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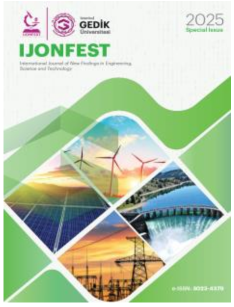

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Identification and Evaluation of Key Critical Success Factors in Design for Circularity

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Abstract

The construction industry is undergoing a significant transformation to implement sustainable practices in line with circular economy (CE) concepts. This research aims to identify and evaluate the design critical success factors (CSFs) necessary for the implementation of design techniques that enhance circularity in building projects. The research aims to provide a framework that identifies the critical success criteria necessary for construction industry professionals to adopt CE ideas. In this context, a two-stage methodology was followed. In the first stage, relevant studies were identified through keyword searches in the Scopus database, excluded studies were eliminated through abstract review, and key components of design success in the context of the CE were identified through full text review. In the second stage, additional components were identified, and data were collected through focus group discussions and face-to-face interviews. The critical success factors were analyzed according to quality, time, and cost criteria by calculating their weights using the fuzzy AHP method and then evaluating them with the fuzzy TOPSIS method.. Thus, the level of effectiveness of the identified factors was evaluated and prioritized. The literature review reveals that existing research provides a basic understanding of the concepts of circular design (CD) and demonstrates its applications in the construction industry. Furthermore, professional opinions were sought to identify the necessary components for the effective implementation of CD methods. The research highlighted critical success criteria of design that facilitate circularity in building projects. These elements include adherence to legal frameworks that encourage circular practices, preference for recyclable and sustainable materials, design flexibility for future changes and various use cases, and effective coordination between various stakeholders. The results of the fuzzy TOPSIS analysis reveal the importance of these factors in terms of quality, time, and cost, providing a guiding framework for decision-making by industry professionals. The research underlines the need to use innovation and technology to promote circularity in design methodologies. It underlines the need for continuous training to ensure that industry personnel are knowledgeable about the best practices in CD. In conclusion, this study provides a comprehensive analysis for the implementation of CD in the construction industry and provides a scientific basis for decision-makers to adopt CE-compliant design techniques.

Keywords: Fuzzy TOPSIS; Circular economy (CE); Construction projects; Circular design (CD).

1. INTRODUCTION

The construction sector plays a crucial role in shaping the functionality of urban areas and the surrounding physical environment. It is accountable for approximately fifty percent of the global consumption of material resources [1, 2]. Moreover, the construction sector plays a crucial role in infrastructure development, generating employment opportunities and significantly contributing to the economies of numerous countries. Nonetheless, it exerts a detrimental effect on the environment, producing considerable waste and utilizing vast quantities of natural resources [2]. According to studies, the construction sector generates 40% of the waste that negatively impacts the environment and contributes 33% of carbon emission [3]. The construction sector is advancing through enhancement initiatives aimed at achieving a one-to-one ratio, where the quantity of materials extracted for human activities matches the volume of waste produced within the sector. The collected data indicates an inequality in material utilization and waste production within the construction sector, highlighting the necessity to transition from a linear take-use-dispose model to approaches that foster a more beneficial environmental impact.

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The construction sector leads in circularity by promoting a cradle-to-cradle methodology and incorporating these concepts across all phases, embracing a whole life cycle perspective instead of concentrating on a single stage. This methodology is founded on CD concepts and seeks to minimize the reusability, recyclability, and ecological footprint of materials. These strategic methodologies in the design process facilitate the sector's enhancement of energy efficiency, minimization of waste, and development of sustainable constructions [2]. Ellen MacArthur characterizes the CE as a regenerative system designed to reduce resource consumption, pollution, waste, and energy loss by efficiently closing and narrowing energy and material cycles [3].

Achieving CE objectives requires a comprehensive strategy that encompasses the manufacture of building components [6], the transportation of materials [7], the design phase [8] building demolition [9] and the recyclability post-demolition [10]. CE presents a significant potential to save material resources and diminish the carbon footprint by facilitating a reduction in the use of raw materials [3, 11]. Consequently, the implementation of a CE is essential for guaranteeing the long-term sustainability of materials used in all buildings [12].

This research aims to identify and assess the critical success factors (CSFs) of design necessary for implementing design techniques that improve circularity in building projects. Consequently, a framework for assessment is established to measure the efficacy of circularity indicators. Moreover, this paradigm enables decision-makers to evaluate the components that ensure circularity. Prior to developing this framework, a comprehensive literature study was undertaken to ascertain the factors associated with CE. A focus group discussion (FGD) was first convened to evaluate and refine the criteria highlighted in the literature research. The objective of conducting FGD sessions was to uncover success elements overlooked in prior research. A questionnaire was conducted to ascertain the prioritization of the critical factors' significance. This questionnaire was sent to specialists engaged in the domain of CE. The data obtained from surveys and interviews were analyzed with the Fuzzy TOPSIS methodology.

This research theoretically contributes to the literature by advancing circularity-based design creation and offering a framework for performance monitoring. The study's practical contribution is to define the essential variables necessary for executing a construction project design in alignment with CE principles, facilitating their usage as assessment tools by industry experts. This will provide the chance to formulate and implement strategies throughout the design phase of a building project, considering the critical success criteria of CE-based design. In addition, some studies in the current literature on CE in construction project design are presented in Table 1.

Table 1. Current Studies on CE in Construction Project Design.

Researchers	Findings	Methodology	Key Themes	References
Antwi-Afari, Ng et al. 2021	Identified gaps in circular product design and end-of-life considerations; lack of holistic CE approach	Scientometric analysis, content analysis, SWOT analysis	Circular product design, end-of-life consideration, modular integrated construction	[1]
Otasowie, Aigbavboa et al. 2024	Identified five research clusters: circular construction intelligence, modular business modeling, eco-construction, sustainable construction economics, smart energy-efficient buildings	Bibliometric approach using Scopus, VOSviewer for co-occurrence and co-authorship mapping	Circular economy business models (CEBMs)	[2]
Chen, Feng et al. 2021	Emphasized the importance of integrating stakeholders and legal, risk, financial, and contractual frameworks	Systematic literature review of 40 journal articles	Digital technologies, material design, building design, urban sustainability	[3]
Osobajo, Oke et al. 2022	Extensive focus on resource use and waste management; limited investigations in other areas	Systematic review of CE literature from 1990-2019	Resource use, waste management, supply chain integration, building designs	[4]
Yang, Guan et al. 2022	Construction industry focuses on recycling and reuse; manufacturing achieves higher circularity with remanufacturing and IS	Scientometric review, science mapping method	Recycling, reuse, remanufacturing, industrial symbiosis (IS)	[5]
Abadi, Moore et al. 2021	Identified varying engagement with circularity indicators; predominant focus on aspirational CE design solutions	Systematic literature review, PLACIT framework	Project life-cycle assessment, circularity indicators	[6]
Ranasinghe, Domingo et al. 2024	Identified design, informational, and technological factors as critical; lack of data traceability	Systematic literature review of 74 papers	Material reclamation, data availability, digitalization	[7]
Osei-Tutu, Ayarkwa et al. 2024	Identified roles of government, academia, professionals, and users in CE implementation	Literature search, content analysis, scientometric study using VOSviewer	Stakeholder roles, policy, legislation, financial investment	[8]
Jayawardana, Sandanayake et al. 2023	DfD strategy showed lowest environmental impacts; highlighted reuse over recycling	Design-stage life cycle assessment	Modular construction, design for disassembly (DfD)	[9]

Torgautov, Zhanabayev et al. 2021	Identified economic benefits as main motivation; virtualization as highest priority	PEST analysis, semi-structured surveys using ReSOLVE framework	CE principles, stakeholder analysis	[10]
Chen, Feng et al. 2022	Identified phase-specific CE strategies and internal/external drivers	Systematic review of 61 publications	Value chain integration, resource loops, BIM, IoT	[11]
Salimi and Taherkhani 2024	Identified key research clusters and knowledge gaps; focus on environmental aspect	Bibliometric analysis using CiteSpace and VOSviewer	Life cycle assessment (LCA), CD solutions	[12]
Talpur, Liuzzi et al. 2023	Highlighted lack of cradle-to-cradle LCA implementation; unavailability of regional database	Literature survey of 71 papers	Life cycle assessment (LCA), cradle-to-cradle methodology	[13]
Dakir, Elmetoui et al. 2023	Emphasized collaboration among stakeholders throughout building lifecycle	Mixed-methods approach: literature review, qualitative and quantitative studies, case study	Integrated CE model, Integrated Project Delivery (IPD)	[14]
Lee, Juan et al. 2023	Small companies and senior executives have higher awareness; identified obstacles to CE adoption	Literature review, questionnaire survey, importance-adoption analysis (IAA) model	CE strategies, BIM, resource recovery	[15]
Nie, Dahanayake et al. 2024	Identified positive initiatives but transition still at initial stage	Multiple case studies, semi-structured interviews, thematic analysis	CDW management, design for waste prevention, prefabricated elements	[16]
Gamage, Senaratne et al. 2024	Identified significant CE practices and their relationships across project stages	Systematic literature review using PRISMA framework	CE practices, project life cycle, design for disassembly	[17]
Srećković, Hartmann et al. 2024	Identified gaps between theory and practice in EoL phase	Semi-structured interviews, literature review	End-of-Life (EoL) phase, reuse, recycle processes	[18]
Victar and Waidyasekara 2024	Identified C&D WM issues and strategies	Delphi technique, expert interviews	C&D waste management, modular design, material reuse	[19]

2. LITERATURE REVIEW

In the Architecture, Engineering, and Construction (AEC) field, the common method is a straight approach. This means that the current building is demolished only after it has reached the end of its useful life [2]. The construction industry produces about 40% of trash that harms the earth and is responsible for 33% of carbon emissions [3]. The end-of-life phase is very important because building and disposal trash makes up about 25% of all waste [21]. Most building materials can't be recovered, so they are usually thrown away when they are no longer useful [22]. The AEC industry greatly affects the environment and plays a significant role in climate change [23]. This is because the building business follows a straight-line approach of "take, make, throw away." [24]. This method involves extraction of raw materials for construction projects. These materials are made into building supplies, used on-site, and cannot be reused once the project is finished, so they end up as trash [25]. This means that trash keeps being created as raw materials are used up [25].

