

# A hybrid fuzzy cognitive–system dynamics framework for modeling environmental risk evolution in construction megaprojects

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## Original Research

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## Abstract:

Emphasizing the critical role of sustainability, this research comprehensively assesses environmental risks in industrial-construction megaprojects and shows that identifying and managing these risks can help reduce negative environmental consequences and improve sustainable decision-making. The present study aims to analyze the environmental risk management system in a megaproject as a case. Therefore, the innovation of this research lies in the use of a system dynamics approach and fuzzy cognitive mapping to identify and assess environmental risks in large-scale industrial and civil engineering projects. Based on this analysis, each aspect of a project's environmental risk management is ranked using the Analytic Network Process (ANP), and Decision Making Trial and Evaluation Laboratory (DEMATEL) and causal relationships are examined. Also, using the Fuzzy Cognitive Map (FCM) approach, the in degree, out degree, and centrality of each risk have been identified. Then, the behavioral model is determined based on the system dynamics. The risk of completing the project timely and the issues related to the increase in time due to environmental laws were ranked first, an over predicted increase in the project time due to environmental laws was ranked second, and the factor of environmental issues and problems was ranked third. Environmental issues and problems have the highest impact and the risk of completing the project timely and the issues related to the increase in time due to environmental laws were the most affected factor. Experts believe that the involvement of several institutions and decision-making from the perspective of environmental climate issues is one of the most significant environmental risks affecting the completion of the project. This issue is because the risk of completing the project timely from an environmental perspective and environmental issues and problems is reduced by controlling and reducing this risk. These two risks are increasing with an increase in the risk of conflict among several decision-making institutions from the perspective of environmental climate issues. The risk of the involvement of several decision-making institutions from a climate and environmental perspective is directly associated with two risks of environmental issues and problems and the risk of completing the project timely. Thus, the institutions involved in the climate and environmental issues of the project can reduce the risk of timely completion of the project and environmental issues and problems with mechanisms and memorandums that reduce the risk of conflict among them.

**Keywords:** Megaproject; Environment; Risk; System dynamics; Fuzzy cognitive map; Environmental risk assessment

## 1. Introduction

Risk management is a major issue in all projects. Risk management is considered a major field of study in many organizations involved in a project [1]. Risk management is a systematic process of identifying, analyzing, and respond-

ing to potential risks in a project to maximize the likelihood of positive outcomes. Also, risk management minimizes the probability of harmful events and their consequences [2]. Boehm and Turner [3] consider a two-step process for risk management in a project. In the first step, major risk threats

and opportunities are identified, each of which can affect project or process outcomes. Risk assessment is the process of estimating the probability of an event, either desirable or undesirable, and its impact. This step helps to select less risky projects and eliminate remaining risks.

It is possible to identify the primary and major threats and opportunities that affect the outcomes of the project or process using one of the risk identification tools. In the second step, after identifying the primary risks, the frequency of occurrence and its outcomes and impacts are assessed [4]. Then, different risks are prioritized according to the results of the analysis. Accordingly, it is possible to compare different risks with each other. In the next steps of the risk management process, it is possible to decide on the appropriate methods to respond to the risk [5]. Environmental risk management in large projects has become a major research subject [6]. Megaprojects mostly need to cross different regions with fragile ecological environments [7]. Thus, megaprojects face more complex environmental risks [8]. One of the unknown factors of these disasters will lead to erosion of water and soil, destruction of the environment, and even endangering the safety of people's lives and property. Additionally, taking preventive measures to minimize environmental risks is the best option to manage environmental risks [9]. This will have a direct beneficial impact on intrinsic value, economics, and ecosystem services [10]. Accordingly, it is essential to investigate the environmental risk factors affecting megaprojects for better management. Generally, there are several risks in a megaproject making it difficult to face the problem of allocation of limited resources. Thus, comprehensive risk management is required [11]. Environmental problems and risks are widely distributed. Improper management of these problems will cause problems for project management and even cause additional project costs or project failure [12].

According to above mentioned, given the rapid growth of these projects and their significant impacts on the environment, the need for new approaches to risk management is increasingly felt [13]. In this regard, the use of the system dynamics approach and fuzzy cognitive mapping as an effective tool for analyzing the complexities of interactions between environmental factors and simulating different scenarios helps to improve the decision-making process and risk management [14]. This research seeks to identify weaknesses and opportunities in order to reduce the negative environmental impacts of projects and enhance their sustainability. Current approach helps to more accurately and comprehensively analyze the complex interactions between environmental factors and their impacts on projects, and allows decision-makers to develop effective strategies for managing risks and reducing negative impacts on the environment by simulating different scenarios. This research can contribute significantly to promoting project sustainability and improving environmental quality. Therefore, the identification and assessment of environmental risks in industrial-construction engineering megaprojects is a critical issue due to the significant environmental impact these projects have. Megaprojects often involve complex interactions between various stakeholders, regulatory frameworks,

and environmental factors, leading to uncertainties and challenges in risk management. Traditional risk assessment methods may not adequately capture the dynamic nature of these interactions and the inherent uncertainties associated with them. As a result, there is a pressing need for innovative approaches that can effectively model and analyze environmental risks in this context. Also, despite the growing recognition of the importance of environmental risk assessment in megaprojects, there remains a lack of comprehensive frameworks that integrate system dynamics and fuzzy cognitive mapping. Existing literature often focuses on either qualitative or quantitative methods in isolation, failing to address the complexities and interdependencies present in megaproject environments. Furthermore, there is limited research on how fuzzy cognitive maps can be utilized to enhance the understanding of environmental risks by incorporating stakeholder perspectives and uncertainties. The fuzzy approach was chosen in current study has advantages because: The uncertainty in current study is linguistic and epistemic, not probabilistic. Expert-based data are more compatible with fuzzy modeling than with stochastic models. FCM inherently relies on fuzzy-weighted causal relationships. Fuzzy logic ensures methodological compatibility with the DANP and system dynamics components. Given these considerations, the fuzzy framework provides the most appropriate, feasible, and theoretically coherent basis for modeling environmental risks in megaprojects within the scope and constraints of current study.

This gap highlights the need for a systematic approach that combines these methodologies to provide a more holistic view of environmental risks in industrial-construction engineering megaprojects, ultimately leading to better decision-making and risk management strategies. Thus, it is essential to consider better management of potential environmental risks during the construction process and the operation and maintenance period in megaprojects. For this purpose, the present study proposes a comprehensive model for managing environmental risks in megaprojects. It includes two goals: (1) identifying and ranking risks and (2) presenting behavioral models of risks and scenarios for the coming years. The contribution of the current research to participation and innovation can be examined from four perspectives. First, this research provides a new analytical framework to better understand the complex interactions between environmental factors and their impacts on projects. Second, by using simulations of different scenarios, it allows decision-makers to develop effective strategies for managing risks and reducing negative impacts on the environment. Third, this research helps to promote awareness and knowledge in the field of environmental risk management and can serve as a reliable source for researchers and professionals in this field. Fourth, the results of this research can help improve environmental policies and planning in large-scale industrial and construction engineering projects and contribute to sustainable development in this industry. Finally, this research can be used as a model for other similar projects at different levels and help improve environmental quality and project sustainability.

