the pursuit of sustainable development goals. Globally, the construction industry ecosystem is estimated to contribute approximately 13% to Gross Domestic Product (GDP). However, it is also among the most resource-intensive and environmentally impactful sectors, with buildings and construction accounting for 36% of global energy consumption and 39% of energy-related carbon dioxide (CO_2) emissions (Kiani Mavi et al., 2021).

The construction industry is projected to grow at an annual rate of 4% over the coming years, positioning it as the fastest-growing industrial sector of the next decade. However, the impacts of this sector are inherently dual. On one hand, construction plays a vital role in enhancing human quality of life by delivering buildings and infrastructure that fulfill the socio-economic needs of individuals, communities, and nations. On the other hand, construction activities heavily rely on the consumption of vast quantities of natural and non-renewable resources, which contribute to environmental degradation through pollution, disruption of sensitive natural ecosystems, and the emission of greenhouse gases that pose serious threats to the future of the planet (Shashi et al., 2023).

In most traditional construction projects, the social and environmental repercussions of project execution have been insufficiently addressed due to limited oversight, budgetary constraints, incomplete construction regulations, and the predominant emphasis of investors and owners on economic returns. In recent years, sustainability in construction project management has garnered increasing attention. Studies in this domain have predominantly examined the processes and factors that influence the integration of sustainability into project management practices (Fathalizadeh et al., 2021). Construction firms are pursuing approaches to transition from conventional construction methods to sustainable practices, thereby enabling them to achieve their commercial objectives without compromising environmental integrity (Ershadi et al., 2021). Sustainable construction should optimize its triple-bottom-line performance—social, economic, and environmental—by systematically establishing the current sustainability baseline, diagnosing performance gaps, and executing targeted remediation measures (Hendiani et al., 2019). Research conducted in the field of sustainable construction project management (Figure 1) has identified numerous key indicators and success factors as critical criteria for the effective execution of sustainable construction projects.

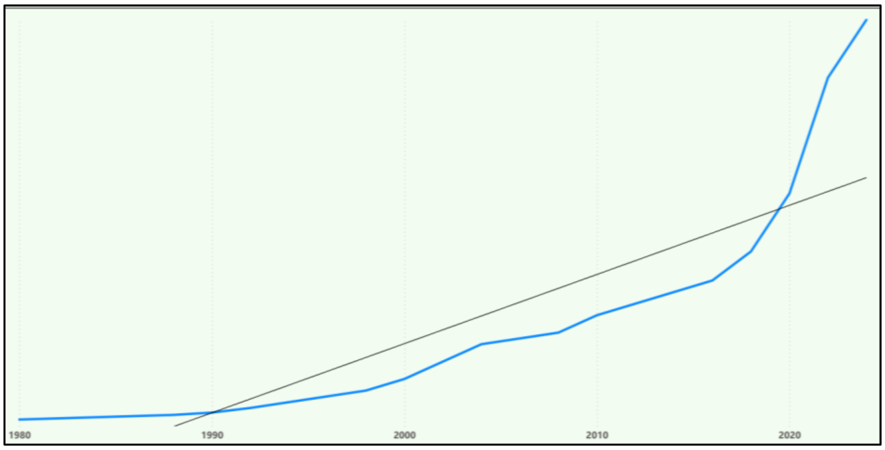

Figure 1. Frequency of the relevant research conducted from 1980 to 2024

These indicators serve as guiding instruments for steering modern construction projects toward sustainability. While identifying these indicators is only half of the equation, the other half involves determining how to assess, refine, and enhance a project that falls short of the required sustainability standards. In the first phase, we must assess our current position against established sustainability benchmarks; in the next phase, we then advance toward those benchmarks and rectify any deficiencies. This domain encompasses the tactics and solutions for enhancing sustainability in construction projects (Stanitsas et al., 2021).

Accordingly, the principal objective of this study is to present a fuzzy inference system for assessing the sustainability of construction projects, emphasizing the economic, social, and environmental dimensions, and to address the following research questions:

- Which sustainability indicators are pivotal for assessing construction projects?
- How can a fuzzy inference system be operationalized to evaluate sustainability levels?

The remainder of this paper is organized as follows. Section 2 provides a comprehensive literature review and examines the empirical background of the study. Section 3 details the research methodology and discusses the execution phases. Section 4 presents the findings derived from the developed fuzzy inference system. Finally, Section 5 offers a discussion of the results and concludes the paper.

Literature Background

Theoretical literature

Project Management and Sustainable Development

In the scholarly literature, a project is defined as a temporary endeavor undertaken to effect beneficial change, such as a unique product, service, or result (Khalifeh et al., 2020). Kerzner (2002) conceptualized a project as a structured mechanism for effectuating organizational change. Within this framework, business transformation encompasses a broad spectrum of modifications in operational procedures, strategic orientations, and corporate governance policies, aimed at enhancing organizational performance and adaptability. According to the Project Management Body of Knowledge Guide (PMBOK[1]), a project is a temporary endeavor undertaken to create a unique product, service, or result. This definition emphasizes that projects have a definite start and end, focusing on creating something new and distinct. The temporary nature of a project contrasts with ongoing business operations (PMBOK, 2021).

In 1992, responding to the World Commission on Environment and Development's report Our Common Future, the United Nations officially recognized sustainability as a guiding principle for the 21st century.

Rodrigues et al., (2023) addressed key global challenges, including food security, species and ecosystem conservation, energy, poverty, etc. It affirmed that sustainable development represents the most effective means of meeting the essential needs of the present generation without compromising the ability of future generations to meet their own (WCED, 1987). Sustainability can be divided into three main components: environmental, social, and economic. Sustainability constitutes a developmental approach that emphasizes the utilization of resources, technologies, investments, and governmental policies to address the needs of people both in the present and the future. The sustainability approach originates from the concept of sustainable development, which concerns the utilization of existing resources without compromising future generations' ability to access them (WCED, 1987). The World Commission on Environment and Development (WCED) defines sustainable development as:
A process of change in which the exploitation of resources, the direction of investments, the orientation of technological development, and institutional change are made consistent with future as well as present needs. In other words, while individuals or organizations pursue their economic objectives, they must remain conscious of how these goals may impact the future. It is imperative to prioritize identifying strategies that not only serve current interests but also safeguard the well-being of future generations. Sustainable development requires balancing

[1] Project Management Body of Knowledge

economic needs with social and environmental concerns, ensuring that meeting present demands does not compromise future generations' ability to meet their needs (Khalifeh et al., 2020).