Over the last four decades, scientists have conducted extensive research on the principles of sustainable buildings [26] and sustainable construction [27]. Nonetheless, these methodologies and ideas have yet to be widely adopted [28]. The Ellen MacArthur Foundation defines the CE ideas as including three fundamental elements: eliminating waste and pollution in design, maintaining the use of materials and products, and restoring natural systems [3]. Recently, there has been an increasing worldwide interest in the CE among policymakers and industry experts. Numerous nations are formulating measures to transcend the linear economy [29]. Numerous studies concentrate on CE strategies for construction in the building sector [24, 30, 31]. For instance, Ghisellini [32], conducts a thorough examination of the CE literature to enhance understanding and development of the approach at micro, meso, and macro levels. The study undertaken in this regard analyzed sixty-four scholarly articles, indicating an increasing knowledge of energy efficiency in the realm of structures. The majority of research focused on energy efficiency methods in buildings, identifying knowledge deficiencies and enumerating CE strategies based on life cycle phases. The examination of knowledge across several disciplines offers a significant foundation for enhancing the comprehension and implementation of CE principles in the construction industry [24]. A separate research examined the implementation of CE principles at different phases of the building life cycle, advocating for proactive design to guarantee continuous monitoring of buildings throughout their entire lifespan. The report concludes with practical solutions for implementing CE in construction and recommends that future research focus on underexplored areas to enhance resource efficiency [33]. A thorough literature analysis was done in another research to evaluate the application of CE concepts in building design and construction. The assessment identified 16 CE solutions for building design and construction, assessing their application and preparedness within the industry. The research revealed that insufficient understanding of the environmental consequences and advantages of these solutions is a major obstacle to the integration of CE. It further presents a novel design typology that emphasizes environmental solutions to improve CE practices within the construction industry. The research introduces a novel design typology that emphasizes environmental techniques to enhance CE implementation in the construction industry [9]. Fregonara et al. created a decision-making instrument to assist designers in choosing the most suitable option for the end of life (EOL) of buildings. This tool employs a multidisciplinary strategy to tackle the issue of excessive material consumption and waste production in buildings [34]. Honic, Kovacic, and Rechberger contended that the material passport serves as an advantageous instrument for designers to enhance the circularity of structures. It was used to assess the environmental implications of two alternatives: wood and concrete [35]. Numerous scholars have suggested the establishment of an online platform to catalog supplementary materials for upcoming building projects. Additionally, this material repository would not only generate and preserve material passports but also compute circularity indicators for the building during its full life cycle, from the construction phase to its decommissioning [15]. Despite a notable rise in the transition towards CE principles within the construction sector, substantial gaps persist that impede the implementation of these ideas.

The CE is influenced by CD concepts that seek to reduce waste and enhance resource efficiency. These strategies enhance lifespan, flexibility, and resource recovery. Principal strategies include the design of goods for durability and modularity to extend their use [20] as well as the implementation of disassembly design to facilitate the easy separation of components for recycling [21]. Moreover, material selection emphasizes biodegradable or recyclable substances to enhance end-of-life management [22], while product-service systems like leasing or sharing models promote effective product reutilization [23]. Moreover, life cycle thinking incorporates the evaluation of environmental consequences across all stages, assuring conformity with sustainability objectives [24]. The research highlights the absence of a comprehensive framework or assessment tool to systematically evaluate the success elements of CD solutions. This deficiency hinders practitioners from assessing efficacy or pinpointing areas for improvement. Furthermore, insufficient legislative frameworks, absence of standardized measuring instruments, and restricted collaboration among stakeholders impede the extensive implementation of CE activities. Addressing these deficiencies, particularly via the formulation of an assessment system, is an essential measure for the progression of CD and its incorporation across many industries [25].

Recent research shows that implementing CE principles in construction projects has great potential to reduce waste, conserve resources and promote sustainability. In this context, material reuse and recycling play a critical role; reusing materials such as steel bars, PVC pipes, stone debris, bamboo and wood minimizes waste and reduces the need for new raw materials [11, 26, 27]. Moreover, recycling construction and demolition waste improves the efficiency of waste management and brings significant gains to the sector [19, 28, 29]. An essential strategy to support these practices is the design for the dismantling approach is also an integral part of this process; the preference for flexible and modular structures makes it possible to easily dismantle and reuse the components of buildings at the end of their lifespan and enables materials to be brought into the CE [11, 27, 30]. In this regard, modular building techniques provide a structure that is in line with these ideas and could make buildings more environmentally friendly, even though they come with high initial costs and design difficulties [31]. To ensure informed decision-making in sustainable building design, Life Cycle Assessment (LCA) helps make the right design decisions by analyzing environmental impacts [11, 28, 32], while Building Information Modeling (BIM) stands out as a critical tool to optimize material use, increase recycling rates and reduce waste [32, 33]. Furthermore, resource efficiency is one of the cornerstones of CE; while practices such as energy-efficient lighting systems, solar panels and rainwater collection systems promote sustainability by reducing energy and water consumption [19, 26], it is also of great importance to prevent resource waste in the construction process by using durable and high-quality materials [19, 34]. However, widespread adoption of CE principles requires raising industry awareness and strengthening education programs [30, 35, 36]. In addition, supportive policies and economic incentives can make sustainable approaches more attractive by encouraging material reuse [35, 37]. At the same time, technological advances can also make CE more effective; the use of smart technologies such as IoT in material tracking, data analytics and logistics optimization can improve the efficiency of the process [11, 32], while assessment tools such as carbon calculators and circularity indexing systems can be of great benefit in measuring and improving the effectiveness of CE practices [38]. In conclusion, integrating CE principles into construction projects has the potential to create a sustainable transformation in the sector. Nonetheless, in order for this transformation to be fully realized, knowledge gaps must be overcome, supportive policies must be put in place and investments in advanced technologies must be made [11, 19, 26-28, 30-32, 35, 38]. In practical applications, construction projects widely apply Fuzzy TOPSIS to integrate CE principles. The method is used to make choices about everything from choosing a contractor to managing risks and making sure materials are sustainable. Therefore, it helps to make sure that CE principles are systematically and effectively built into project design. Table 2 presents a comprehensive review of the application of Fuzzy TOPSIS in various studies.

The project management triangle is a vital framework for understanding and managing time, cost and quality constraints in projects. Effective project management requires careful balancing and continuous optimization of these elements to achieve project success. By leveraging advanced optimization techniques and focusing on quality, project managers can better navigate the complexity of the iron triangle [46-50]. In addition, cost, time and quality criteria are recognized as key factors in many decision-making processes. Especially in areas such as supplier selection, project management and risk assessment, these criteria provide a holistic view of performance and efficiency [51-53]. There is a strong relationship between the three; improvements in one can lead to changes in the others. For example, improving quality often increases costs or may increase project duration, and similarly reducing costs may negatively affect quality [52, 53]. Therefore, it is critical for decision makers to achieve an optimal balance between these criteria. Diverse industries and scenarios widely apply these criteria. In supplier selection, evaluations based on cost, delivery time and product quality create a balanced procurement process [51, 53, 54]. In project management, the integration of these three criteria helps effectively identify and mitigate risks and ensure project success [52]. The fuzzy TOPSIS method is a highly effective tool for managing uncertainty when evaluating these criteria. This method allows to express the intensity of preferences and the importance of criteria through linguistic variables and fuzzy numbers [55-57]. Various studies show that Fuzzy TOPSIS gives successful results in ranking alternatives according to these criteria [51-53, 57]. Applications such as supplier evaluation and project management prominently utilize this method. For example, one study used the Three-Dimensional Fuzzy TOPSIS framework to evaluate suppliers based on cost, quality and time factors and found that these criteria are critical for a comprehensive supplier evaluation [51]. Another study used Fuzzy TOPSIS to rank suppliers based on product quality, cost and delivery time, emphasizing that these factors are decisive in making informed procurement decisions [53]. In construction risk management, Fuzzy TOPSIS has been shown to be successful in identifying and ranking risk factors by integrating cost, time and quality criteria [52]. Similarly, in multimodal transportation route selection, it has been reported that this method offers prioritization based on transportation cost, time and quality and provides an effective decision support mechanism in the field of logistics [57]. In this context, integrating cost, time and quality into the Fuzzy TOPSIS method finds broad support in the literature. While these three fundamental criteria form a comprehensive and balanced framework for decision-making, the ability of Fuzzy TOPSIS to handle uncertainty provides a powerful tool for ranking alternatives in a more robust manner [51-53, 57].

Table 2. Applications of fuzzy TOPSIS in construction industry.