The remainder of the paper is structured as follows. Sec-

tion 2 reviews the related literature. Section 3 describes the research methodology. Section 4 details the proposed model, and section 5 presents the overall conclusions of the study.

## 2. Literature review

Risk assessment is a crucial step in the risk management process of a construction project [15, 16]. It has been a scientific field for more than 40 years [17]. It is extensively used in the construction industry [18, 19]. Although issues such as project management and risk management have been discussed in detail, none of them has attempted to examine environmental risk management as one of the most crucial issues involved in the results and performance of projects. However, they have focused more on the conceptual and organizational aspects of risk. Generally, a comprehensive study has not been conducted on the relationship between environmental and project risk [20].

Risk assessment has also been used as a crucial part of construction project management in existing studies on megaprojects to analyze various potential risks [21, 22]. Several complex analysis methods and techniques have been developed for risk assessment, such as the limit equilibrium method [18], Bayesian networks [16, 20, 21], fault tree analysis [15], Monte Carlo simulation (Albugami and Daoud, 2015), regression analysis (Nguyen et al. 2023), and analytic hierarchy process [10]. Using MCDM techniques and fuzzy logic, Olfat et al. [22] ranked the risks of construction projects based on the Project Management Body of Knowledge (PMBOK) criteria. Referring to the existence of a fuzzy decision-making environment Carbone and Tipett [23] examined and analyzed project risks using the hybrid approach of PMBOK and FMEA technique. FMEA is a well-known approach implemented in many risk management projects with different scopes [20–22]. Nguyen and Macchion [24] investigated the factors frequently encountered by green building (GB) projects in Vietnam. Initially, 53 risk factors were identified by reviewing previous studies and interviewing industry professionals. Then, a questionnaire was designed to collect data from 207 construction professionals to assess the importance of GB risk factors. Koc et al. [25] a four-step analysis method was designed to assess the risks of the life cycle of green building (GB) and emphasize the role of stakeholders in managing the associated risks. For this purpose, a comprehensive literature review and group discussions were used to build a decision-making framework suitable for the GB life cycle. A fuzzy analytic hierarchy process (F-AHP) was used to prioritize the identified risks based on expert opinions. Also, the fuzzy technique for prioritization based on similarity to the ideal solution (F-TOPSIS) was used to relate the role of stakeholders to the management of GB risks that may arise during GB projects. Doung et al. [26] performed to develop and validate a measurement scale of risk in sustainable construction supply chains (SCs). Exploratory factor analysis (EFA) and confirmatory factor analysis (CFA) are used to test the reliability, convergent validity, and discriminant validity of the risk constructs. The results indicate that all tests strongly support the measurement scale, and

seven reliable risk constructs are identified including supply, demand, internal processes, information, financial, time, and environmental risks. Nguyen et al. [27] developed a comprehensive risk assessment model that considers three important risk characteristics: impact level, probability of occurrence, and risk manageability. Used the mean scoring method and fuzzy mixed assessment to assess green building (GB) risks. Based on expert assessments, the model can determine the importance of risk factors, risk groups, and overall risk. Specifically, this study applied the proposed model to assess GB risks in Vietnam by surveying 58 experienced GB professionals. Seyedi et al. [28] identified and rank the risks of industrial megaprojects using the Delphi method and to provide a structural model for the factors affecting industrial megaprojects risk using the DEMATEL-ANP technique. Khalilzadeh et al. [29] Focused on the operational phase of a selected energy project and uses a multifaceted approach. Risks are systematically identified through a comprehensive literature review, organizational insights, and expert judgment. The identified risks are then filtered using the fuzzy Delphi method to ensure their relevance and accuracy. High-priority risks are determined through a probability-impact matrix, and then the fuzzy best-worst method (FBWM) is used to weight and prioritize criteria in risk response planning. Finally, the Grey Combined Compromise Solution (G-COCOSO) method is employed to rank and select the most effective risk response strategies under uncertainty.

Using the studies conducted by other researchers, the present study explains the issues related to environmental risks in a megaproject and tries to define a model to reduce the risk. Several methods are used to analyze risks. Most project managers prefer to use matrix-based decision-making processes over other methods. Successful project managers use open communication across the organization about their needs. The present study identifies the project risks using expert opinions and ranks them using MCDM techniques. Also, a behavioral model is recommended in this study to predict its impacts in the next ten years. Given the identified research gap and the critical role of environmental risks in construction and industrial projects, it is proposed that future studies should focus on the integration of system dynamics approaches into modeling and managing environmental risk. System dynamics is a powerful tool for a better understanding of complexities and internal interactions within projects, and it enhances the ability to forecast the outcomes of different risk management policies in highly uncertain contexts. This approach can contribute to the design of flexible and resilient strategies to deal with environmental risks in construction projects. System dynamics could be used to analyze the long-term and unknown impacts of environmental risks on the performance and profitability of the project, as well as to examine the effectiveness of risk management strategies over time. Moreover, this method could be employed in the development of optimization models for balancing costs, time, quality, and environmental impacts in construction projects. Therefore, future research should move towards the development and application of system dynamics models for identifying, eval-

uating, and managing environmental risks in construction projects. This approach could improve our understanding of the complex dynamics involved in environmental risk management and lead to the development of strategies that effectively protect projects against unpredictable changes and environmental challenges.

The existing body of literature on the current study reveals a significant gap in the synthesis of methodologies that effectively integrate system dynamics with fuzzy cognitive mapping. While both approaches have been explored separately, their combined application remains under-researched, particularly in the context of megaprojects where environmental risks are multifaceted and dynamic.

1. **Limited Integration of Methodologies:** Most studies tend to focus on either system dynamics such as Seyedi et al. [28] or fuzzy cognitive mapping or other MCDM approach like as Fuzzy AHP; TOPSIS; BWM and COCOSO such as ([25, 29]) independently, neglecting the potential benefits of their integration. This separation limits the ability to capture the complex interactions and feedback loops inherent in megaproject environments, which are crucial for a comprehensive risk assessment.
2. **Lack of Stakeholder Perspectives:** Current research often overlooks the importance of incorporating diverse stakeholder perspectives in the risk assessment process. Fuzzy cognitive mapping, with its ability to represent subjective judgments and uncertainties, can enhance understanding by integrating these perspectives. However, this potential remains largely untapped in existing frameworks.
3. **Insufficient Focus on Dynamic Interactions:** The dynamic nature of environmental risks in megaprojects necessitates a more robust modeling approach that can adapt to changing conditions over time. Existing risk assessment methods frequently fail to account for these dynamics, leading to static analyses that do not reflect real-world complexities.
4. **Need for Holistic Frameworks:** There is a clear need for the development of holistic frameworks that combine system dynamics and fuzzy cognitive mapping to provide a more nuanced understanding of environmental risks. Such frameworks should facilitate the identification of key risk factors, their interdependencies, and the potential impacts of various scenarios, ultimately leading to more effective risk management strategies.