Integrating Sustainable Practices in Construction Project Cost Management

Sustainable construction methods employ strategic approaches that comprehensively address environmental externalities and societal impacts while ensuring compliance with internationally recognized environmental stewardship protocols and social responsibility standards. These methods focus on reducing energy consumption, minimizing waste generation, and optimizing natural resource efficiency. Materials are carefully selected to minimize environmental impact while fostering a healthier and more productive work environment. Additionally, sustainable construction emphasizes end-of-life considerations, incorporating systematic strategies for material reuse and recycling to enhance long-term sustainability (Ershadi et al., 2021).

Empirical background

Sustainability in the construction industry has emerged as a shared priority among governments, construction practitioners, and academia. Sustainability does not merely entail ensuring that construction projects demonstrate environmentally sound performance. In this industry, sustainability fundamentally necessitates the assurance of optimal cost management to uphold their economic viability. A broad spectrum of economic aspects must be considered, including industry competition, material costs, and project timelines. Additionally, social components must also be addressed, covering ensuring compliance with safety and health standards and incorporating local community needs into project planning (Kiani Mavi et al., 2021). Sustainability is a comprehensive concept that the construction industry must consider in all its aspects. By considering all relevant factors, construction projects can enhance environmental sustainability, foster economic stability, address social needs, and achieve technical excellence, ensuring long-term success and responsible development. Ultimately, the sustainability assessment of a project is based on analyzing these three main domains (Kiani Mavi et al., 2021). Therefore, the primary objective of sustainable construction is to reduce the negative environmental impacts of construction activities while enhancing the quality of life. To achieve this, sustainable construction must holistically address the three interconnected dimensions of economic viability, social equity, and environmental stewardship. In other words, it requires simultaneously optimizing the use of natural resources, mitigating adverse ecological consequences, and aligning project outcomes with socioeconomic imperatives through integrated consideration of economic, social, and environmental impacts. The dimensions of sustainability in the construction industry encompass three fundamental pillars:

- Economic Dimensions: This dimension encompasses sustainable economic development, resource efficiency, optimal cost management, and profitability enhancement.

- Social Dimensions: These include quality of life enhancement, job creation, sustainable community development, and the provision of high-quality living/working spaces.
- Environmental Dimensions: These involve mitigation of adverse environmental impacts, responsible utilization of natural resources, construction waste minimization, and incorporation of recycled materials (Ershadi et al., 2021).

Mavi and Standing (2018), in their article titled "Critical Success Factors for Sustainable Project Management in Construction: A Fuzzy DEMATEL-ANP Approach", focused on identifying Critical Success Factors (CSFs) for sustainable project management in the construction industry. The term "Critical Success Factors" refers to key elements essential for the success of a project, which may vary depending on the industry, project type, and contextual variables. This study employs a Fuzzy DEMATEL-ANP (Decision-Making Trial and Evaluation Laboratory-Analytic Network Process) hybrid methodology to classify and prioritize CSFs. The Fuzzy DEMATEL method is utilized to determine interdependencies and assign weights to CSFs, enabling the identification of causal relationships and hierarchical weighting. In this research, CSFs are categorized into five criteria groups:

1. Project
2. Project Management
3. Organization
4. External Environment
5. Sustainability

Stanitsas et al. (2021), in their article titled "Sustainability in Project Management: A Case Study of the Construction Industry", investigate the integration of sustainability principles into construction project management practices. Their primary objective was to explore how sustainability indicators can be effectively embedded into project management frameworks, enabling construction project managers to make decisions that yield positive environmental and social impacts while maintaining financial viability. Through a systematic synthesis of existing literature and semi-structured interviews with construction experts, the study identified and categorized sustainability indicators relevant to cost-optimized project management in construction. A total of 82 sustainability indicators were identified, classified into three dimensions:

1. Economic Sustainability (27 indicators, e.g., lifecycle cost efficiency, ROI on green investments)
2. Environmental Sustainability (18 indicators, e.g., embodied carbon reduction, circular material utilization)

3. Social/Managerial Sustainability (37 indicators, e.g., stakeholder equity, occupational health compliance)

Kiani Mavi et al. (2021), in their article titled "Sustainability in Construction Projects: A Systematic Review of the Research Literature", conducted a comprehensive analysis of key concepts and existing research on sustainability in construction projects. The primary objective of this study was to provide a holistic perspective on sustainability frameworks within construction projects, contributing to the advancement of sustainable development in the industry. The research employed a systematic literature review (SLR) methodology, encompassing an exhaustive examination of scholarly works related to sustainability in construction project management.

Wen et al. (2018), in their article titled "Measuring the Sustainability of Construction Projects throughout Their Life Cycle", argued that the construction industry is widely criticized as unsustainable due to its low productivity and high resource consumption. Despite this critique, effective tools for monitoring and achieving stakeholder-expected sustainability outcomes in construction projects remain scarce. To address this gap, the authors proposed a Construction Project Sustainability Assessment System (CPSAS), designed to equip engineers and managers with a structured framework for monitoring and controlling sustainability throughout a project's lifecycle. This evaluation system has four following levels: The first level consists of 3 main pillars. The second level includes 8 categories. The third level covers 19 sub-categories and the fourth level encompasses 31 indicators.

Goel et al. (2021), in their article titled "Integrating Sustainability into Construction Project Management: A Morphological Analysis of over Two Decades of Research Literature", synthesized more than two decades of published research on Sustainability Integration in Construction Project Management (SIMCP). The study employed a three-phase methodological framework:

1. Search and Shortlisting: Systematic identification of relevant literature across Scopus, Web of Science, and ASCE databases (2000–2020).
2. Systematic Review: Critical appraisal of 130 peer-reviewed articles using PRISMA-SCR guidelines.
3. Morphological Analysis: Categorization of SIMCP knowledge into 7 dimensions through ISO 21500-aligned thematic coding.

These dimensions include motivations, stakeholder orientation, organizational context, time orientation, benefits, barriers, and risks.

Ershadi and Goodarzi (2021), in their article titled "Core Capabilities for Achieving Sustainable Construction Project Management", investigated the challenges, competencies, and strategies critical to sustainable construction project management. The study synthesized diverse perspectives to identify core capabilities that reflect sustainability-driven project management practices in the construction industry. Through an SLR adhering to the PRISMA protocol (Preferred Reporting Items for Systematic Reviews and Meta-Analyses), the authors analyzed scholarly works from databases such as Scopus and Web of Science, ultimately extracting 42 capabilities and 23 thematic clusters to construct a conceptual framework. Additionally, the research identifies two distinct paradigms of sustainable project management:

1. Implementation-Focused Sustainable Project Management: Prioritizes process optimization (e.g., waste reduction, energy efficiency).
2. Product-Focused Sustainable Project Management: Emphasizes sustainable deliverables (e.g., LEED-certified buildings, circular material use).