Researchers	Study Focus	Application of Fuzzy TOPSIS	Key Findings
Koc, Ekmekcioglu et al. 2023 [39]	Sustainable Contractor Selection	Used Fuzzy TOPSIS to evaluate the circularity and eligibility of contractors based on CE indicators.	Contractors with strong financial viability, CE strategies (e.g. ReSOLVE), and sustainable construction methods (e.g. modular construction) were preferred.
Mahpour 2018 [40]	C&D Waste Management	Applied Fuzzy TOPSIS to prioritize barriers in transitioning to CE in construction and demolition (C&D) waste management.	Identified high-priority barriers such as ineffective waste processes and lack of sustainable integration.
Nofal and Hammad 2020 [41]	Material Selection	Utilized Fuzzy TOPSIS to compare sustainability criteria of construction materials.	Sandwich Panels were identified as the most sustainable material in a UAE case study.
Koc, Kunkcu et al. 2023 [42]	Risk Assessment in Green Building Projects	Employed Fuzzy TOPSIS to associate stakeholders' roles with managing risks in green building projects.	Key risks included lack of experienced staff and inflation of green materials' prices.
Toker and Görener 2023 [43]	CE Business Model Selection for SMEs	Used spherical Fuzzy TOPSIS to select the most appropriate CE business model for SMEs in developing countries.	Resource recovery model was found to be the most suitable for initial CE transition.
Aghazadeh and Yildirim 2024 [44]	Sustainable Material Selection Framework	Combined Fuzzy AHP and Fuzzy TOPSIS to develop a framework for sustainable material selection in construction.	Prioritized criteria included minimizing environmental impacts and optimizing energy consumption.
Koc, Durdyev et al. 2024 [45]	CE Implementation in Construction	Applied Fuzzy AHP and Fuzzy TOPSIS to identify critical success factors for CE implementation in construction	"Optimize" and "Loop" were the most critical dimensions for successful CE transition.

The research questions:

Based on the research gaps presented above, the following research questions were analyzed in this study:

RQ1- What are the design critical success factors according to CE principles in construction projects?
RQ2- What are the importance level of design critical success factors to achieve CD alternatives?

3. RESEARCH METHODOLOGY

This research employs the methods shown in Figure 1. The technique has two primary components: identification of critical success factors of design and analysis of critical success factors. A thorough literature research on the application of CE in construction was done, leading to the establishment of successful design criteria. The assessment of success criteria of CD included two-phased focus group meetings with CE specialists to assess the data derived from comprehensive literature review. A questionnaire survey and fuzzy TOPSIS were used to rank the criteria based on time, cost, and quality.

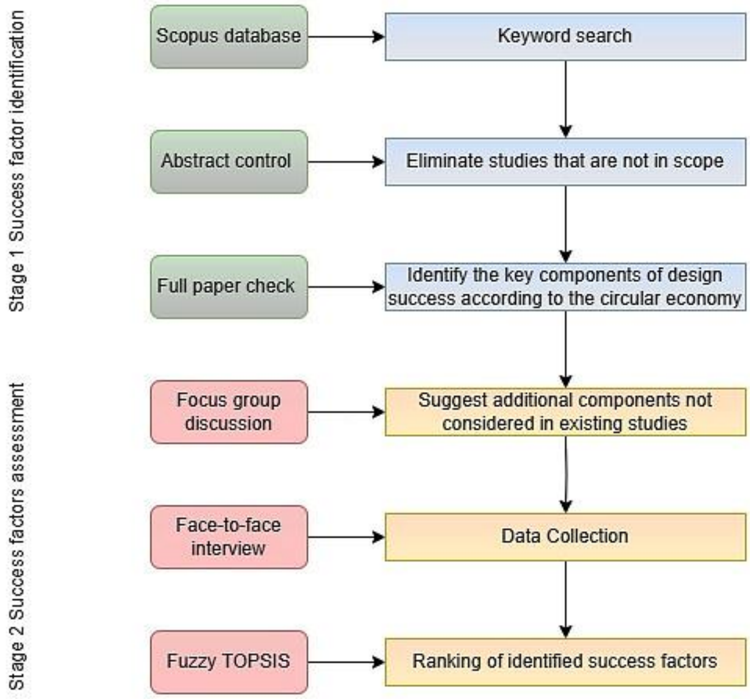

Figure 1. Research flow.

3.1. Identification of Critical Success Factors of Design

A comprehensive literature review was conducted to identify critical success factors. The literature review was conducted on the Scopus search engine. In this context, based on the definitions of CEs, previous studies were reviewed to examine the methodologies, criteria, advantages and effects of previous research. The success factors found as a result of the literature review are presented in Table 3.

Table 3. Critical success factor list.

Strategy ID	Design Strategy	Definition	References
SD1	Lifecycle-Based Design	Minimizing environmental impacts and resource consumption throughout the entire lifecycle of the structure.	[58-62]
SD2	Design with Reusable Materials	Reducing waste and promoting circularity by utilizing reusable materials.	[63-67]
SD3	Design with Recycled Materials	Reducing resource consumption through the use of recycled materials.	[68-80]
SD4	Design for Easy Assembly and Disassembly	Ensuring structural elements can be easily assembled and disassembled.	[35, 81-91]
SD5	Design for Adaptability and Flexibility	Creating flexible structures that can adapt to different usage scenarios and changing needs.	[35, 84, 86-88, 92-94]
SD6	Modular Design	Planning structures composed of interchangeable and combinable modules.	[35, 84, 89, 91, 93, 95]
SD7	Prefabrication-Based Design	Designing structures with prefabricated elements for rapid on-site assembly.	[35, 82, 84, 86, 88, 92, 95, 96]
SD8	Durability-Oriented Design	Developing durable materials and solutions to ensure the long lifespan of the structure.	[35, 84, 88]
SD9	Design with Standardization	Planning materials and components based on standardized dimensions and features.	[35, 82, 84, 86, 87, 89, 91, 92]
SD10	Material and Component Optimization	Planning materials and components to minimize resource usage.	[35, 84, 86, 92, 95]
SD11	Design for Accessibility	Providing access and usability for individuals with disabilities and diverse user groups.	[84, 86, 91]
SD12	Design with Independent Units	Planning structural units to operate independently from one another.	[82, 84, 87]

SD13	Design for Material Storage Ease	Facilitating the storage of materials to enable recycling and reuse.	[86]
SD14	Design for Short-Term Use	Creating structures that can be quickly assembled and disassembled for temporary needs.	[87]
SD15	Design for Sharing and Common Use	Developing solutions that enable different users to share the same structure or space.	[92, 97]
SD16	Design with Building Information Modeling (BIM)	Planning construction processes more efficiently and transparently with digital tools.	[65, 98, 99]
SD17	Design for End-of-Life	Planning structures for recycling and reuse at the end of their lifecycle.	[100-104]
SD18	Material Management and Waste Reduction	Optimizing resources to minimize waste.	*
SD19	Energy-Efficient Design	Implementing solutions that reduce energy consumption and support sustainable energy sources.	*
SD20	Water Management-Based Design	Designing solutions that reduce water consumption and support water recycling.	*
SD21	Design with Local Materials	Using local resources to reduce transportation costs and carbon emissions.	*

(*) Factors recommended by experts.

3.2. Focus Group Discussion (FGD) and Evaluation of Critical Success Factor of Design

During the first phase of FGD, participants received an introduction of several subjects and terminology, including the CE, sustainable construction, and the proposed framework. The experts performed a comprehensive assessment and analysis of the proposed framework based on their knowledge. During the first evaluation, all experts collectively acknowledged the need of an assessment-support framework for construction projects. As a result, they had a positive attitude towards the proposed framework, the appropriate expert selection methodology was applied as shown in Figure 2. As shown in Table 4; a total of 10 experts were asked to participate in the FGD.

In this session, experts assessed the validity of the components outlined in the literature. The assessments were carried out utilizing a Likert scale that spans from 1 to 5. This segment of the research employed the Likert scale, recognized for its extensive application as a response scale in survey methodologies [105]. Furthermore, the Likert scale offers flexibility and simplifies the analysis process. The scale may indicate subtle differences in the perspectives of the survey respondents [106]. The scale intervals are as follows: (1) not suitable; (2) partially suitable; (3) suitable; (4) very suitable; and (5) most suitable. The responses from the participants were assessed utilizing descriptive analytic techniques [107]. The mean value of 3 was established as the lower limit in comparable research conducted by Budayan et al. [107] Given that it is the median of the commonly used scale of one to five. In order to enhance the practical and theoretical value of the framework, experts were invited to present novel elements that have not been previously addressed in the existing literature and that have the potential to impact the circularity of the project in accordance with the principles of CE. Following this session, it was determined that there were 17 criteria that were examined by the experts and received an average score of 3 or above. This was the conclusion reached. Additionally, the experts suggested four additional success criteria that were not included into the study that had been conducted before, increasing the total number of components to a total of 21 factors.

The second phase of FGD involved the evaluation of the experts using the scales used in the fuzzy TOPSIS technique. This technique allowed for a more detailed analysis of the data obtained and provided new insights that could improve the literature. Focus group discussions emerged as an important approach for both in-depth analysis of existing data and identification of new elements through different expert opinions. This approach enhanced the integrity of the study and provided important insights for practice. Table 4 shows the profile information of the relevant experts.

CD is a critical phase for many reasons, including the evaluation of key success factors of design, the prevention of bad effects, the support of decision-making processes, and the maximization of resource use. For the purpose of this investigation, the impacts of design techniques on cost, time, and quality criteria are investigated, and the Fuzzy TOPSIS approach is used to make strategy design ranking measurements. To use the fuzzy TOPSIS approach and assess the methods, the experts filled out the method questionnaire in person. The appropriate expert selection methodology was applied as shown in Figure 2, and as a result of this application, the expert profiles to be included in the Fuzzy TOPSIS analysis are presented in Table 4.