Therefore, the research gap lies in the limited synthesis of system dynamics and fuzzy cognitive mapping methodologies for environmental risk assessment in industrial-construction engineering megaprojects. Addressing this gap is essential for advancing the field and improving decision-making processes in the face of complex environmental challenges.

### 3. Research methodology

The primary indicators related to environmental materials were first identified through a systematic literature review. The criteria obtained the previously identified indicators by using authentic articles and Persian and Latin books. The present study is applied research in terms of purpose and descriptive and library in terms of the method of collecting information. The data collection tools were reliable databases and articles related to the research. They were collected using a systematic review approach. The systematic review conducted in this study to determine the indicators is as follows:

**Step 1:** Purpose Determination - In this step, key questions such as topic, population, time and methodology are identified by focusing on the research objective.

**Step 2:** Systematic literature review - In this step, published articles are searched and relevant keywords are selected.

**Step 3:** Search and select appropriate texts - Inappropriate articles are eliminated and the methodological quality of the articles is reviewed to ensure that the findings are valid.

**Step 4:** Extraction of text information - Information from selected articles is continuously reviewed and categorized, including reference records, methodological notes and pages of interest.

**Step 5:** Analysis and synthesis of qualitative findings - The aim of this step is to create a unified interpretation of the findings and identify common themes across the articles.

**Step 6:** Quality Control - In this step, various procedures are considered to maintain the quality of the study, including documenting the steps and using various search methods.

**Step 7:** Analysis of Findings - In this step, the findings from the previous steps are presented.

After reviewing several articles, books, and documents, the following risks were obtained in the environmental area are shown in the Table 1. Then, by designing a questionnaire and distributing it among the experts, their survey was conducted according to the Delphi method. The participant of the present study, according to the data analysis steps to finalize the input and output variables, includes experts whose characteristics are as follows:

- Managers and those with management experience in industrial-construction projects.
- Experts with work experience in the field of industrial-construction projects.

Table 2 shows the profiles of the experts in the current study based on their job position, education, and work experience. The method of selecting the experts was based on snowballing. After collecting the questionnaires, the threshold

**Table 1.** Identified environment criteria.

Criteria	References
Climate conditions	[30, 31]
The cost of solving internal and external legal disputes of the project	[18, 20, 26]
Implementation of environmental regulations	[17, 20, 22]
Environmental assurance	[32, 33]
Environmental uncertainties	[20, 25, 34]
An over predicted increase in the project price	[35, 36]
An over predicted increase in the project time	[37]
Involvement of several decision-making institutions	[20, 23, 25–27]
Reducing the project quality	[11, 15, 23]
The risk of completing the project timely and related issues regarding time increase	[38]
The risk of reducing the project quality due to excessive cost increases	[30–35]
Social problems	[32, 35]
Social complaints	[21, 26, 38]
Worksite coordination problems	[12, 15, 17]

for each of the indicators was calculated, and the Delphi stages continued until all the indicators were found to be thresholds. After determining the indicators using the DANP method, the importance of the factors and then the cause-and-effect relationships were identified. Finally, the dynamic impact of the system was evaluated using the system dynamics model. Figure 1 illustrates research methodology flowchart.

### 3.1 Developin a questionarie

In this step, 15 indicators were obtained through reviewing the subject literature and interviewing experts. These indicators were submitted to the experts for prioritizing and selecting the final indicators through a 7-option Likert scale questionnaire and analysis by the Delphi technique.

### 3.2 Solution approach

In this section, the research data is analyzed. This study aims to identify the important risks in the social dimensions of megaprojects and analyze their behaviors. To access this target, the DANP method has been used. The ANP method

requires the internal relationships between the factors to calculate the weight and is identified by the DEMATEL method, the effectiveness and influence of factors; then, ANP super matrices are made up by the DEMATEL communication matrix, and next, after reaching the causal relationships between the factors, the model will be analyzed and simulated in the VENSIM software.

#### 3.2.1 DANP technique

In the traditional ANP, it is assumed that every cluster has the same weight although it is clear that the effect of each on others may be different. So, the assumption of traditional ANP based on the same cluster weight is not rational to create a balanced super matrix. Subsequently, an effective balanced DANP can eliminate this weakness. In this method, the results are obtained from the completed relationship between  $T_C$  and  $T_D$  computed by DEMATEL based on the basic conception of ANP. Therefore, the DEMATEL technique is used to build a network structure model for each criteria and dimension as well as to improve the normalization trend of traditional ANP [25]. This technique

**Table 2.** Participant ID.

Row	Job position	Education	Work experience
1	Deputy Director of Research and Technology, National Gas Company	Ph.D.	27
2	Engineering Director of Bu-Ali Sina Petrochemical Development Project	M.Sc.	26
3	Construction and Installation Manager of the Sixth National Gas Pipeline Project	B.Sc.	26
4	Executive of Support Projects and Tonbak Export Port Project, Pars Oil and Gas Company	M.Sc.	20
5	Executive Manager of APADANA Petrochemical Company	M.Sc.	26
6	Engineering Manager of Shiraz Petrochemical Utility Project	B.Sc.	25
7	Manager of Construction Engineering Department, Pars Oil and Gas Company	Ph.D.	18
8	Head of Planning and Project Control, Sixth National Gas Development Engineering Project	M.Sc.	28
9	Management of Engineering Projects of Pars Economic Energy Region	M.Sc.	24



$$T_c^{\alpha 11} = \begin{bmatrix} \frac{t_{c11}^{11}}{d_{c1}^{11}} & \dots & \frac{t_{c1j}^{11}}{d_{c1}^{11}} & \dots & \frac{t_{c1m_1}^{11}}{d_{c1}^{11}} \\ \vdots & & \vdots & & \vdots \\ \frac{t_{ci1}^{11}}{d_{ci}^{11}} & \dots & \frac{t_{cij}^{11}}{d_{ci}^{11}} & \dots & \frac{t_{cim_1}^{11}}{d_{ci}^{11}} \\ \vdots & & \vdots & & \vdots \\ \frac{t_{cm_1 1}^{11}}{d_{cm_1}^{11}} & \dots & \frac{t_{cm_1 j}^{11}}{d_{cm_1}^{11}} & \dots & \frac{t_{cm_1 m_1}^{11}}{d_{cm_1}^{11}} \end{bmatrix} \quad (8)$$

$$= \begin{bmatrix} t_{c11}^{\alpha 11} & \dots & t_{c1j}^{\alpha 1j} & \dots & t_{c1m_1}^{\alpha 1n} \\ \vdots & & \vdots & & \vdots \\ t_{ci1}^{\alpha i1} & \dots & t_{cij}^{\alpha ij} & \dots & t_{cim_1}^{\alpha in} \\ \vdots & & \vdots & & \vdots \\ t_{cm_1 1}^{\alpha n1} & \dots & t_{cm_1 j}^{\alpha nj} & \dots & t_{cm_1 m_1}^{\alpha nn} \end{bmatrix}$$