Beni-Hashemi et al. (2017), in their article titled "Critical Success Factors (CSFs) for Integrating Sustainability into Construction Project Management Practices in Developing Countries", identified and validated the CSFs critical to embedding sustainability into construction project management (CPM) practices in developing nations. The study employed a mixed-methods approach structured across four phases:

1. SLR
2. Contextual Customization
3. Validation Survey
4. PLS-SEM Analysis

Stanitsas et al. (2021), in their article titled "Examining the Significance of Sustainability Indicators for Enhancing Sustainable Construction Project Management", investigated the critical role of sustainability metrics in improving sustainable construction project management practices. By prioritizing sustainability and incorporating the perspectives of all stakeholders—including project managers, engineers, architects, and residents—the authors systematically evaluated and ranked the importance of diverse sustainability indicators. Utilizing an analytical research methodology, the study synthesized prior research findings and incorporated insights from semi-structured interviews with industry professionals and community representatives.

Gündüz et al. (2020), in their article titled "Critical Success Factors (CSFs) for Sustainable Construction Project Management", focused on identifying and categorizing CSFs that influence the success of construction projects. The primary objective of this research was to determine the key factors that contribute to project success while accounting for the impact of diverse stakeholders, a distinguishing feature of this study compared to existing literature. Through a comprehensive literature review, the authors identify 40 CSFs, which are organized into 7 categories:

1. Project-Related Factors (e.g., scope clarity, budget alignment)
2. Company/Work-Related Factors (e.g., organizational culture, resource allocation)
3. Client-Related Factors (e.g., client engagement, payment timelines)
4. Project Management Factors (e.g., risk management, scheduling)
5. Design Team-Related Factors (e.g., interdisciplinary collaboration, innovation)
6. Contractor-Related Factors (e.g., subcontractor coordination, quality control)
7. Project Manager-Related Factors (e.g., leadership, decision-making agility)

Rajabi et al. (2022), in their article titled "Identification and Evaluation of Sustainability Performance Indicators for Construction Projects", focused on identifying and assessing sustainability performance indicators (SPIs) for construction projects, particularly during the execution phase. The study aimed to determine the relative importance of environmental and socio-economic sustainability indicators in civil engineering projects. Utilizing the Analytic Hierarchy Process (AHP), the research provided actionable insights for contractors to prioritize sustainability metrics aligned with global best practices. Key findings emphasized renewable energy adoption as the most critical environmental indicator and construction site safety as the paramount socio-economic indicator.

Adomi et al. (2024), in their study addressing the construction industry's pivotal role in mitigating climate change, analyzed the role of stakeholders in developing ESG (Environmental, Social, and Governance) frameworks. Prior research has established several sustainability assessment frameworks—such as BREEAM, LEED, and Green Star certification—to evaluate project sustainability. This study employed document analysis to investigate how these frameworks can assist UK construction firms in demonstrating compliance with ESG objectives. Key findings revealed that while BREEAM partially addresses environmental and social dimensions, it inadequately incorporates governance criteria. The authors recommended that future iterations of such frameworks integrate novel metrics to comprehensively align with ESG goals, ensuring their application in decision-making processes actively contributes to achieving these objectives.

Meshkud et al. (2024), in their study titled "The Impact of the Construction Industry on the Three Pillars of Sustainability (Economic, Environmental, and Social)", investigated how construction practices influence sustainability outcomes in New Zealand. The New Zealand government prioritizes developing a sustainable construction sector focused on high performance, productivity, innovation, and enhancing community well-being through improved built environments. However, prior research has inadequately integrated comprehensive sustainability metrics into project success evaluations. Utilizing the Scopus database and ATLAS.ti 9 software for qualitative analysis, this study identified critical sustainability success metrics in construction projects. Key findings revealed that the primary challenges in implementing sustainable practices include:

- Low organizational awareness of ESG (Environmental, Social, Governance) frameworks
- Misalignment of stakeholder understanding regarding sustainability goals
- Insufficient regulatory frameworks and enforcement mechanisms
- Ineffective execution of sustainability guidelines

The research underscored the pivotal role of organizational factors (e.g., leadership commitment, resource allocation) and individual factors (e.g., technical expertise, ethical decision-making) in driving sustainable construction adoption. Notably, the study emphasized the necessity of enhancing project managers' awareness to establish robust sustainability criteria aligned with global benchmarks such as ISO 21929-1 (Sustainability Indicators), and UN SDGs (e.g., Goal 11: Sustainable Cities).

Sirin et al. (2024), in their study titled "Development of an ANFIS System for Identifying Critical Success Factors (CSFs) in Pavement Projects", addressed critical challenges in pavement project management, including cost overruns, budgetary escalations, contractual disputes, and productivity decline. By conducting an SLR, and surveying 287 pavement engineering experts, the researchers identified 60 CSFs, classified into 7 categories: financial, bureaucratic, governmental, technical, environmental, communication, and stakeholder-related. Utilizing the Relative Importance Index (RII), and an Adaptive Neuro-Fuzzy Inference System (ANFIS), the study identified financial constraints, bureaucratic inefficiencies, governmental regulations, and communication barriers as the most pivotal factors influencing project success. The ANFIS model, validated through k-fold cross-validation (10 folds, 90% training/10% testing), demonstrated robust predictive accuracy (RMSE = 0.18, R^2 = 0.92), offering a data-driven tool to enhance decision-making in pavement project management. This framework provided actionable insights for optimizing resource allocation, streamlining regulatory compliance, and enhancing stakeholder coordination in pavement projects, aligning with ISO 21500:2021 (Project Governance), and AASHTO Pavement Design Guidelines.

Chen et al. (2024), in their article titled "A Dynamic Fuzzy Evaluation Method for Assessing Sustainability in Large-Scale Infrastructure Projects", proposed an innovative framework integrating Dynamic Fuzzy Cognitive Maps (D-FCM), and expert knowledge to create a dynamic sustainability assessment model. Applied to a metro construction case study, the model identified public participation (S1), light pollution mitigation (H1), wastewater discharge compliance rate (H2), soil contamination prevention (H3), and water-soil conservation practices (Z2) as the most sensitive sustainability indicators. This approach enabled project managers to implement cost-effective sustainability enhancements while aligning with ISO

14001 (Environmental Management), and ISO 21500 (Project Governance) standards. Below, a summary of the literature review is presented in Table 1.