In the appendix, evaluation tables for 10 experts (A1 to A10) based on the Fuzzy TOPSIS method are presented. Additionally, the aggregated fuzzy evaluation matrix for these 10 experts is provided in Table A11. The Weighted Normalized Fuzzy Decision Matrix is presented in Table A12, while the final evaluation results can be found in Table 6. In addition, to determine the weights of cost, time and quality criteria, evaluations were made in line with the opinions received from the same group of experts and the Fuzzy Analytic Hierarchy Process (Fuzzy AHP) method was applied to determine the relative importance of the criteria precisely.

The Fuzzy Analytic Hierarchy Process (Fuzzy AHP) is an extension of the traditional Analytic Hierarchy Process (AHP) and incorporates fuzzy set theory to deal with uncertainty and imprecision in human judgment. While classical AHP uses precise numerical values to determine the relative importance of criteria and alternatives, Fuzzy AHP offers a more flexible and realistic evaluation by using fuzzy numbers [108-110]. This approach strengthens the decision-making process, especially when information is uncertain. One of the most important advantages of Fuzzy AHP is its ability to deal effectively with uncertainty and imprecise information. Human judgment can be inherently fuzzy, and while classical AHP cannot fully reflect this fuzziness, fuzzy numbers allow for more reliable and flexible decisions [109-111]. In addition, the use of fuzzy logic in the decision-making process enables more accurate calculation of criteria weights and helps to achieve better quality results, especially in complex and uncertain environments [109, 110] [112]. Fuzzy AHP offers decision makers a great deal of flexibility, allowing them to express their judgments in linguistic terms rather than exact numbers. For example, the importance of a criterion can be expressed in terms such as “high”, “medium” or “low”, which can then be transformed into fuzzy numbers and analyzed. This allows experts to participate more easily in the decision process and makes the evaluation process more natural [110, 112, 113]. Furthermore, the fuzzification and clarification mechanisms offered by the method increase consistency in pairwise comparisons, creating a more robust decision process [108, 112]. Fuzzy AHP has a wide range of applications. It has been successfully applied to a wide range of decision-making processes such as supplier selection, risk assessment and comparison of alternatives. This versatility proves the flexibility and effectiveness of the method [112-114]. Moreover, the integration of fuzzy logic with AHP better captures the subjective nature of human judgment, making decision processes more realistic and reliable [109, 113]. In conclusion, Fuzzy AHP provides a powerful and flexible method for multi-criteria decision-making processes where uncertainty and imprecise information are important. The fact that it better captures the inherent fuzziness of human judgment and provides a flexible evaluation mechanism makes this method highly valuable for complex decision processes.

This method transformed the uncertainty in expert opinions and subjective evaluations into a more mathematically consistent structure and ensured a reliable and balanced determination of criteria weights. The criteria evaluations were conducted using the Fuzzy AHP method, incorporating expert contributions. The Initial Criterion Evaluation Matrix is included in the appendix as Table A13. Furthermore, the Aggregated Fuzzy Criterion Matrix According to the Fuzzy AHP Method is presented in Table A14, and the Final Criterion Weights According to the Fuzzy AHP Method are detailed in Table A15.

3.3. Fuzzy TOPSIS

Fuzzy TOPSIS is an important method in multi-criteria decision-making processes because of its ability to deal effectively with uncertain data. This method ensures the correct ranking of alternatives by taking into account the proximity to the ideal solution and the distance to the negative ideal solution. It also has the capacity to better discriminate between alternatives and, thanks to its flexibility, it can work with different types of fuzzy numbers and can be customized according to different decision maker attitudes.

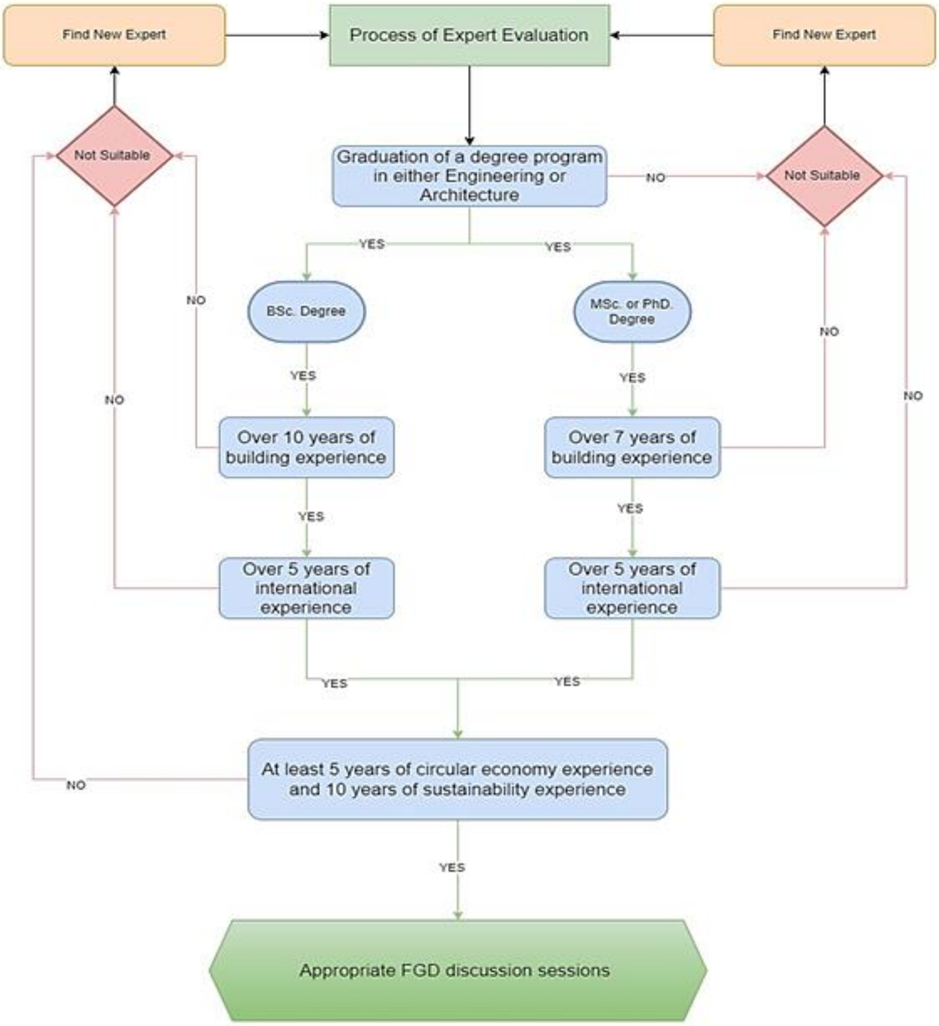

Figure 2. The systematic expert evaluation methodology.

Table 4. Expert Information.

Expert ID	Profession	Years of Experience	Education Status
ED1	Academician	17	PhD
ED2	MSc. Architect	15	M.Sc
ED3	MSc. Architect	12	M.Sc
ED4	MSc. Civil Engineer	16	M.Sc
ED5	Civil Engineer	20	Bachelor's degree
ED6	Environmental Engineer	25	Bachelor's degree
ED7	Mechanical Engineer	12	Bachelor's degree
ED8	Research Assistant	15	PhD
ED9	Architect	11	Bachelor's degree
ED10	Civil Engineer	17	Bachelor's degree

Fuzzy TOPSIS can also be integrated with other methods such as AHP and can strengthen the decision-making process [115-118]. However, it may face challenges such as the scores of alternatives being too close, in which case the ideal solutions may need to be redefined [119, 120]. Furthermore, the method can be complex in terms of implementation, especially when a large number of comparisons and various fuzzy numbers are required [121-124]. Compared to other methods, Fuzzy TOPSIS manages uncertainties more effectively and provides more accurate rankings, but it has some limitations such as complexity and time-consuming [116, 125]. Fuzzy TOPSIS has significant advantages such as managing uncertainties, improved discrimination between alternatives and flexibility with different fuzzy numbers. However, there are limitations in this method, such as the fact that if the scores of the alternatives are very close, it may be difficult to discriminate correctly and the application may be complex [119, 120]. The AHP/FAHP method provides consistency checks by making structured pairwise comparisons, but it can be difficult to adapt to fuzzy data and can be time consuming [116, 125]. While Fuzzy ELECTRE has advantages such as its non-compensatory nature and good ranking distribution, it can be complex and requires integration with other methods [120]. Fuzzy TOPSIS is a highly effective method for multi-criteria decision making in uncertain environments, offering better discrimination between alternatives and flexibility. However, there may be challenges such as close scores and implementation complexity, but these can be overcome by method adaptations and integrations. Comparisons with other methods such as AHP and Fuzzy ELECTRE show that Fuzzy TOPSIS works more effectively with fuzzy data and its strengths in providing decision support. With these features in mind, Fuzzy TOPSIS can be effectively used for factor rankings in decision-making processes.

The fuzzy TOPSIS method was developed to find solutions to multi criteria decision making (MCDM) processes under uncertainty by utilizing the principles of the TOPSIS method. The fuzzy TOPSIS method ranks and evaluates alternatives according to their distance from positive and negative solutions [126]. The steps of the fuzzy TOPSIS method are as follows.

Table 5. Linguistic scales of the Fuzzy TOPSIS Method.