Sixth step- creating the balanced super matrix:

In this step, the transpose of the complete communication matrix was normalized,  $T_c^\alpha$  calculated, and the balanced super matrix obtained in Eq. (9):

$$W = \begin{bmatrix} W_c^{11} & \dots & W_c^{1j} & \dots & W_c^{1n} \\ \vdots & & \vdots & & \vdots \\ W_c^{i1} & \dots & W_c^{ij} & \dots & W_c^{in} \\ \vdots & & \vdots & & \vdots \\ W_c^{n1} & \dots & W_c^{nj} & \dots & W_c^{nn} \end{bmatrix} \quad (9)$$

Seventh step- restricting the balanced super matrix:

The balanced super matrix is restricted by exponents to a large number  $Z$  until the supermatrix is converged and stabilized. The output of this step is the effective weights of DANP:

$$\lim_{Z \rightarrow \infty} (W^\alpha)^Z \quad (10)$$

### 3.2.4 Fuzzy cognitive map (FCM) approach

A fuzzy cognitive map (FCM) is a graphical representation of knowledge that models complex systems and their inter-relationships using fuzzy logic. It combines concepts from cognitive mapping and fuzzy set theory to represent how different elements (or concepts) influence one another in a system. Here’s a breakdown of its key components and features:

1. **Nodes and Edges:** In an FCM, nodes represent concepts or variables, while directed edges (arrows) indicate the relationships between these concepts. The direction of the arrow shows the influence of one concept on another.
2. **Fuzzy Relationships:** Unlike traditional cognitive maps that use binary relationships (either a concept influences another or it does not), FCMs allow for varying degrees of influence. Each edge is assigned a weight, typically ranging from  $-1$  to  $+1$ , where:
  - o A positive weight indicates a positive influence (as one concept increases, the other also increases).
  - o A negative weight indicates a negative influence (as one concept increases, the other decreases).

3. **Dynamic Behavior:** FCMs can be used to simulate the dynamic behavior of systems over time. By iteratively updating the values of the nodes based on their relationships, FCMs can predict how changes in one part of the system affect other parts.

FCMs are widely used in various fields, including decision-making, system modeling, risk assessment, and forecasting. They are particularly useful in scenarios where uncertainty and complexity are prevalent, such as environmental studies, social sciences, and management. Therefore, FCMs provide a flexible and intuitive way to model complex systems. They can incorporate expert knowledge and allow for qualitative assessments, making them suitable for situations where quantitative data may be scarce. While FCMs are powerful tools, they also have limitations, such as the challenge of accurately determining the weights of relationships and the potential for oversimplification of complex interactions. Finally, fuzzy cognitive maps are valuable tools for understanding and analyzing complex systems by representing the interdependencies and influences among various concepts in a flexible and intuitive manner.

### 3.2.5 System dynamic simulation approach

System dynamic simulation is a modeling approach used to understand and analyze complex systems over time. It focuses on the feedback loops and time delays that characterize the behavior of systems, making it particularly useful for studying dynamic processes in various fields such as economics, ecology, engineering, and social sciences. Here’s an overview of its key components and features:

1. **Feedback Loops:** System dynamics emphasizes the importance of feedback loops, which can be either positive (reinforcing) or negative (balancing). Positive feedback loops amplify changes, leading to exponential growth or decline, while negative feedback loops work to stabilize the system by counteracting changes.
2. **Stocks and Flows:** In system dynamics, the system is represented using stocks (quantities that accumulate over time) and flows (rates of change that affect stocks). Stocks can represent resources, populations, or any measurable quantity, while flows indicate how these stocks increase or decrease.
3. **Time Delays:** System dynamics takes into account time delays in the system, which can significantly affect the behavior and outcomes. These delays can arise from various factors, such as decision-making processes, resource availability, or natural delays in system responses.
4. **Simulation Models:** System dynamic simulation involves creating a model that captures the essential elements of the system being studied. This model is then simulated over time to observe how the system behaves under different scenarios or policy interventions. The simulation results can provide insights into system behavior, potential outcomes, and leverage points for intervention.

System dynamic simulation is widely used in various domains, including:

- **Business and Management:** To analyze supply chains, project management, and organizational behavior.
- **Environmental Studies:** To model ecosystems, resource management, and climate change impacts.
- **Public Policy:** To evaluate the effects of policies on social systems, healthcare, and urban planning.

System dynamics offers an integrated perspective on complex systems, enabling the examination of relationships and interdependencies within them. By simulating different scenarios, it helps uncover leverage points for effective intervention and strengthens decision-making processes. Despite its strengths, system dynamics modeling demands thoughtful attention to the model's structure and underlying assumptions. The reliability of its outcomes is closely tied to the quality of available data and the depth of understanding of the modeled system. Moreover, certain complexities may still be simplified within the model. Overall, system dynamics serves as a powerful approach for analyzing and managing complex systems by capturing their behavior over time, emphasizing feedback loops, stocks and flows, and temporal delays. It effectively supports policy development

and strategic decisions by revealing system behavior and potential future outcomes.

## 4. Results

### 4.1 System dynamic simulation approach

In this section, the Delphi method is used to identify and screen indicators. The steps of this method are presented below. In the first step, a questionnaire containing the factors affecting the risk in environmental dimensions was designed. It includes 11 indicators. It was given to 8 experts to score each indicator based on a 7-point Likert scale. In the next round of Delphi, it is examined whether this coefficient will have a significant improvement or not. Table 3 presents the results of the first round of Delphi.

In the second round of Delphi, the factors obtained a mean of less than 4 in the first round of Delphi were removed. In the second round of Delphi, the confirmed factors of the first step were again submitted to the experts through a questionnaire to score each indicator as in the first step. Also, in this round, the mean scores of the first round of Delphi were placed so people could make decisions based on the total mean. In this round, many experts confirmed their opinions in the first step. Table 4 presents the results of the second round of Delphi.