Despite extensive research on sustainability indicators, critical success factors, and frameworks in construction project management, most studies remain limited to single-dimensional analyses—focusing solely on identifying indicators or categorizing factors. However, they often overlook integrated sustainability modeling, which considers the complex interactions among social, economic, environmental, and governance dimensions throughout the lifecycle of construction projects. Additionally, the systematic integration of multi-stakeholder perspectives using hybrid quantitative-qualitative methodologies has been insufficiently explored in the literature.

Table 1. Summary of related literature review

Author / Year	Findings/Main Focus	Research Method	Main topic
Mavi and Standing (2018)	Categorizing critical success factors into 5 criteria groups and identifying causal relationships between factors.	DEMATEL-ANP Fuzzy	Critical success factors of sustainable project management in construction: A fuzzy DEMATEL-ANP approach
Stanitsas et al. (2021)	Identification and classification of 82 sustainability indicators in three dimensions: economic, environmental, and social/management.	Literature review + semi-structured interviews	Sustainability indicators in construction projects
Goel et al. (2021)	Identify 7 key dimensions in sustainability integration: benefits, barriers, stakeholders, time, risks, incentives, and organizational context.	Systematic review + morphological analysis	Morphological analysis of SIMCP research in the last two decades
Gündüz et al.(2020)	Extracting 40 CSF factors in 7 categories, considering the role of all stakeholders in the success of the project.	Literature review + factor classification	Critical Success Factors for Sustainable Project Management
Rajabi et al. (2022)	Emphasizing the importance of renewable energy and construction site safety as key environmental and socio-economic indicators.	AHP (Analytical Hierarchy Process)	Evaluation of sustainability performance indicators during the project implementation phase
Adomi et al. (2024)	It showed that current frameworks, such as BREEAM, do not pay enough attention to governance aspects; there is a need to improve ESG comprehensiveness.	Document analysis	Exploring ESG frameworks in the UK manufacturing industry

This research addresses these gaps by employing a comprehensive and integrative approach to identify multidimensional sustainability indicators, model their interdependencies, and establish priorities. Existing studies emphasized the effectiveness of sustainability assessment frameworks (e.g., BREEAM, LEED), critical success factors (CSFs) in project management, and advanced methodologies such as ANFIS (Adaptive Neuro-Fuzzy Inference Systems) and D-FCM (Dynamic Fuzzy Cognitive Maps) in driving the construction industry toward ESG (Environmental, Social, and Governance) objectives and sustainable development. However, ongoing challenges—including inadequate regulatory frameworks, limited stakeholder awareness, and the absence of standardized governance metrics—require further scholarly and policy-driven attention to bridge implementation gaps. While most existing research has focused on identifying sustainability indicators for the construction industry, only a few studies have gone further to develop models, frameworks, or measurement systems for assessing sustainability at the industry level.

Materials and Methods

This research adopts an applied purpose and a descriptive data collection methodology. The study utilizes a mixed-methods approach, integrating qualitative techniques, such as fuzzy rule design through expert interviews, with quantitative validation via structured questionnaires. While survey-based methods were employed to assess model reliability, the core of the research remains rooted in fuzzy system modeling.

The study population comprises construction projects, with a purposive judgmental sampling method guiding participant selection. During the indicator validation phase, structured interviews were conducted with a predefined cohort of industry experts. Selection criteria included a minimum of five years of practical experience, organizational authority, and a diverse project portfolio to ensure a representative inclusion of key stakeholders.

To minimize biases associated with judgmental sampling, future research should adopt hybrid methodologies, such as stratified random sampling, with sample sizes determined using Cochran’s formula. During the indicator measurement phase, construction industry managers and practitioners participated through a purpose-designed questionnaire. The data collection instrument for validating indicators and the framework—derived from a literature review—consisted of semi-structured interviews. The measurement phase relied on a questionnaire built upon the finalized and validated framework established through expert interviews.

Content validity methodology was employed to validate the sustainability assessment questionnaire for construction projects. Subsequently, the finalized questionnaire was distributed to construction industry experts, and through aggregation of their evaluations, the validity of the proposed indicators within the questionnaire was confirmed. The questionnaire was developed based on a framework systematically derived from the literature review, thereby providing empirical substantiation for the content validity of the research instrument utilized in this study.

To evaluate the reliability of the questionnaire, it was initially distributed to 50 experts in construction projects, yielding a Cronbach's alpha coefficient of 0.81. Given that this value exceeds the 0.7 threshold, the questionnaire demonstrates sufficient internal consistency for continued application in the research.

The questionnaire was distributed among 50 experts based on the following criteria:

- ✓ Practical experience (at least 5 years of experience in sustainable construction projects),
- ✓ Organizational position (senior managers, consulting engineers, and members of supervisory teams),
- ✓ Project diversity (participation in infrastructure projects).

These parameters were established to ensure diversity of perspectives and comprehensive coverage of sustainability aspects. To enhance methodological transparency, future studies should employ sample size determination formulas (e.g., Cochran's formula) with a 95% confidence level and 5% margin of error to compute an optimized sample cohort. This research employed a mixed-methods approach, integrating semi-structured interviews (qualitative) with questionnaires (quantitative) to enhance both internal and external validity. The interviews facilitated in-depth extraction of sustainability indicators, while the questionnaires enabled empirical objectification and statistical measurement of findings.

Results

The design of the target fuzzy inference system necessitates the initial identification of critical indicators influencing the sustainability performance of construction projects. The outputs from this phase will inform the architecture of requisite subsystems within the fuzzy inference framework. Accordingly, researchers conducted an SLR to extract and categorize relevant sustainability indicators. Figure 3 delineates the principal dimensions affecting project sustainability levels derived from this review. The identified dimensions and their sub-criteria were subsequently validated through semi-structured interviews with construction industry experts. Building upon these core dimensions, the research team designed the intended fuzzy inference system (FIS) comprising three interconnected subsystems. The architecture of the designed fuzzy subsystems is illustrated in Figure 3.

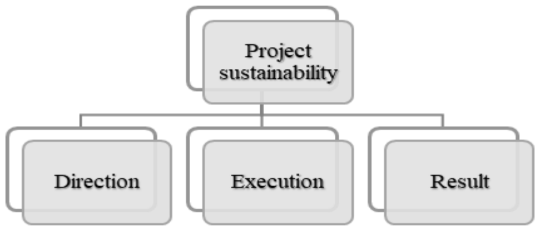

Figure 2. Key Dimensions Affecting the Sustainability Level of Construction Projects

The Direction subsystem serves as the primary input layer of the proposed fuzzy inference system (FIS). Like the other two subsystems, it comprises dual input/output layers. To operationalize the FIS, fuzzy sets must be defined for each input variable. These fuzzy sets are mathematically represented via membership functions (MFs), which quantify the degree to which an input belongs to a specific fuzzy set. While MFs can assume various forms (triangular, trapezoidal, Gaussian, etc.), this study has employed triangular and trapezoidal functions based on expert consensus and bibliometric analysis of construction sustainability literature.