Linguistic variables	Corresponding Triangular Fuzzy Number
Worst (1)	(0, 0, 1)
Very poor (2)	(0, 1, 3)
Poor (3)	(1, 3, 5)
Fair (4)	(3, 5, 7)
Good (5)	(5, 7, 9)
Very Good (6)	(7, 9, 10)
Excellent (7)	(9, 10, 10)

Step 1. Weighting of criteria: $\tilde{w}_j$ corresponds to the weights of the identified risks on the time, quality and cost selection factors. Risks were assessed by experts on a scale of 1-7.

$$W=[\tilde{w}_1\tilde{w}_2--\tilde{w}_j--\tilde{w}_n] \quad (1)$$

Step 2. Aggregation of group judgments: aggregation of assessments is calculated as shown in equation 2.

$$\tilde{x}ij = \frac{1}{K}[\tilde{x}^{1}{}_{ij}+\tilde{x}^{2}{}_{ij}+\cdots\tilde{x}^{K}{}_{ij}] \quad (2)$$

Step 3. Aggregation of the decision matrix: The decision matrix is as in equation 3.

$$\tilde{D} = \begin{bmatrix} \tilde{x}_{11} & ,,, & \tilde{x}_{11} \\ \vdots & \ddots & \vdots \\ \tilde{x}_{m1} & ,,, & \tilde{x}_{mn} \end{bmatrix} \; i=1,2,...., m; j=1,2,....,n \quad (3)$$

Step 4. Calculation of Normalized Fuzzy Decision Matrix: $\tilde{R}$ is calculated via Equation (4) shown below. $\tilde{R}$ means the normalized decision matrix.

$$\tilde{R} = [r_{ij}]_{xn} \; i=1,2,.....m; j=1,2,.....n.$$
$$\tilde{r}_{ij} \; (\frac{a_{ij}}{c_j^*}, \frac{b_{ij}}{c_j^*} \frac{c_{ij}}{c_j^*}) \text{ ve } cj*=maxi\, cij \; (benefit\ criteria) \quad (4)$$

Step 5. Weighted normalized fuzzy decision matrix: The weights of the [116-118] evaluation criteria are multiplied by the normalized decision matrix to obtain a weighted normalized decision matrix.

$$\tilde{V}=[\tilde{v}_{ij}]_{mxn} \; i=1,2,.....m; j=1,2,.....n \; where \; \tilde{v}_{ij}= \tilde{r}_{ij}(.)W_j \quad (5)$$

Step 6. Definition of fuzzy PIS and fuzzy NIS: Fuzzy PIS and fuzzy NIS are defined by using Eq. (6).

$$A+=\{\tilde{v}_1+,\tilde{v}_2+,\tilde{v}_3+....\tilde{v}_j+\}$$
$$A-=\{\tilde{v}_1-,\tilde{v}_2-,\tilde{v}_3-....\tilde{v}_j-\} \quad (6)$$
$$\tilde{v}_1+ = (1,1,1), \tilde{v}_1- = (0,0,0)$$

Step 7. Calculating the distance of each alternative to the fuzzy PIS and fuzzy NIS: The distances to the fuzzy PIS and fuzzy NIS are calculated using equations (7) and (8).

$$d(\tilde{v}_{ij},\tilde{v}_j^+)=\sqrt{\frac{1}{3}[(\tilde{v}_{ija}-\tilde{v}_{ja}^+)^2+(\tilde{v}_{ijb}-\tilde{v}_{jb}^+)^2+(\tilde{v}_{ijc}-\tilde{v}_{jc}^+)^2]}$$
$$d(\tilde{v}_{ij},\tilde{v}_j^-)=\sqrt{\frac{1}{3}[(\tilde{v}_{ija}-\tilde{v}_{ja}^-)^2+(\tilde{v}_{ijb}-\tilde{v}_{jb}^-)^2+(\tilde{v}_{ijc}-\tilde{v}_{jc}^-)^2]} \quad (7)$$

$$d_i^+=\sum_{j=1}^{n} d(\tilde{v}_{ij},\tilde{v}_j^+), i=1,2,3,...m$$
$$d_i^-=\sum_{j=1}^{n} d(\tilde{v}_{ij},\tilde{v}_j^-), i=1,2,3,\ldots m \quad (8)$$

Step 8: Closeness coefficient (CCi) of each alternative: CCi, (closeness coefficient) indicates the distances from fuzzy PIS and fuzzy NIS simultaneously.

$$CC_i=\frac{d_i^-}{d_i^+ + d_i^-} \quad (9)$$

As a result of the fuzzy TOPSIS application, an evaluation of the success factors was made and explained in the following section.

4. RESULTS AND DISCUSSIONS

In this research, the critical success factors of the circularity design were evaluated using Fuzzy TOPSIS method after FGD with experts with respect to cost, time and quality criteria and the importance ranking of the factors is shown in Table 6.

The ranking results of the evaluated factors reveal a clear distinction between high, medium and low performing factors. “Design with Building Information Modeling (BIM) (SD16)” stands out as the best performing factor, followed by “Durability-Oriented Design (SD8)”, “Design with Recycled Materials (SD3)” and “Design with Standardization (SD9)”, showing a strong alignment with the evaluation factors. In contrast, “Lifecycle-Based Design (SD1)”, “Design with Independent Units (SD12)” and “Design for End-of-Life (SD17)” ranked the lowest, indicating that these factors need significant improvements. Mid-level factors such as “Prefabrication-Based Design (SD7)”, “Energy-Efficient Design (SD19)” and “Material Management and Waste Reduction (SD18)” showed moderate effectiveness, indicating that these factors need improvement.

Table 6. Fuzzy TOPSIS results.

Strategy ID	Design Strategy	Closeness Coefficient (CC)	Ranking
SD1	Lifecycle-Based Design	0.04764	21
SD2	Design with Reusable Materials	0.059766	11
SD3	Design with Recycled Materials	0.065249	3
SD4	Design for Easy Assembly and Disassembly	0.054095	18
SD5	Design for Adaptability and Flexibility	0.056988	15
SD6	Modular Design	0.057015	14
SD7	Prefabrication-Based Design	0.061638	7
SD8	Durability-Oriented Design	0.06643	2
SD9	Design with Standardization	0.063652	4
SD10	Material and Component Optimization	0.060216	9
SD11	Design for Accessibility	0.054258	17
SD12	Design with Independent Units	0.048556	20
SD13	Design for Material Storage Ease	0.056635	16
SD14	Design for Short-Term Use	0.057035	13
SD15	Design for Sharing and Common Use	0.058599	12
SD16	Design with Building Information Modeling (BIM)	0.067857	1
SD17	Design for End-of-Life	0.052633	19
SD18	Material Management and Waste Reduction	0.062553	5
SD19	Energy-Efficient Design	0.062424	6
SD20	Water Management-Based Design	0.061573	8
SD21	Design with Local Materials	0.059838	10

When the findings that were acquired are evaluated, the design that was created using Building Information Modeling is the most important aspect that contributed to the design's success. The research conducted by Kim [65] shown the significance of including building information modeling into the process. Building Information Modeling (BIM) is playing an important role in reshaping the design of construction projects around the CE. BIM makes materials management much more efficient. Thanks to material passports, materials used can be tracked throughout their lifecycle, leading to more informed decisions on recycling and reuse. As a result, waste rates are decreasing and recovery rates are increasing [127]. The integration of BIM with life cycle assessment (LCA), which supports sustainable design, facilitates the adoption of CE principles in the construction industry. This integration helps us analyze the environmental impacts of construction projects more accurately [128]. BIM also enables strategies such as adaptability and flexibility in the design phase. This not only makes buildings more sustainable, but also reduces costs in the long run [129]. Projects in Taiwan also demonstrate the benefits of BIM in CD, increasing material recovery and making more efficient use of resources [130]. However, in order to realize the full potential of BIM, some challenges, such as data accuracy and cross-system alignment, need to be overcome. To overcome these obstacles, it is crucial to create more robust data structures and establish strong collaboration between all stakeholders [127, 131]. Nevertheless, BIM offers great opportunities to accelerate the transition to a CD in the construction industry. Additionally, the durability -oriented design component is recognized as the second most important design success factor. The inclusion of the pertinent element in the research [35] served to highlight the significance of the factor in question. Durability-oriented design is crucial to integrating CD thinking into construction projects. This design approach ensures that buildings and materials are planned to last longer, eliminating the need for frequent replacement and minimizing waste. Durability also brings with it the reusability and recyclability of materials, which increases sustainability [28, 132, 133]. Design for deconstruction (DfD) strategies allow buildings to be designed so that they can be easily dismantled and materials reused. This extends the lifespan of materials and facilitates their reuse [30, 134-136]. In addition, through life cycle assessment (LCA), environmental impacts are analyzed and more sustainable materials and construction techniques are preferred [9, 132, 137]. Modular construction methods also increase the reusability of building components, reducing both waste and environmental impact [9, 31]. However, it should be noted that for this process to be successful, there needs to be good cooperation between stakeholders and the right legal regulations [27, 30]. When all these strategies come together, both environmental impacts are reduced and more sustainable construction projects are realized.

Incorporating recycled materials into construction design is an important part of CD principles. This approach can significantly reduce greenhouse gas emissions and conserve natural resources by providing environmental benefits; for example, reuse practices in modular buildings can offset emissions by 88% [138]. Likewise, materials such as recycled aggregates and tires improve resource efficiency by reducing waste generation in construction processes [139, 140]. Furthermore, using recycled materials can provide cost savings and create new economic opportunities in local and international markets [141, 142]. Projects built with CD principles facilitate the reuse and recycling of materials and contribute to sustainable economies [143, 144]. However, barriers to the use of recycled materials should be overcome through education, policy support and new strategies [140, 145, 146]. Using recycled materials in the design is the third most important component that contributes to success. The fact that it is a significant influence was proved once again in the research [68], which presented the findings.