**Table 3.** The results of the first round of Delphi.

Environmental risks	Lowest score	Highest score	Mean	SD
Environmental issues and problems	1	7	4.38	1.996
Climatic conditions	1	7	4.38	1.867
The cost of resolving internal and external environmental legal disputes of the project	2	6	3.63	1.317
Implementation of environmental regulations	1	5	3.75	1.392
Environmental assurance	1	5	3.38	1.111
Environmental uncertainty	1	5	3.50	1.323
Over predicted increase in the price of the project from an environmental perspective	1	5	2.63	1.495
Over predicted increase in project time due to environmental laws	2	7	5.00	1.871
The conflict among several decision-making institutions from the perspective of climate and environmental issues	3	7	5.00	1.500
Reducing the project quality due to the implementation of environmental laws	1	6	3.38	2.176
The risk of completing the project timely and related issues regarding the increase in the time of environmental laws	1	7	4.50	2.062
The risk of reducing the project quality due to the excessive cost of implementing environmental laws	1	7	3.88	2.147
Social complaints due to non-implementation of environmental laws	1	6	3.50	1.871
Creating social problems as a result of implementing the project and possible environmental pollution	1	6	3.38	1.495
Worksite coordination problems given the environmental restrictions	1	5	3.50	1.414

**Table 4.** The results of the second round of Delphi.

Environmental risks	Lowest score	Highest score	Mean	SD
Environmental issues and problems	2	7	4.88	1.536
Climatic conditions	4	7	5.13	0.927
Over predicted increase in project time due to environmental laws	5	7	6.25	0.661
The conflict among several decision-making institutions from the perspective of climate and environmental issues	3	7	5.00	1.500
The risk of completing the project timely and related issues regarding the increase in the time of environmental laws	2	7	5.00	1.581

**4.2 DANP method results**

In this section, a DANP method is implemented for the sub-criteria of each primary criterion. Generally, 5 DANP models will be implemented, which are given below.

**4.2.1 Implementation DANP method of environmental sub criteria**

• **Formation of direct correlation matrix**

Table 5 presents the direct correlation matrix. This matrix is completed based on a scale from 0 to 4.

• **Normalizing the direct correlation matrix**

Three relations were used to normalize the obtained matrix. First, the sum of the rows and columns of the direct correlation matrix should be obtained. Then, the highest value should be calculated among the total numbers, as presented in Table 6.

Then, we divide the rows of the direct correlation matrix (3) by the number 13 to normalize. The normalized matrix is presented in Table 7.

• **Calculation of the total correlation matrix (T)**

To calculate the total correlation matrix, the identity matrix ( $I_{5 \times 5}$ ) is first formed. Then, we subtract the identity matrix from the normal matrix and invert the resulting matrix. Finally, we multiply the normal matrix by the inverse matrix. Table 8 shows the total correlation matrix.

• **Formation of causal diagram**

To form the causal diagram, we obtain the sum of rows (D) and the sum of columns (R) of the total correlation matrix. Then, we calculate  $D + R$  and  $D - R$  in Table 9.

**Table 5.** Direct correlation matrix of criteria.

	C1	C2	C3	C4	C5
C1	0	2	4	3	4
C2	3	0	4	2	3
C3	2	1	0	2	3
C4	2	1	1	0	2
C5	2	2	3	2	0

**Table 6.** Total rows and columns of direct correlation matrix.

	Sum of rows	Sum of columns
C1	13	9
C2	12	6
C3	8	12
C4	6	9
C5	9	12
Maximum value = 13		

Based on Table 9, the factor of environmental issues and problems has the highest impact and the factor of risk of completing the project timely and related issues regarding the increase in the time of environmental laws is the most affected factor. According to the values of  $D + R$  and  $D - R$  in Table 9, we can draw the causal diagram of the criteria, which is shown in figure 2. Accordingly, the criteria that are above the X-axis have positive  $D - R$ . These criteria

**Table 7.** Normalized matrix of the DEMATEL method.

	C1	C2	C3	C4	C5
C1	0.000	0.154	0.308	0.231	0.308
C2	0.231	0.000	0.308	0.154	0.231
C3	0.154	0.077	0.000	0.154	0.231
C4	0.154	0.077	0.077	0.000	0.154
C5	0.154	0.154	0.231	0.154	0.000

**Table 8.** The total correlation matrix of the criteria.

	C1	C2	C3	C4	C5
C1	0.481	0.480	0.856	0.681	0.869
C2	0.654	0.335	0.843	0.609	0.297
C3	0.452	0.306	0.408	0.461	0.606
C4	0.389	0.260	0.405	0.264	0.467
C5	0.492	0.390	0.649	0.499	0.468

**Table 9.** Importance and effect of criteria.

	D	R	D + R	D - R
C1	3.366	2.467	5.833	0.989
C2	3.238	1.771	5.009	1.467
C3	2.233	3.161	5.394	-0.927
C4	1.785	2.514	4.298	-0.729
C5	2.498	3.207	5.705	-0.709

have a cause aspect. The criteria that are below the X-axis have a negative  $D - R$ . These criteria are the effect side of the research. This means that they are the most affected criteria.

**4.2.2 Determine internal relationships between criteria**

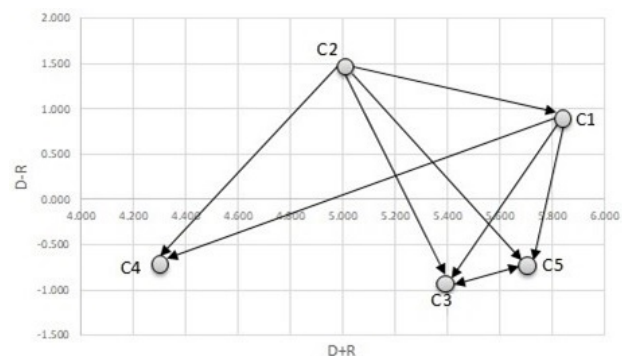
In this step, to draw significant relationships, we specify the threshold (arithmetic mean of the variables) from the total correlation matrix (Table 6). When each of the numbers is less than the limit, the value will be zero; otherwise, the value will be one. The threshold value of the criteria is 0.525. These relationships are presented in Table 10.

• **Normalizing the total correlation matrix ( $T_c$ ) and forming the unbalanced super matrix**

In this step, we normalize the total correlation matrix (Table 10), which is the result of forming an unbalanced super matrix. Table 11 presents the results.

• **Formation of balanced super matrix**

In this step, the normal total correlation matrix ( $T_c$ )



**Figure 2.** Causal diagram of factors.

**Table 10.** Significant relationships between factors.

Significant relationships	C1	C2	C3	C4	C5
C1	0	0	1	1	1
C2	1	0	1	1	1
C3	0	0	0	0	1
C4	0	0	0	0	0
C5	0	0	1	0	0
Unbalanced super matrix	C1	C2	C3	C4	C5
C1	0.143	0.143	0.254	0.202	0.258
C2	0.202	0.103	0.260	0.188	0.146
C3	0.202	0.137	0.183	0.207	0.271
C4	0.218	0.146	0.227	0.148	0.262
C5	0.197	0.156	0.260	0.200	0.187
Balanced super matrix	C1	C2	C3	C4	C5
C1	0.143	0.202	0.202	0.218	0.197
C2	0.143	0.103	0.137	0.146	0.156
C3	0.254	0.260	0.183	0.227	0.260
C4	0.202	0.188	0.207	0.148	0.200
C5	0.258	0.246	0.271	0.262	0.187
Limit super matrix	C1	C2	C3	C4	C5
C1	0.1925	0.1925	0.1925	0.1925	0.1925
C2	0.1397	0.1397	0.1397	0.1397	0.1397
C3	0.2345	0.2345	0.2345	0.2345	0.2345
C4	0.1903	0.1903	0.1903	0.1903	0.1903
C5	0.2430	0.2430	0.2430	0.2430	0.2430

calculated in the previous step is transposed to form the balanced super matrix. Table 10 presents the results.