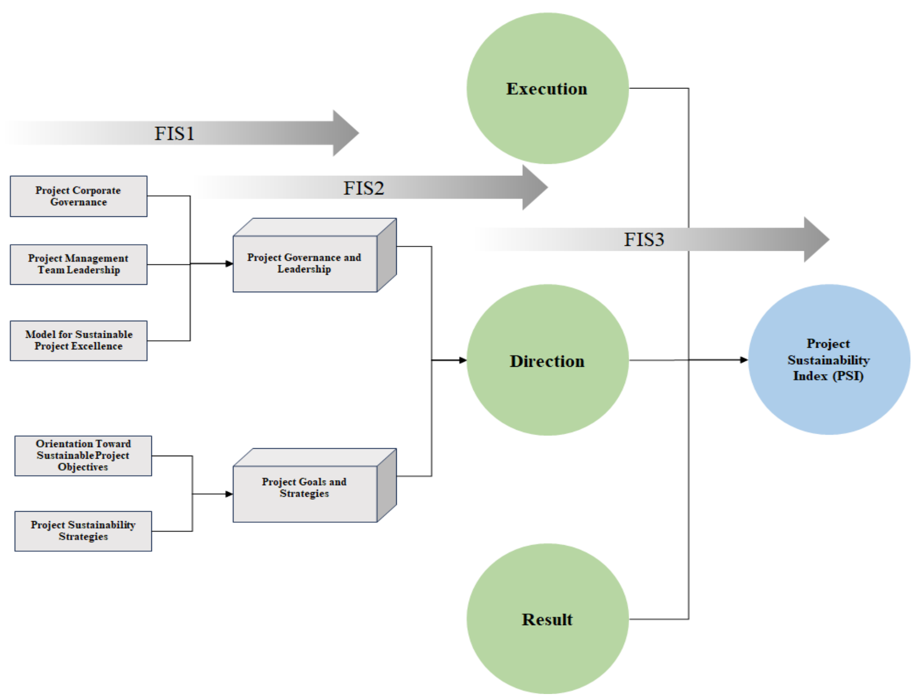

Figure3. The conceptual framework, incorporating sample sub-indicators of the strategic Direction subsystem

To determine the output variable of the designed fuzzy inference system (FIS), specifically the Project Sustainability Index (PSI), the researchers developed two distinct output types for each tier within the three core dimensions (Direction, Execution, Result). The weighting coefficients assigned to these dimensions, derived from expert consensus and prior empirical studies, are as follows:

- Direction = 250
- Execution = 350
- Result = 400

Table 2. Partitioning of Linguistic Variables and Corresponding Fuzzy Numbers

Partitioning of Linguistic Variables and Corresponding Fuzzy Numbers				
Membership Function Parameters	Membership Function Shape	Abbreviation	Variable	Row
{0,0,25,40}	Trapezoidal	(W)	Weak	1
{30,50,75}	Triangular	(M)	Moderate	2
{70,85,100,100}	Trapezoidal	(G)	Good	3

This study has employed purposive expert judgment to determine the weighting coefficients of the three sustainability dimensions (Direction, Execution, and Result). This methodology aligns with established practices in exploratory research and preliminary fuzzy model design, particularly when extensive numerical datasets are unavailable or when addressing conceptually complex phenomena. The credibility of the weighting protocol has been enhanced through the selection of domain-specific experts and the integration of consensus-building mechanisms among panelists. This rationale stems from the nascent stage of sustainability integration in construction projects and the critical necessity to operationalize sustainability principles effectively. As previously established, given that the input parameters at the foundational tier of the RADAR logic model represent the lowest granularity level, the membership functions for this tier across all three subsystems have been configured as follows (Table2):

The Direction subsystem has initially been designed using RADAR logic and expert judgment as its primary input. Subsequently, through the application of 27 if-then inference rules (Figure 4), these inputs have been transformed into the subsystem's primary output.

The output function of this layer has been assigned a range of 0 to 150 based on expert consensus (Table 3).

Table 3. Output of the first layer of the Direction subsystem

Partitioning of Linguistic Variables and Corresponding Fuzzy Numbers Project Governance and Leadership				
Membership Function Parameters	Membership Function Shape	Abbreviation	Variable	Row
{0,0,25}	Triangular	(VW)	VeryWeak	1
{15,25,50,60}	Trapezoidal	(W)	Weak	2
{50,60,85,95}	Trapezoidal	(M)	Moderate	3
{85,95,120,130}	Trapezoidal	(G)	Good	4
{120,150,150}	Triangular	(E)	Excellent	5

The selection of membership functions has been predicated on two criteria: (1) expert recommendations addressing the inherent uncertainty of qualitative indicators (e.g., public engagement metrics), necessitating trapezoidal functions to capture transitional ambiguity, and (2) computational efficiency for quantitative indicators (e.g., energy consumption indices), which were modeled via triangular functions to streamline analytical workflows.

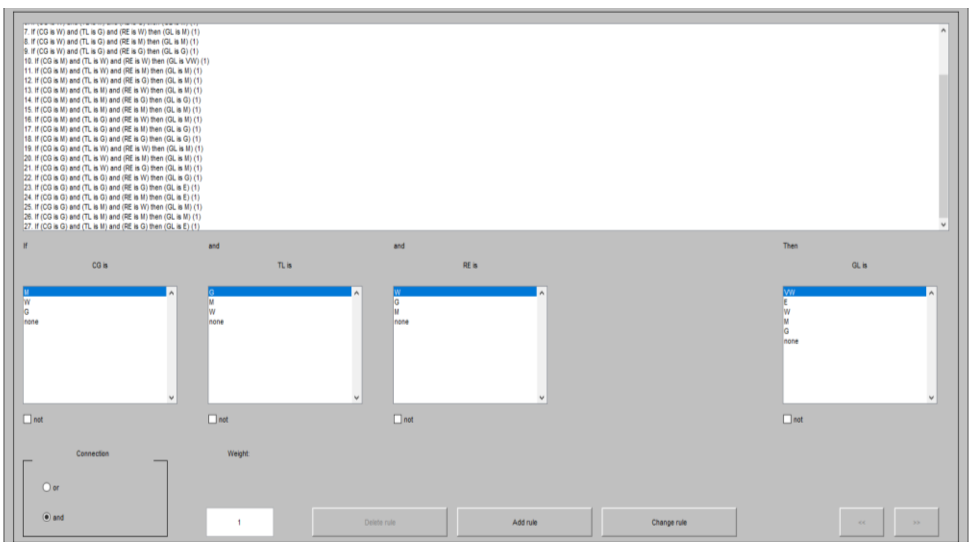

Figure 4. Exemplar Rule Base for the Fuzzy Inference System (FIS) in the Sustainability Excellence Framework