Also, the use of standardized materials in construction projects is of great importance in the implementation of CE principles. This approach allows buildings to be dismantled more easily and materials to be reused, thus reducing environmental impacts and ensuring sustainability. Strategies such as design for deconstruction (DfD) and design for adaptability (DfA) also help this process to work effectively [30, 147]. Furthermore, using standard materials speeds up construction processes, reducing costs and minimizing waste [32, 148]. Digital tools, in particular Building Information Modelling (BIM), increase the efficiency of projects and reinforce sustainability [32, 149]. These include resistance in the industry, insufficient knowledge of designers and a lack of appropriate policies [8, 148]. Projects in the Nordic countries and Ghent show how circular CD structures [27, 143].

Furthermore, when the outcomes of the fuzzy TOPSIS analysis are assessed, it becomes clear once again that the success of a CE design does not depend solely on the implementation of a recycling plan. There are other important factors to consider for a successful design. Among them, designing with building information modeling (BIM) improves resource management and project efficiency, while durability-driven design minimizes waste by ensuring the longevity of materials. Furthermore, designing with recycled materials reduces the use of natural resources and lowers environmental impact. Standardization facilitates the dismantling, reuse and recycling of building components. It should also be noted that the factors in Table 6 should also be taken into account. All these elements are important components that increase the effectiveness of CE design.

5. CONCLUSION

This study explores how circular design (CD) principles can be effectively integrated into the construction industry by identifying the key factors that contribute to their success. In order to evaluate these factors, Fuzzy AHP and Fuzzy TOPSIS methods were used, focusing on quality, time, and cost criteria. The research provides a structured framework for decision-makers to assess the impact of these factors. This research seeks to discover critical success factors for construction projects' designs based on the CE. The study shows decision-makers who want to implement CE concepts in the design phase and researchers who want to learn more about this subject, which factors they should focus on to achieve success. First, a comprehensive literature review was conducted and 17 success factors were identified in the literature. Then, in focus group interviews with experts, four new success factors were proposed that will further develop CE applications in the sector. As a result, a total of 21 factors were discovered. These criteria were evaluated with the Fuzzy TOPSIS method, considering their impact on key criteria such as project time, quality and cost.

The research findings reveal that factors such as "Design with Building Information Modeling (BIM)", "Durability-Oriented Design", "Design with Recycled Materials" and "Design with Standardization" have the highest priority in the success of CE projects. BIM enables data management during the design process, while durability-oriented design ensures that structures are long-lasting and sustainable. The use of recycled materials reduces environmental impacts, while standardization processes increase efficiency and minimize waste. These four factors are the cornerstones of CE design and greatly affect the success of projects.

In addition, the other factors listed in Table 6 are also very important and should be taken into account. Focusing on just a few factors is not enough for the success of CE design. Evaluating all these factors together ensures that projects are more efficient, environmentally friendly and sustainable. Each factor has different impacts and should be evaluated as a whole. One of the limitations of the research is that it did not focus on a specific project type (e.g., infrastructure or superstructure). The application of success criteria may vary depending on the project type. For example, the proportion of recycled materials used in a superstructure project may differ from that in an infrastructure project. Future research can provide more information on how to integrate CE principles more effectively into each type of project by taking these differences into account.

In the future, it is clear that these factors need to be examined in more depth in order to further spread CE practices and increase sustainability in the construction sector. In particular, the integration of digital technologies (such as BIM), further development of standardization processes and increasing the use of recycled materials have the potential to reduce the environmental impacts of construction projects. In addition, it should be emphasized that all stakeholders in the sector should embrace CE principles more and effectively implement these principles in the design stages. In addition, future research on different project types can be conducted to determine success criteria suitable for each type of construction project. This will contribute to making CE design more efficient and sustainable in every aspect.

In conclusion, this study provides valuable guidance to professionals in the sector by addressing the important factors affecting the success of construction projects based on CE principles. However, considering the limitations of the study, more research is needed on how CE design can be applied to different project types. Such studies will help to ensure that CE practices are more widely adopted in the construction sector and will make significant contributions to the sector's achievement of sustainability goals.

Authors' Contributions

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1- Study design 2- Data collection 3- Data analysis and interpretation 4- Manuscript writing 5- Critical revision			

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Appendix

Table A1. 1st Expert Factor Evaluation Based on Cost, Time and Quality Criteria According to Fuzzy TOPSIS Method.

Strategy ID	Linguistic variables			Corresponding Triangular Fuzzy Number								
	Cost	Time	Quality	Cost			Time			Quality		
SD1	6	6	7	7	9	10	7	9	10	9	10	10
SD2	3	5	5	1	3	5	5	7	9	5	7	9
SD3	7	7	6	9	10	10	9	10	10	7	9	10
SD4	5	3	7	5	7	9	1	3	5	9	10	10
SD5	6	5	7	7	9	10	5	7	9	9	10	10
SD6	7	5	6	9	10	10	5	7	9	7	9	10
SD7	7	7	7	9	10	10	9	10	10	9	10	10
SD8	7	7	7	9	10	10	9	10	10	9	10	10
SD9	7	6	5	9	10	10	7	9	10	5	7	9
SD10	7	3	5	9	10	10	1	3	5	5	7	9
SD11	2	2	2	0	1	3	0	1	3	0	1	3
SD12	2	2	2	0	1	3	0	1	3	0	1	3
SD13	4	4	6	3	5	7	3	5	7	7	9	10
SD14	3	5	4	1	3	5	5	7	9	3	5	7
SD15	4	3	5	3	5	7	1	3	5	5	7	9
SD16	7	7	7	9	10	10	9	10	10	9	10	10
SD17	3	3	6	1	3	5	1	3	5	7	9	10
SD18	6	5	7	7	9	10	5	7	9	9	10	10
SD19	7	6	7	9	10	10	7	9	10	9	10	10
SD20	6	5	7	7	9	10	5	7	9	9	10	10
SD21	7	6	7	9	10	10	7	9	10	9	10	10

Table A2. 2nd expert factor evaluation based on cost, time and quality criteria according to Fuzzy TOPSIS Method.

Strategy ID	Linguistic variables			Corresponding Triangular Fuzzy Number								
	Cost	Time	Quality	Cost			Time			Quality		
SD1	2	2	6	0	1	3	0	1	3	7	9	10
SD2	4	3	5	3	5	7	1	3	5	5	7	9
SD3	6	3	4	7	9	10	1	3	5	3	5	7
SD4	3	4	5	1	3	5	3	5	7	5	7	9
SD5	3	2	6	1	3	5	0	1	3	7	9	10

SD6	4	3	5	3	5	7	1	3	5	5	7	9
SD7	6	5	4	7	9	10	5	7	9	3	5	7
SD8	4	4	4	3	5	7	3	5	7	3	5	7
SD9	5	3	4	5	7	9	1	3	5	3	5	7
SD10	6	2	4	7	9	10	0	1	3	3	5	7
SD11	2	2	4	0	1	3	0	1	3	3	5	7
SD12	1	2	4	0	0	1	0	1	3	3	5	7
SD13	4	4	6	3	5	7	3	5	7	7	9	10
SD14	5	5	3	5	7	9	5	7	9	1	3	5
SD15	6	5	2	7	9	10	5	7	9	0	1	3
SD16	6	6	4	7	9	10	7	9	10	3	5	7
SD17	2	3	7	0	1	3	1	3	5	9	10	10
SD18	3	2	4	1	3	5	0	1	3	3	5	7
SD19	2	1	3	0	1	3	0	0	1	1	3	5
SD20	2	1	3	0	1	3	0	0	1	1	3	5
SD21	4	3	5	3	5	7	1	3	5	5	7	9

Table A3. 3rd expert factor evaluation based on cost, time and quality criteria according to Fuzzy TOPSIS Method.

Strategy ID	Linguistic variables			Corresponding Triangular Fuzzy Number								
	Cost	Time	Quality	Cost			Time			Quality		
SD1	6	3	7	7	9	10	1	3	5	9	10	10
SD2	4	3	5	3	5	7	1	3	5	5	7	9
SD3	6	2	4	7	9	10	0	1	3	3	5	7
SD4	3	3	5	1	3	5	1	3	5	5	7	9
SD5	2	2	7	0	1	3	0	1	3	9	10	10
SD6	3	2	4	1	3	5	0	1	3	3	5	7
SD7	6	7	6	7	9	10	9	10	10	7	9	10
SD8	5	4	4	5	7	9	3	5	7	3	5	7
SD9	6	3	2	7	9	10	1	3	5	0	1	3
SD10	5	2	4	5	7	9	0	1	3	3	5	7
SD11	2	2	5	0	1	3	0	1	3	5	7	9
SD12	1	1	3	0	0	1	0	0	1	1	3	5
SD13	5	4	4	5	7	9	3	5	7	3	5	7
SD14	1	4	2	0	0	1	3	5	7	0	1	3
SD15	1	3	3	0	0	1	1	3	5	1	3	5
SD16	3	5	4	1	3	5	5	7	9	3	5	7
SD17	2	2	4	0	1	3	0	1	3	3	5	7
SD18	5	5	6	5	7	9	5	7	9	7	9	10
SD19	6	5	6	7	9	10	5	7	9	7	9	10
SD20	5	6	6	5	7	9	7	9	10	7	9	10
SD21	3	2	3	1	3	5	0	1	3	1	3	5

Table A4. 4th expert factor evaluation based on cost, time and quality criteria according to Fuzzy TOPSIS Method.