#### • Forming the limit super matrix

In this step, the balanced super matrix is brought to the power to converge. In this study, the balanced matrix is converged to the power 3. Table 10 presents the results.

#### 4.2.3 The final weights of the factors calculation

The final weight of the criteria is the same number obtained from the limit super matrix, as shown in Table 11.

According to figure 3, the factor of the risk of completing the project timely and the issues related to the increase in the time of environmental laws was ranked first with a weight of 0.243.

#### 4.2.4 Results of FCM approach

This section of the research is based on qualitative findings. In this way, a  $5 \times 5$  matrix, whose rows and columns are formed by environmental risks in large industrial-construction engineering projects, was designed and provided to the sample members. Using a three-point spectrum

(-1, 0, and 1), the sample members measured the degree of valuing each component to the other and gave the components a scale. So that the scale of -1 means the opposite relationship, the scale of zero means no relationship, and the relationship of +1 means a positive relationship between the variables. After the questionnaires were collected, a  $5 \times 5$  matrix, which is the relationship matrix, was formed according to Table 12.

After the relationship matrix was drawn, each of the indices of influence capacity, influence power, and centrality were calculated for each of the components. The influence index indicates the sum of the input edges to each node (the sum of the column elements related to each node in the relationship matrix) (which here are the environmental risks C1, C2, and C3 with an influence capacity of 4, which have the highest influence capacity). The influence index indicates the degree of influence by a factor. In other words, it indicates the sum of the output edges from each node (the sum of the horizontal elements related to each node in the relationship matrix). Which here are the environmental risks C1, C3, C4, and C5 with an influence capacity of 4, which have the highest influence power. The sum of the previous two

**Table 11.** Final weights of factors.

Criterion name	Criterion code	Criterion weight	Rank
Environmental issues and problems	C1	0.1925	3
Climatic conditions	C2	0.1397	5
Over predicted increase in project time due to environmental laws	C3	0.2345	2
The conflict among several decision-making institutions from the perspective of climate and environmental issues	C4	0.1903	4
The risk of completing the project timely and related issues regarding the increase in the time of environmental laws	C5	0.2430	1

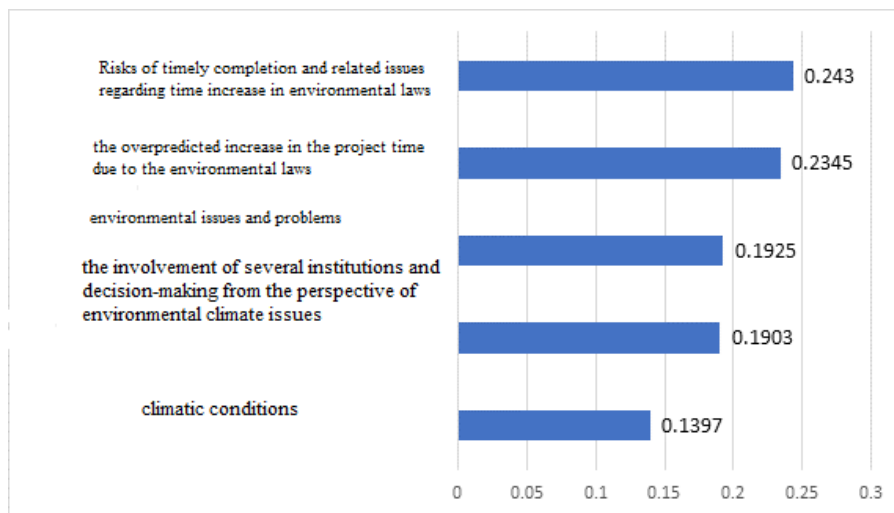


Figure 3. The final weight of the criteria.

factors is influence and influence, which is identified as the superiority index. Any factor with a higher degree of centrality actually has either a higher capacity for influence or a higher power of influence, which is therefore an important factor and should be given special attention. As shown in Table 12, risks C1, C3 and C5 have been identified due to their higher capacity for influence of 8. Table 13 shows an example of calculating the capacity for influence, power of influence and the pivotal index.

Therefore, based on the results obtained in Table 13, the simulated system dynamics model is designed and implemented in the next step to design long-term forecast scenarios.

#### 4.2.5 Results of system dynamic simulation approach

##### State-flow model of environmental risks

After selecting the risks in the environmental dimension through the Delphi technique, to obtain causal relationships using the DANP method, based on the experts' opinions, in figure 4 the state-flow model of risks from the perspective of environmental issues is depicted.

In this model, the risks of timely completion and related issues, especially the increase in time in environmental laws and environmental issues and problems, are part of the level variables. In figure 5, the behavior of environmental issues and problems is shown.

Climatic conditions, the risk of involvement of several decision-making institutions from the perspective of climate and environmental issues, and the risk of an over predicted increase in the project time given the environmental laws affect these two risks. Based on the model, these two risks will have an upward trend in 10 years. It increases by 10 units in these ten years. In figure 6, risks of timely completion and related issues regarding time increase in environmental laws is depicted.

#### 4.2.6 Scenario analysis

Experts believe that the involvement of several institutions and decision-making from the perspective of environmental climate issues is one of the most significant environmental risks affecting project completion. In figures 7 and 8 be-

Table 12. Effect of environment risk.

Environment risk	C1	C2	C3	C4	C5
Environmental issues and problems (C1)	1.00	-1.00	-1.00	1.00	1.00
Climatic conditions (C2)	0.00	-1.00	1.00	-1.00	1.00
Over predicted increase in project time due to environmental laws (C3)	-1.00	1.00	0.00	1.00	1.00
The conflict among several decision-making institutions from the perspective of climate and environmental issues (C4)	1.00	0.00	-1.00	0.00	-1.00
The risk of completing the project timely and related issues regarding the increase in the time of environmental laws (C5)	-1.00	1.00	1.00	-1.00	-1.00

Table 13. Results of out degree, in degree and centrality of concepts.