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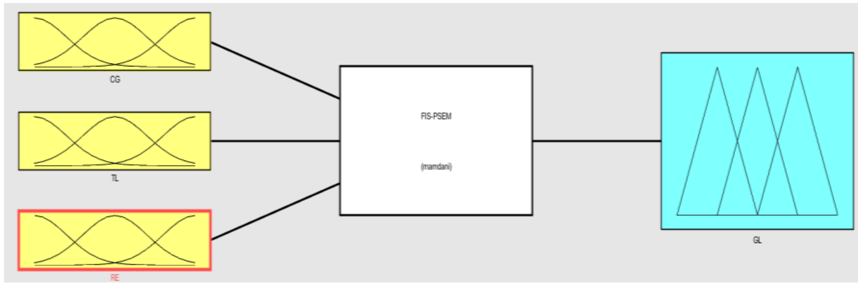

Figure 5. The designed fuzzy inference system (FIS) for the governance and leadership output variables within the Direction subsystem of the project

The designed fuzzy inference system for the output variables corresponding to the governance and leadership parameters of the Direction subsystem is illustrated in Figure 5, and 6. Additionally, the schematic representation of the FIS model, as implemented in MATLAB software, is depicted in Figure 7.

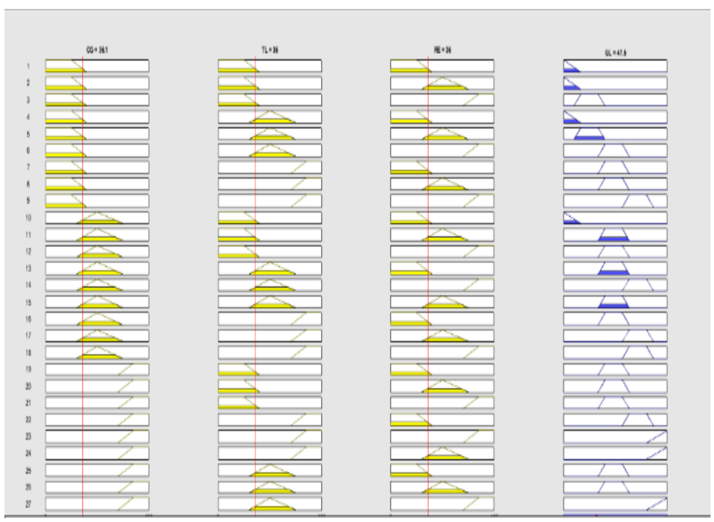

Figure 6. The designed Fuzzy Inference System (FIS) model for the governance and leadership output of the Direction subsystem in the project

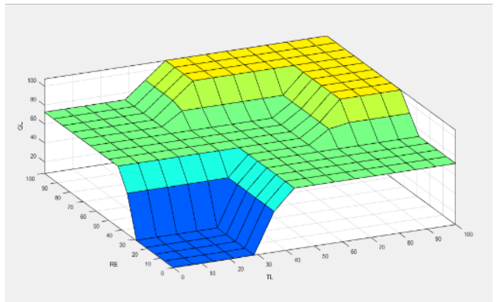

Figure 7. The designed Fuzzy Inference System (FIS) model for the governance and leadership output of the Direction subsystem in the project

Following the aforementioned methodology, nine inference rules have been applied to transform the sub-criteria inputs of the project goals, and strategies variable into the second output of the Direction subsystem. The output function of this layer has been assigned a range of 0 to 100 based on expert consensus. Subsequently, both outputs from this tier serve as inputs to the secondary layer, where 25 additional rules synthesize the final output of the Direction subsystem, representing its numerical index. The output function of this terminal layer has been calibrated to a 0 to 250 scale, again derived from expert judgment. The designed fuzzy inference system (FIS) has employed the Mamdani model, and it has been implemented within the MATLAB environment using the Fuzzy Logic Toolbox. The system has utilized the following operators and defuzzification method:

- AND Operator: Minimum (Min)
- OR Operator: Maximum (Max)
- Defuzzification Method: Centroid

The fuzzy inference system (FIS) architecture has employed triangular and trapezoidal membership functions for input/output variables across all subsystems. Function parameters (start, peak, and endpoint values) have been calibrated through expert judgment, and SLR. The rule base comprised 9 rules in the primary layer and 25 rules in the secondary layer, defining input-output relationships through weighted antecedent-consequent linkages. The Direction subsystem's final output has been scaled to the [0, 250] interval, derived via rule aggregation and expert-validated weighting coefficients. This modular design has ensured adaptability and reproducibility for analogous projects or domains.

Subsequently, the Execution and Result subsystems have been derived through a systematic synthesis of literature and expert consultations, as illustrated in the subsequent figures. The input and output variables of the developed model have been identified via a structured methodological process. Initially, an SLR of scholarly sourced in construction project sustainability yielded three core dimensions (Direction, Execution, Result) and 13 subordinate indicators. These indicators have then been evaluated and validated through semi-structured interviews with 10 industry experts in Iran's construction sector to ensure localization and enhance the framework's validity. Upon finalizing the sustainability indicators, they have been modeled as fuzzy input variables using triangular and trapezoidal membership functions (selected per indicator typology) and integrated into the fuzzy inference system (FIS). The system's output – a numerical representation of the project's overall sustainability level – has been defined as the weighted aggregation of outputs from the three subsystems (Direction, Execution, Result).