Strategy ID	Linguistic variables			Corresponding Triangular Fuzzy Number								
	Cost	Time	Quality	Cost			Time			Quality		
SD1	5	4	7	5	7	9	3	5	7	9	10	10
SD2	6	4	7	7	9	10	3	5	7	9	10	10
SD3	5	5	6	5	7	9	5	7	9	7	9	10
SD4	4	6	7	3	5	7	7	9	10	9	10	10
SD5	5	5	6	5	7	9	5	7	9	7	9	10
SD6	4	5	7	3	5	7	5	7	9	9	10	10
SD7	3	6	6	1	3	5	7	9	10	7	9	10
SD8	6	4	7	7	9	10	3	5	7	9	10	10
SD9	5	5	6	5	7	9	5	7	9	7	9	10
SD10	5	4	7	5	7	9	3	5	7	9	10	10
SD11	6	5	7	7	9	10	5	7	9	9	10	10
SD12	4	5	6	3	5	7	5	7	9	7	9	10
SD13	5	6	5	5	7	9	7	9	10	5	7	9
SD14	6	5	5	7	9	10	5	7	9	5	7	9
SD15	6	5	6	7	9	10	5	7	9	7	9	10
SD16	5	4	7	5	7	9	3	5	7	9	10	10
SD17	5	6	7	5	7	9	7	9	10	9	10	10
SD18	5	5	7	5	7	9	5	7	9	9	10	10
SD19	6	4	7	7	9	10	3	5	7	9	10	10
SD20	6	4	7	7	9	10	3	5	7	9	10	10
SD21	4	5	6	3	5	7	5	7	9	7	9	10

Table A5. 5th expert factor evaluation based on cost, time and quality criteria according to Fuzzy TOPSIS Method.

Strategy	Linguistic variables			Corresponding Triangular Fuzzy Number								
ID	Cost	Time	Quality	Cost			Time			Quality		
SD1	3	5	6	1	3	5	5	7	9	7	9	10
SD2	4	4	6	3	5	7	3	5	7	7	9	10
SD3	4	4	5	3	5	7	3	5	7	5	7	9
SD4	3	6	6	1	3	5	7	9	10	7	9	10
SD5	3	4	5	1	3	5	3	5	7	5	7	9
SD6	4	5	6	3	5	7	5	7	9	7	9	10
SD7	2	6	5	0	1	3	7	9	10	5	7	9
SD8	5	4	6	5	7	9	3	5	7	7	9	10
SD9	4	5	5	3	5	7	5	7	9	5	7	9
SD10	3	5	6	1	3	5	5	7	9	7	9	10
SD11	5	4	6	5	7	9	3	5	7	7	9	10
SD12	3	5	5	1	3	5	5	7	9	5	7	9
SD13	4	6	6	3	5	7	7	9	10	7	9	10
SD14	5	5	4	5	7	9	5	7	9	3	5	7
SD15	4	5	5	3	5	7	5	7	9	5	7	9
SD16	3	5	6	1	3	5	5	7	9	7	9	10
SD17	4	6	6	3	5	7	7	9	10	7	9	10
SD18	3	5	6	1	3	5	5	7	9	7	9	10
SD19	4	4	6	3	5	7	3	5	7	7	9	10
SD20	4	4	5	3	5	7	3	5	7	5	7	9
SD21	3	4	5	1	3	5	3	5	7	5	7	9

Table A6. 6th expert factor evaluation based on cost, time and quality criteria according to Fuzzy TOPSIS Method.

Strategy	Linguistic variables			Corresponding Triangular Fuzzy Number								
ID	Cost	Time	Quality	Cost			Time			Quality		
SD1	4	6	5	3	5	7	7	9	10	5	7	9
SD2	5	5	5	5	7	9	5	7	9	5	7	9
SD3	4	5	5	3	5	7	5	7	9	5	7	9
SD4	4	7	5	3	5	7	9	10	10	5	7	9
SD5	4	6	5	3	5	7	7	9	10	5	7	9
SD6	3	7	6	1	3	5	9	10	10	7	9	10
SD7	2	7	5	0	1	3	9	10	10	5	7	9
SD8	4	5	6	3	5	7	5	7	9	7	9	10
SD9	3	6	5	1	3	5	7	9	10	5	7	9
SD10	3	6	6	1	3	5	7	9	10	7	9	10
SD11	4	5	6	3	5	7	5	7	9	7	9	10
SD12	3	6	5	1	3	5	7	9	10	5	7	9
SD13	4	7	5	3	5	7	9	10	10	5	7	9
SD14	5	6	4	5	7	9	7	9	10	3	5	7
SD15	4	6	5	3	5	7	7	9	10	5	7	9
SD16	4	6	6	3	5	7	7	9	10	7	9	10
SD17	4	7	6	3	5	7	9	10	10	7	9	10
SD18	4	6	5	3	5	7	7	9	10	5	7	9
SD19	5	6	6	5	7	9	7	9	10	7	9	10
SD20	5	6	5	5	7	9	7	9	10	5	7	9
SD21	4	6	5	3	5	7	7	9	10	5	7	9

Table A7. 7th expert factor evaluation based on cost, time and quality criteria according to Fuzzy TOPSIS Method.

Strategy	Linguistic variables			Corresponding Triangular Fuzzy Number								
ID	Cost	Time	Quality	Cost			Time			Quality		
SD1	5	4	6	5	7	9	3	5	7	7	9	10
SD2	6	5	7	7	9	10	5	7	9	9	10	10
SD3	5	4	6	5	7	9	3	5	7	7	9	10
SD4	4	3	5	3	5	7	1	3	5	5	7	9
SD5	5	4	6	5	7	9	3	5	7	7	9	10
SD6	6	5	7	7	9	10	5	7	9	9	10	10
SD7	5	4	6	5	7	9	3	5	7	7	9	10
SD8	4	3	5	3	5	7	1	3	5	5	7	9
SD9	6	5	7	7	9	10	5	7	9	9	10	10
SD10	5	4	6	5	7	9	3	5	7	7	9	10
SD11	4	3	5	3	5	7	1	3	5	5	7	9
SD12	5	4	6	5	7	9	3	5	7	7	9	10
SD13	4	3	5	3	5	7	1	3	5	5	7	9
SD14	3	2	4	1	3	5	0	1	3	3	5	7
SD15	5	4	6	5	7	9	3	5	7	7	9	10

SD16	6	5	7	7	9	10	5	7	9	9	10	10
SD17	5	4	6	5	7	9	3	5	7	7	9	10
SD18	5	4	6	5	7	9	3	5	7	7	9	10
SD19	4	3	5	3	5	7	1	3	5	5	7	9
SD20	3	2	4	1	3	5	0	1	3	3	5	7
SD21	5	4	6	5	7	9	3	5	7	7	9	10

Table A8. 8th expert factor evaluation based on cost, time and quality criteria according to Fuzzy TOPSIS Method.

Strategy ID	Linguistic variables			Corresponding Triangular Fuzzy Number								
	Cost	Time	Quality	Cost			Time			Quality		
SD1	5	4	6	5	7	9	3	5	7	7	9	10
SD2	4	5	6	3	5	7	5	7	9	7	9	10
SD3	5	4	7	5	7	9	3	5	7	9	10	10
SD4	4	3	5	3	5	7	1	3	5	5	7	9
SD5	5	4	6	5	7	9	3	5	7	7	9	10
SD6	3	5	6	1	3	5	5	7	9	7	9	10
SD7	4	3	5	3	5	7	1	3	5	5	7	9
SD8	6	4	7	7	9	10	3	5	7	9	10	10
SD9	4	3	5	3	5	7	1	3	5	5	7	9
SD10	5	4	6	5	7	9	3	5	7	7	9	10
SD11	4	5	6	3	5	7	5	7	9	7	9	10
SD12	3	4	5	1	3	5	3	5	7	5	7	9
SD13	4	3	5	3	5	7	1	3	5	5	7	9
SD14	2	3	4	0	1	3	1	3	5	3	5	7
SD15	3	4	6	1	3	5	3	5	7	7	9	10
SD16	5	4	7	5	7	9	3	5	7	9	10	10
SD17	4	3	6	3	5	7	1	3	5	7	9	10
SD18	5	6	6	5	7	9	7	9	10	7	9	10
SD19	4	5	7	3	5	7	5	7	9	9	10	10
SD20	5	4	6	5	7	9	3	5	7	7	9	10
SD21	6	3	5	7	9	10	1	3	5	5	7	9

Table A9. 9th expert factor evaluation based on cost, time and quality criteria according to Fuzzy TOPSIS Method.