Concepts	Out degree	In degree	Centrality
C1	4.00	4.00	8.00
C2	4.00	3.00	7.00
C3	4.00	4.00	8.00
C4	3.00	4.00	7.00
C5	4.00	4.00	8.00

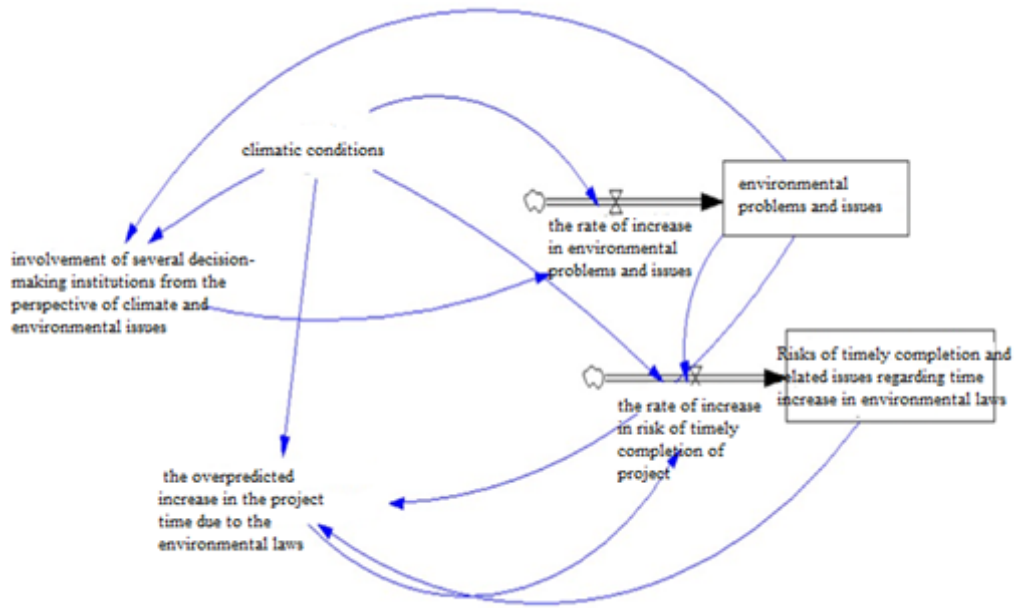


Figure 4. State-flow model of environmental risks.

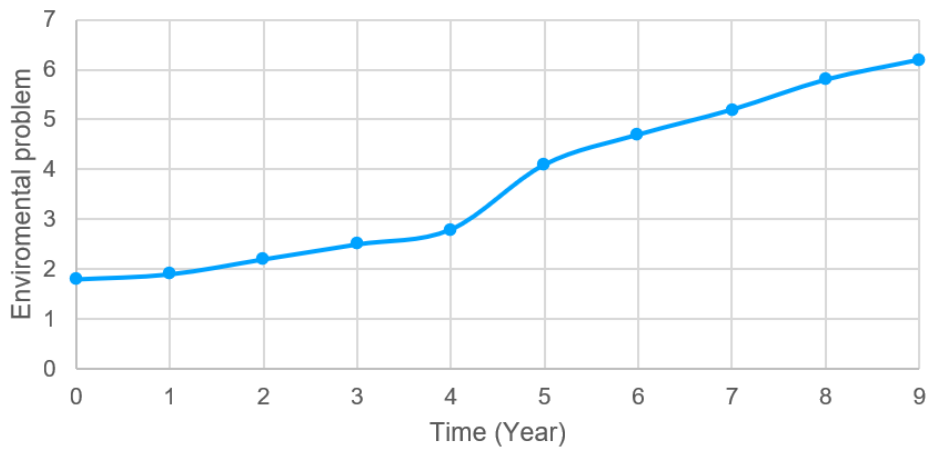


Figure 5. The behavior of environmental issues and problems.

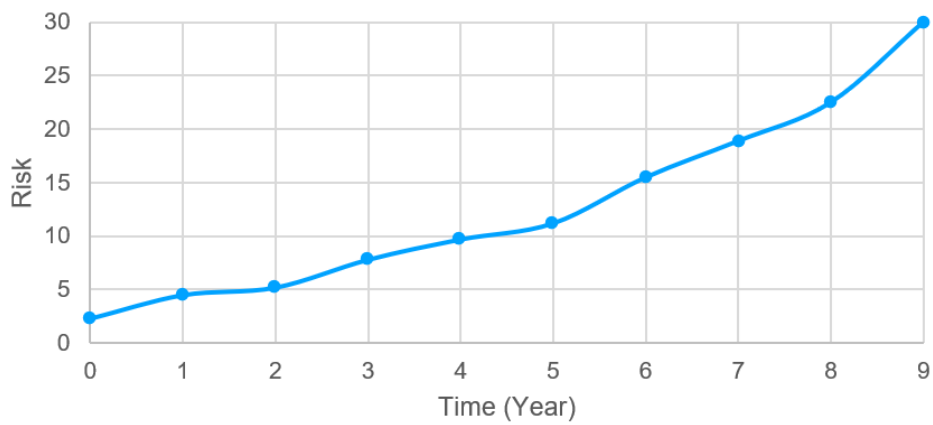
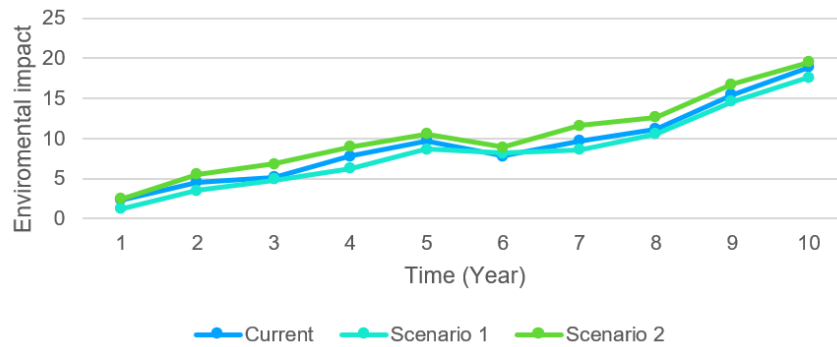
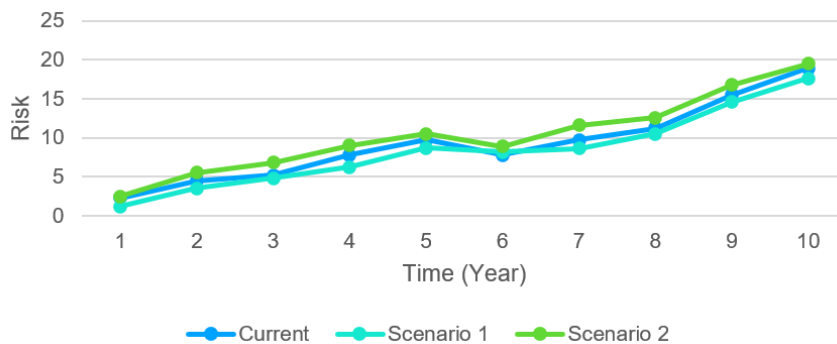


Figure 6. Risks of timely completion and related issues regarding time increase in environmental laws.



**Figure 7.** Scenario of environmental issues and problems.



**Figure 8.** The scenario of the risks of timely completion and related issues regarding the increase in time in environmental laws.

haviour of environmental scenario are shown.