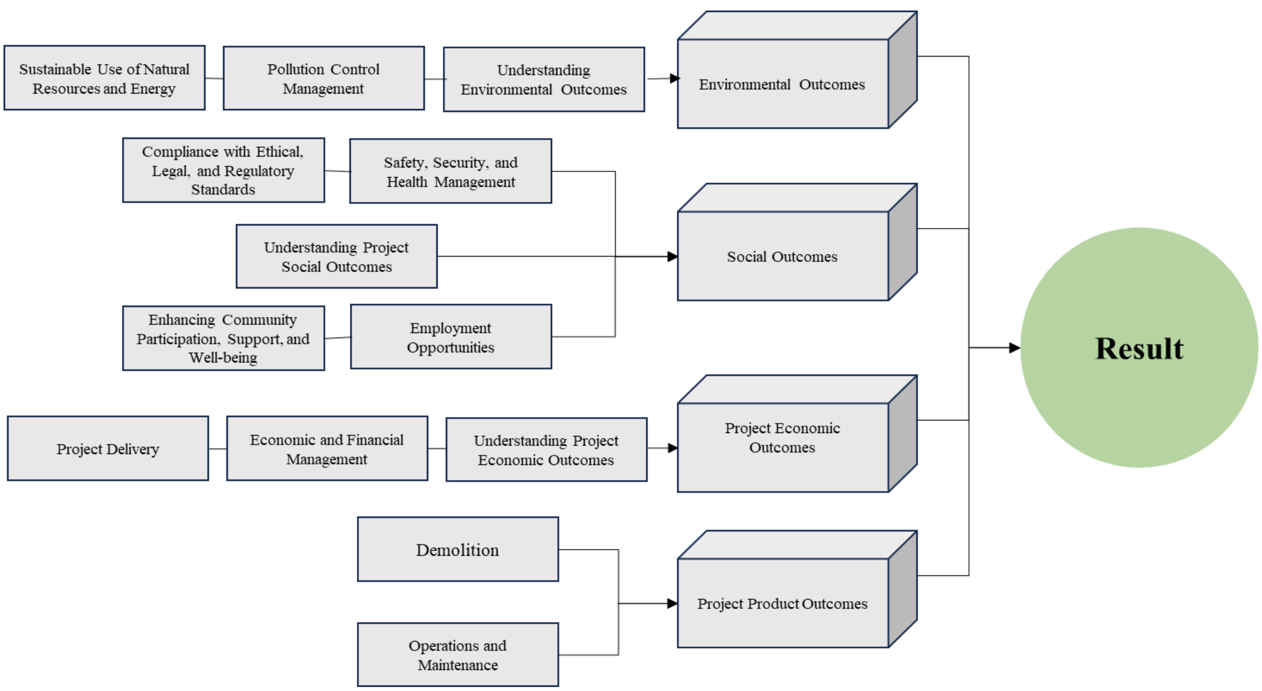

Figure 8. Sub-Criteria of the subsystem results

To compute the Project Sustainability Index (PSI), the three subsystems (Direction, Execution, Result) have been activated to process requisite inputs and generate intermediate outputs. These subsystem outputs have then been fed into a 125-rule fuzzy inference system (FIS) for final sustainability computation. The architecture of the FIS governing sustainability calculation is illustrated in the subsequent figure (Figure 9).

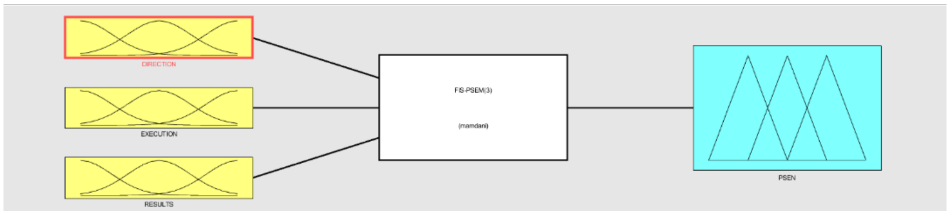

Figure 9. Fuzzy Inference System (FIS) for Sustainability Assessment of Construction Industry Projects