Strategy ID	Linguistic variables			Corresponding Triangular Fuzzy Number								
	Cost	Time	Quality	Cost			Time			Quality		
SD1	4	5	6	3	5	7	5	7	9	7	9	10
SD2	5	4	7	5	7	9	3	5	7	9	10	10
SD3	5	5	6	5	7	9	5	7	9	7	9	10
SD4	4	4	5	3	5	7	3	5	7	5	7	9
SD5	5	4	6	5	7	9	3	5	7	7	9	10
SD6	3	5	6	1	3	5	5	7	9	7	9	10
SD7	4	3	5	3	5	7	1	3	5	5	7	9
SD8	6	4	7	7	9	10	3	5	7	9	10	10
SD9	4	3	5	3	5	7	1	3	5	5	7	9
SD10	5	4	6	5	7	9	3	5	7	7	9	10
SD11	4	5	6	3	5	7	5	7	9	7	9	10
SD12	3	4	5	1	3	5	3	5	7	5	7	9
SD13	4	3	5	3	5	7	1	3	5	5	7	9
SD14	2	3	4	0	1	3	1	3	5	3	5	7
SD15	3	4	6	1	3	5	3	5	7	7	9	10
SD16	5	4	7	5	7	9	3	5	7	9	10	10
SD17	4	3	6	3	5	7	1	3	5	7	9	10
SD18	4	5	7	3	5	7	5	7	9	9	10	10
SD19	5	4	6	5	7	9	3	5	7	7	9	10
SD20	6	3	5	7	9	10	1	3	5	5	7	9
SD21	5	4	6	5	7	9	3	5	7	7	9	10

Table A10. 10th expert factor evaluation based on cost, time and quality criteria according to Fuzzy TOPSIS Method.

Strategy ID	Linguistic variables			Corresponding Triangular Fuzzy Number								
	Cost	Time	Quality	Cost			Time			Quality		
SD1	5	4	7	5	7	9	3	5	7	9	10	10
SD2	4	5	6	3	5	7	5	7	9	7	9	10
SD3	6	3	7	7	9	10	1	3	5	9	10	10
SD4	3	4	5	1	3	5	3	5	7	5	7	9
SD5	5	5	6	5	7	9	5	7	9	7	9	10
SD6	2	3	4	0	1	3	1	3	5	3	5	7
SD7	4	3	6	3	5	7	1	3	5	7	9	10
SD8	7	4	7	9	10	10	3	5	7	9	10	10

SD9	3	3	5	1	3	5	1	3	5	5	7	9
SD10	5	4	6	5	7	9	3	5	7	7	9	10
SD11	4	5	6	3	5	7	5	7	9	7	9	10
SD12	2	3	4	0	1	3	1	3	5	3	5	7
SD13	3	2	5	1	3	5	0	1	3	5	7	9
SD14	1	2	2	0	0	1	0	1	3	0	1	3
SD15	3	3	5	1	3	5	1	3	5	5	7	9
SD16	6	4	7	7	9	10	3	5	7	9	10	10
SD17	5	2	6	5	7	9	0	1	3	7	9	10
SD18	6	3	5	7	9	10	1	3	5	5	7	9
SD19	7	3	6	9	10	10	1	3	5	7	9	10
SD20	5	4	7	5	7	9	3	5	7	9	10	10
SD21	4	5	6	3	5	7	5	7	9	7	9	10

Table A11. Aggregated factor evaluation based on cost, time, and quality criteria according to the Fuzzy TOPSIS Method.

Strategy ID	Corresponding Triangular Fuzzy Number								
	Cost			Time			Quality		
SD1	4.1	6	7.8	3.7	5.6	7.4	7.6	9.2	9.9
SD2	4	6	7.8	3.6	5.6	7.6	6.8	8.5	9.6
SD3	5.6	7.5	9	3.5	5.3	7.1	6.2	8	9.2
SD4	2.4	4.4	6.4	3.6	5.5	7.1	6	7.8	9.3
SD5	3.7	5.6	7.5	3.4	5.2	7.1	7	8.8	9.8
SD6	2.9	4.7	6.4	4.1	5.9	7.7	6.4	8.2	9.3
SD7	3.8	5.5	7.1	5.2	6.9	8.1	6	7.9	9.3
SD8	5.8	7.6	8.9	3.6	5.5	7.3	7	8.5	9.3
SD9	4.4	6.3	7.9	3.4	5.4	7.2	4.9	6.7	8.4
SD10	4.8	6.7	8.4	2.8	4.6	6.5	6.2	8.1	9.3
SD11	2.7	4.4	6.3	2.9	4.6	6.6	5.7	7.5	8.8
SD12	1.2	2.6	4.4	2.7	4.3	6.1	4.1	6	7.8
SD13	3.2	5.2	7.2	3.5	5.3	6.9	5.4	7.4	9.1
SD14	2.4	3.8	5.5	3.2	5	6.9	2.4	4.2	6.2
SD15	3.1	4.9	6.6	3.4	5.4	7.3	4.9	6.8	8.4
SD16	5	6.9	8.4	5	6.9	8.5	7.4	8.8	9.4
SD17	2.8	4.6	6.6	3	4.7	6.3	7	8.8	9.7
SD18	4.2	6.2	8	4.3	6.2	8	6.8	8.5	9.5
SD19	5.1	6.8	8.2	3.5	5.3	7	6.8	8.5	9.4
SD20	4.5	6.4	8.1	3.2	4.9	6.6	6	7.7	8.9
SD21	4	5.9	7.6	3.5	5.4	7.2	5.8	7.7	9.1

Table A12. Weighted normalized fuzzy decision matrix.

Strategy ID	Cost			Time			Quality		
SD1	0.217872577	0.161074833	0.353027746	0.150596552	0.144185061	0.263975495	0.262939676	0.212203487	0.315294328
SD2	0.219201068	0.166108421	0.364059863	0.151105324	0.148690845	0.279582154	0.242613747	0.202184369	0.315294328
SD3	0.320224169	0.216663158	0.438332946	0.153295256	0.146843753	0.272544617	0.230824332	0.1985647	0.315294328
SD4	0.135763242	0.125742289	0.308351778	0.155979689	0.150746478	0.26961403	0.220976468	0.191518856	0.315294328
SD5	0.198623009	0.151870557	0.342913529	0.139798123	0.135252313	0.255858212	0.244652518	0.205048445	0.315294328
SD6	0.164047251	0.134315627	0.308351778	0.177643535	0.161709859	0.292398314	0.235708232	0.201340336	0.315294328
SD7	0.214958467	0.157177861	0.342077754	0.225303995	0.189118309	0.307587837	0.220976468	0.193974226	0.315294328
SD8	0.328094502	0.217191226	0.428801692	0.155979689	0.150746478	0.277208791	0.257805879	0.208706445	0.315294328
SD9	0.275567057	0.199330106	0.421402626	0.16309781	0.16386338	0.30270549	0.199799556	0.182135835	0.315294328
SD10	0.271526484	0.191471212	0.404711709	0.121317536	0.126078873	0.246829746	0.22834235	0.198884966	0.315294328
SD11	0.161411696	0.132886737	0.320780019	0.132789527	0.133242445	0.264867304	0.221855352	0.19461597	0.315294328
SD12	0.080935779	0.088591158	0.252759511	0.139481837	0.140521018	0.27618642	0.180039161	0.175653388	0.315294328
SD13	0.184996066	0.151870557	0.354519833	0.154979819	0.148457421	0.267777934	0.203249784	0.185690725	0.315294328
SD14	0.182985239	0.146368	0.357160178	0.186874217	0.184709124	0.353156406	0.119135139	0.13899529	0.283307947
SD15	0.194149517	0.155034527	0.35205789	0.16309781	0.16386338	0.306909733	0.199799556	0.18485428	0.315294328
SD16	0.279831151	0.195089039	0.400406265	0.214333793	0.187106412	0.319343558	0.269638307	0.213773911	0.315294328
SD17	0.151858884	0.126036905	0.304874874	0.124622948	0.123507565	0.229369624	0.247174709	0.207162347	0.315294328
SD18	0.23258387	0.173452162	0.377325202	0.182386777	0.16635487	0.297394868	0.245167576	0.204312625	0.315294328
SD19	0.285427774	0.192261662	0.390872783	0.150033655	0.143719418	0.262988813	0.247775742	0.206486164	0.315294328
SD20	0.265996802	0.191118004	0.407797392	0.144880011	0.140337426	0.261891267	0.230907995	0.197560721	0.315294328
SD21	0.231245083	0.17231467	0.374215379	0.154979819	0.151258504	0.279420453	0.218305324	0.193218727	0.315294328

Table A13. Initial criterion evaluation matrix according to Fuzzy AHP Method.

	Criteria	**Cost**	**Time**	**Quality**
1.Expert	**Cost**	1	3	5
	Time	7	1	7
	Quality	5	3	1
2.Expert	**Cost**	1	1	3
	Time	9	1	3
	Quality	7	7	1
3.Expert	**Cost**	1	5	3
	Time	5	1	3
	Quality	7	7	1
4.Expert	**Cost**	1	7	9
	Time	3	1	1
	Quality	1	9	1
5.Expert	**Cost**	1	4	2
	Time	6	1	3
	Quality	8	7	1
6.Expert	**Cost**	1	1	3
	Time	9	1	2
	Quality	7	8	1
7.Expert	**Cost**	1	7	9
	Time	3	1	1
	Quality	1	9	1
8.Expert	**Cost**	1	5	5
	Time	5	1	5
	Quality	5	5	1
9.Expert	**Cost**	1	6	1
	Time	4	1	1
	Quality	9	9	1
10.Expert	**Cost**	1	2	1
	Time	8	1	4
	Quality	9	6	1

Table A14. Aggregated fuzzy criterion matrix according to Fuzzy AHP Method.

	Cost			Time			Quality		
Cost	1	1	1	0.350952381	0.393571429	0.486666667	0.363888889	0.412222222	1
Time	0.163452381	0.19734127	0.259285714	1	1	1	0.4575	0.509285714	0.464285714
Quality	0.304166667	0.317579365	0.339285714	0.137896825	0.158690476	0.196785714	1	1	1

Table A15. Final criterion weights according to Fuzzy AHP Method.

W	Cost	0.413309905
	Time	0.337000842
	Quality	0.295385753