This issue is because the risk of completing the project timely from an environmental perspective and environmental issues and problems is reduced by controlling and reducing this risk. Also, these two risks follow an increasing trend with the increase of the risk of conflict among several decision-making institutions from the perspective of climate and environmental issues.

As seen in the figure 8, the risk of involvement of several decision-making institutions from a climate and environmental perspective is directly associated with the two risks of environmental issues and problems and the risk of timely completion of the project. The institutions involved in the climate and environmental issues of the project can reduce the risk of timely completion of the project and environmental issues with mechanisms and memorandums that reduce the risk of conflict among them.

### 4.3 Managerial insights

The current study highlights a significant limitation in the current research landscape regarding the methodologies used for environmental risk assessment in megaprojects. It points out that most studies tend to concentrate on specific approaches, such as system dynamics, fuzzy cognitive mapping, or various multi-criteria decision-making (MCDM) techniques like Fuzzy Analytic Hierarchy Process (AHP), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Best-Worst Method (BWM), and COCOESO. Notable references include Seyedi et al. [28] for system dynamics and Koc et al. [25] and Khalilzadeh et al. [29] for MCDM approaches. The core argument is that

this tendency to treat these methodologies in isolation overlooks the potential advantages that could be gained from their integration. By failing to combine these approaches, researchers limit their capacity to effectively capture the intricate interactions and feedback loops that characterize megaproject environments. These interactions are essential for conducting a thorough risk assessment, as they reflect the dynamic nature of the projects and the complex relationships among various risk factors. Therefore, managers need to prioritize the identification of key environmental issues that may arise during the lifecycle of megaprojects. This includes assessing potential pollution, habitat destruction, and resource depletion. By utilizing fuzzy cognitive maps, decision-makers can visualize the relationships between various environmental factors and their impacts, enabling a more proactive approach to risk management. Also, Climatic conditions play a crucial role in the planning and execution of megaprojects. Managers should incorporate climate data into their risk assessment frameworks to understand how changing weather patterns may affect project timelines and costs. A system dynamics approach can help simulate different climatic scenarios and their potential impacts, allowing for better preparedness and adaptability in project planning. More over, Environmental regulations can lead to delays if not adequately anticipated. Managers should engage in thorough stakeholder consultations to understand the implications of environmental laws on project timelines. By integrating fuzzy cognitive mapping, they can assess the likelihood of regulatory changes and their potential impact on project schedules, enabling more accurate time predictions and contingency planning. Conflicts

among various decision-making institutions regarding environmental and climate issues can hinder project progress. Managers should foster collaboration and communication among stakeholders to align objectives and mitigate conflicts. Utilizing system dynamics can help model the interactions between different institutions and identify strategies for conflict resolution, ensuring that environmental concerns are addressed without compromising project timelines. The risk of delays due to environmental laws and climatic conditions necessitates a robust risk management strategy. Managers should develop flexible project schedules that account for potential environmental disruptions. By employing fuzzy cognitive maps, they can visualize the interdependencies between project activities and environmental risks, allowing for the identification of critical paths and alternative strategies to maintain timely completion. Finally, Environmental risks are dynamic and require ongoing monitoring. Managers should implement adaptive management practices that allow for real-time adjustments based on environmental assessments and stakeholder feedback. A system dynamics approach can facilitate continuous learning and adaptation, ensuring that environmental risks are effectively managed throughout the project lifecycle. According above mentioned, managerial insights for current research is important in various aspects:

1. **Developing Preventive Strategies:** By identifying environmental risks, managers can design preventive strategies that help reduce negative impacts on the environment. These strategies can include optimizing processes, selecting environmentally friendly materials, and improving waste management methods.
2. **Using New Technologies:** Using new technologies such as smart systems and analytical tools can help managers identify and assess risks. These tools can provide more accurate data and lead to better decision-making.
3. **Training and Empowering Employees:** Training employees in environmental risk management and the importance of environmental protection can help increase their awareness and responsibility. This, in turn, can lead to risk reduction and improved project performance.
4. **Collaborate with stakeholders:** Managers should collaborate with various stakeholders, including government, local communities, and non-governmental organizations. This collaboration can help to better identify risks and find common solutions to manage them.
5. **System Dynamics Analysis:** Using a system dynamics approach allows managers to analyze the long-term impacts of environmental risks on projects. This analysis can help identify weaknesses and opportunities for improvement in project processes.
6. **Develop risk management plans:** Based on the results of risk identification and assessment, managers should develop comprehensive risk management plans

that include the steps of identifying, assessing, responding, and monitoring risks.

7. **Continuous Monitoring and Evaluation:** Managers should establish a continuous monitoring and evaluation system for environmental risks so that they can continuously assess the impacts of risks and take necessary actions.

These insights can help managers manage industrial-construction projects more effectively and minimize environmental risks. Therefore, integrating system dynamics and fuzzy cognitive mapping provides valuable managerial insights for identifying and assessing environmental risks in industrial-construction engineering megaprojects. By addressing environmental issues, adapting to climatic conditions, and navigating institutional conflicts, managers can enhance decision-making processes and improve project outcomes in the face of complex environmental challenges.

## 5. Conclusion

Risk management during the project life cycle is one of the crucial tools to achieve success in projects. The goal of risk management is to identify as many risks as possible, find ways to manage the risks and identify the factors related to each of them. Effective risk management requires a proper understanding of project risks. This is beyond simply documenting risks and prioritizing them based on their likelihood of occurrence and impact on the project. Several risks created during the risk management process should be categorized in a way that allows for their proper identification. This article presents a method for analyzing and ranking risks in megaprojects, investigating cause-and-effect, and behavioral models based on systems dynamics using the DEMATEL and DANP methods. Thus, the factor of the risk of completing the project timely and the issues related to the increase in the time of environmental laws was ranked first, and the factor of the over predicted increase in the project time due to the environmental laws was ranked second, and the factor of environmental issues and problems was ranked third. Experts believe that the involvement of several institutions and decision-making from the perspective of environmental climate issues is one of the most significant environmental risks affecting project completion. This issue is because the risk of completing the project timely from an environmental perspective and environmental issues and problems is reduced by controlling and reducing this risk. Also, these two risks follow an increasing trend with the increase of the risk of conflict among several decision-making institutions from the perspective of climate and environmental issues. The risk of involvement of several decision-making institutions from a climate and environmental perspective is directly associated with the two risks of environmental issues and problems and the risk of timely completion of the project. The institutions involved in the climate and environmental issues of the project can reduce the risk of timely completion of the project and environmental issues with mechanisms and memorandums that reduce the risk of conflict between them.

**Authors contributions**

Authors have contributed equally in preparing and writing the manuscript.

**Availability of data and materials**

The data that support the findings of this study are available from the corresponding author upon reasonable request.

**Conflict of interests**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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