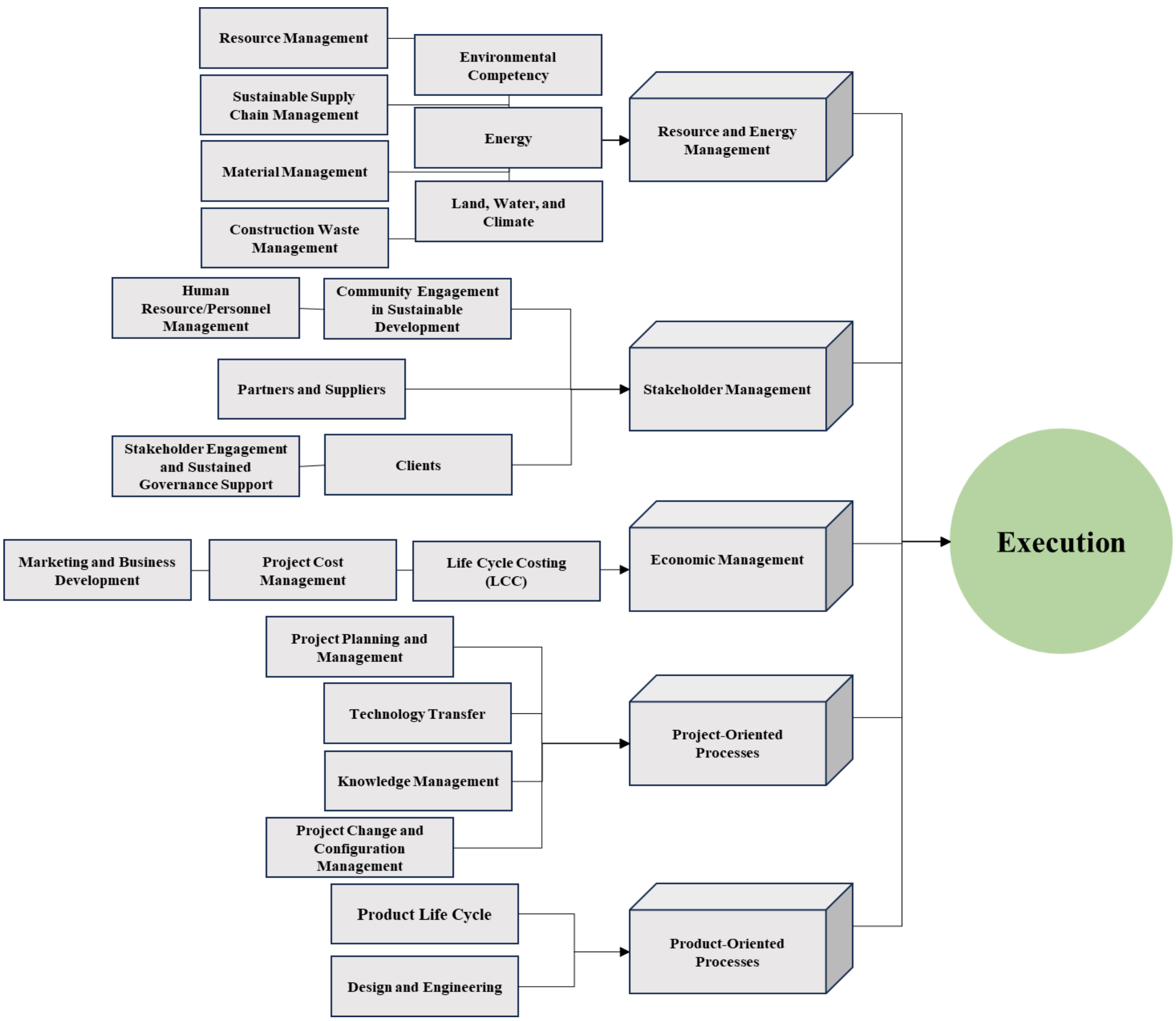

Figure 10. Sub-Criteria of the execution subsystem

Following the design and validation of the fuzzy inference system (FIS), the sustainability performance of the Apadana Project in the Persian Gulf has been assessed to evaluate the efficacy of the developed framework. For this purpose, a 39-item questionnaire—encompassing key indicators influencing the sustainability of construction projects—has been designed and distributed among industry experts. The questionnaire has employed a 0–100 Likert scale for response quantification. Subsequently, the average scores of indicators associated with each sustainability dimension have been calculated based on expert ratings. Concurrently, leveraging the fuzzy subsystems, the scores of all dimensions and factors have been computationally derived and comparatively analyzed (Table 4).

Table 4. Comparing FIS outputs with expert opinions

Expert output	FIS output	Model dimensions
51.55	65	Direction
30.05	27.52	Execution
115.39	127.66	Result
189.65	169	Project sustainability level

Given the negligible discrepancy between the FIS system's evaluations and expert assessments, it can be concluded that the system exhibits high precision, with its outputs closely aligned with expert judgments. This congruence underscores the robust validity of the fuzzy inference system.

Discussion

The results obtained from the fuzzy inference model, designed in this research, demonstrate its strong capability in assessing the sustainability of construction projects. A comparison between the system's output and the average of expert opinions reveals a high level of agreement, confirming that the proposed model is an effective tool for assessing and continuously monitoring the sustainability of large-scale projects. Additionally, the findings highlight that integrating fuzzy methods with expert opinions helps address the uncertainties inherent in qualitative assessments.

Building on this foundation, the researchers developed a fuzzy sustainability measurement model for construction projects using a fuzzy inference system. To achieve this, the model's input and output variables were initially determined through a comprehensive literature review. The resulting system comprises three layers. In the first layer, numerical values between 0 and 100 were assigned to identified subcategories using RADAR logic, supported by codes and guidelines for each subcategory.

Notably, the results dimension of the model incorporates two types of indicators: judgmental and measurable, corresponding to different outcome types. Judgmental indicators capture perceptions of environmental, social, and economic outcomes, measured through various methods such as questionnaires and interviews. The assigned values for these indicators serve as input variables, which are transformed into the model's initial output based on predefined membership functions and expert-driven rules.

The numerical output from the primary layer, representing the sustainability levels of categorical indices, serves as input for the secondary layer. This input is processed through predefined membership functions and inference rules to generate the second-layer output. The sustainability level for each model dimension, derived from this process, then becomes the input for the tertiary layer. Ultimately, the tertiary layer applies domain-specific inference rules and membership functions to construct the final output.

To defuzzify the final numerical outputs and compute the Project Sustainability Index (PSI), the researchers employed the Center of Gravity Method. The aggregated enabler values—comprising the Direction dimension (250) and the Execution dimension (350)—total 600, while the aggregated result values sum to 400. These numerical values were established based on expert evaluations and comparative analyses of existing sustainability frameworks. The higher weighting of enablers relative to results reflects the novelty of sustainability considerations, emphasizing the need to first implement sustainability principles before focusing on their outcomes.

Unlike previous models for sustainability assessment in construction projects, such as those developed by Yazdani et al. (2020), and Abdolqader and Sharif (2022), the distinctiveness of the current model lies in its three-tier hierarchical architecture and goal-oriented subsystems: Direction, Execution, and Result. While prior studies predominantly measured performance metrics, this research enhances evaluation precision and adaptability by integrating fuzzy logic and tailoring membership functions to indicator typologies (quantitative vs. qualitative). The findings further demonstrate that the weighting of the three sustainability dimensions—particularly the emphasis on Execution and Results—aligns with the realities of Iranian projects, such as the Apadana project in the Persian Gulf. This alignment enhances the model's accuracy and applicability in similar contexts.

From this perspective, the proposed model offers local adaptability and can be customized for various projects, positioning it as a prototype for developing decision support systems (DSS) within the construction industries of developing nations.

Conclusion

The integration of sustainability into construction projects, alongside the optimization of cost management, has gained increasing attention from academic researchers in recent years. While significant efforts have been made to identify key indicators and critical success factors for implementing sustainability principles at the project level, this identification primarily serves to recognize the factors influencing project sustainability. However, the true objective of integrating sustainability into projects is to enhance their adherence to sustainability principles and improve overall performance.

Given these considerations, there is a critical need for a model that not only measures project sustainability and determines its maturity levels but also identifies and implements targeted improvement strategies. This study addresses this gap by introducing a model that incorporates three core dimensions—Direction, Execution, and Result—to establish a dynamic framework for improving sustainability performance in construction projects. Specifically, the model's results dimension provides a clear perspective on expected economic, environmental, and social outcomes, both from projects that integrate sustainability principles and from the final products of such projects.

With the successful development of the fuzzy evaluation system, it is recommended that organizations overseeing civil engineering projects adopt this model as a sustainability assessment tool during key project phases: Pre-implementation Planning, Execution, and Closure. This system enables decision-makers to identify latent vulnerabilities across economic, environmental, and social dimensions, allowing for timely intervention and mitigation. Additionally, the creation of a management dashboard based on the model's outputs facilitates continuous monitoring of sustainability status and enables trend analysis of parametric variations over time.

Future studies could consider employing alternative multi-criteria decision-making techniques, such as ANFIS, DEMATEL, or fuzzy AHP, to enhance or compare the model's performance. Further expansions of the model could incorporate additional dimensions, including risk assessment, resource productivity metrics, or innovative construction technologies. Moreover, evaluating and validating the model across a diverse range of civil engineering projects at different scales (national, regional, local) would strengthen its precision and generalizability.

Data Availability Statement

Data available on request from the authors.

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Ethical considerations

The study was approved by the Ethics Committee of the University of Tehran (Ethical code: IR.UT.REC.2024.500). The authors avoided data fabrication, falsification, plagiarism, and misconduct.

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Conflict of interest

The authors declare no conflict of interest.

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