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Abstract

Purpose: Megaprojects are large-scale long-term investments. Three pillars of sustainable construction objectives, social, environmental, and economic, should be integrated into megaproject risk management to ensure their long-term success. A risk assessment method, RAMSCOM, was developed for this purpose.

Design/methodology/approach: RAMSCOM was developed based on the latest concepts and identifying relevant and critical sustainability objectives and risks through an extensive literature review. Analytical Hierarchy Process (AHP) and Cross-Impact Analysis (CIA) were used to determine and quantify the threats regarding the importance of the sustainability objectives. The applicability of RAMSCOM was demonstrated on a real megaproject.

Findings: The findings revealed that sustainability risk assessment requires integration of economic, environmental, social objectives, and analysis of cross-impacts of risk factors. Visualisation of interrelated threats, vulnerabilities and objectives has a potential to support risk mitigation decisions to achieve sustainability goals.

Research limitations/implications: The method has been developed based on the findings from a detailed literature survey on sustainability objectives and risks. RAMSCOM was tested on a single project with the assistance of three experts' views. Findings from the case project cannot be directly generalized for various megaprojects considering the unique nature of megaprojects.

Practical implications: Decision-makers can use RAMSCOM to assess sustainability risks in megaprojects and develop risk management plans for the most vulnerable and important sustainable objectives in a visual and quantified approach to ensure megaproject's sustainability in the long-term.

Originality/value: The theoretical contribution is a novel risk assessment method that integrates all dimensions of sustainability and quantifies the vulnerability of sustainability objectives considering their priorities, interrelations, and risks. Sustainability dimensions, objectives, and risks used in RAMSCOM can be useful for other researchers aiming to develop similar methods.

Keywords: Decision support systems, Megaprojects, Novel method, Performance, Project risk management, Sustainable construction

Paper type: Research paper

1. Introduction

The number of megaprojects has increased in recent decades due to rapid urbanization, globalization, and population growth. Consequently, megaprojects have become critical undertakings from the perspective of sustainability, considering their long-term impacts on the economy, environment, and society (Brookes and Locatelli, 2015). Nevertheless, megaprojects face challenges that create significant risks for sustainability objectives. Dikmen and Birgonul (2017) point out that risk assessment is generally performed considering the iron triangle (cost, schedule, quality), which gives limited scope for risk assessment of megaprojects with sustainability objectives. Atombo *et al.* (2015) emphasize that performance and risk assessment of megaprojects should be carried out by integrating economic, environmental, and social sustainability principles. Even though Sabini *et al.* (2019) express that there has been a rise in interest in sustainability and project management concepts from 1993 to 2017, Dikmen and Birgonul (2017) indicate that there are limited studies that include sustainability within the context of project risk management in the construction industry. Javed *et al.* (2020) emphasise the research gap regarding implementing project risk management in the context of green buildings. Qazi *et al.* (2021) also highlight the necessity to enhance risk methods to assess and manage sustainability risks in construction projects.

It is anticipated that decision-makers involved in mega construction projects should be able to analyse the threats to sustainable construction objectives in the earlier stages of the megaproject and take necessary actions. To facilitate this, in this study, we aim to integrate sustainable construction objectives and risk management concepts to develop a framework and a quantification method to analyse risks in mega construction projects. The steps of the method development process, namely RAMSCOM (Risk Assessment Method for Sustainable Construction Objectives in Megaprojects) will be explained in the forthcoming parts of this paper and its utilisation will be demonstrated by a real megaproject.

2. Research Background

The term sustainable construction, introduced in the construction sector by Kibert in 1994, is defined as creating a healthy living space using efficient and ecologically based principles (Udomsap and Hallinger, 2020). Athapaththu and Karunasena (2018) specify sustainable construction as the implementation of sustainable development principles into the whole construction cycle from the extraction and beneficiation of raw materials, through the planning, design, and construction of buildings and infrastructure, until their final deconstruction and management of the resultant waste. Qazi *et al.* (2021) underline the importance of integrating sustainability in the construction sector. Furthermore, Sourani and Sohail (2005) state that sustainable construction should incorporate at least three dimensions which are social, economic, and environmental. Hussin *et al.* (2013), Kim and Park (2013), and Atombo *et al.* (2015) handle sustainable construction dimensions in terms of economic, social, and environmental aspects, while some authors like Hill and Bowen (1997) and Enhassi *et al.* (2016) mention technical sustainability in addition to the other dimensions of sustainable construction.

Wang *et al.* (2020) pinpoint the importance of achieving sustainable construction objectives through megaprojects. Megaprojects are often classified as projects that cost more than a billion dollars. Alternatively, the size of a project can be evaluated in relation to the Gross Domestic Product (GDP) of the country, which can be an appropriate indicator, especially for underdeveloped and developing countries. Thus, the 0.01% of the country's GDP can be considered a cost threshold value for the megaprojects (Damayanti *et al.*, 2021). As megaprojects are large-scale and complex ventures that take many years to develop and construct, and include multiple public and private stakeholders, the significant impacts of megaprojects on sustainability objectives are inevitable (Flyvbjerg, 2014). Various authors mention the megaprojects' economic, environmental, and social impacts. For instance, Hosseini *et al.* (2018) state that approximately $57 trillion will be reserved for megaprojects worldwide, and two-thirds of this amount will come from developing countries. According to Goel (2019), the resource-intensive nature of the expanding-built environment may lead to the deterioration of the ecosystem of more than 70 percent of the earth's surface by 2032. Murtagh *et al.* (2020) point out the construction sector as one of the environmentally damaging sectors. Phelan and Dawes (2013) point out that megaprojects significantly affect communities due to displacement, resettlement, change in access to productive resources, and loss of livelihood opportunities.

The complex and unique nature of megaprojects may cause sustainable construction objectives to expose to more threats throughout the project life cycle. Within the project management context, risks are defined as uncertain future events or conditions which may cause negative or positive impacts on projects (PMI, 2017). Risk management is a process that identifies and assesses the project risks and suggests action plans to deal with the threat to the project (Mhetre *et al.*, 2016). Risk assessment is a crucial step in risk management to control uncertainties

(Nguyen *et al.*, 2023). The identified risks can be assessed by qualitative (risk matrices, failure mode and effect analysis, etc.) and quantitative (probabilistic methods, decision trees, etc.) methods (Qazi *et al.*, 2020). As an illustration, Alashwal and Chew (2017) utilized a simulation technique, Monte Carlo simulation, to model uncertainties regarding the cost estimation of construction projects. Furthermore, Heravi *et al.* (2022) conducted a probabilistic assessment of deep excavation projects' time and cost with the contribution of Bayesian belief networks (BBNs), fuzzy comprehensive analysis, and Monte Carlo simulation.

Although there are several studies that propose risk assessment methods for estimating project budget and duration, there are limited studies integrate risk assessment methods into a sustainability perspective. For instance, Qazi *et al.* (2021) prioritized risks influencing sustainability in international construction projects by Monte Carlo simulation. In another study, El-Sayegh *et al.* (2018) used a subjective risk rating method to rank the top five risks in sustainable construction projects in the United Arab Emirates. There is a gap in the literature on sustainability risk assessment methods integrating different dimensions of sustainability and risk impacts, which is the main motivation for this research study.

3. Research Objective and Methodology

In this study, we aim to develop a sustainability risk assessment method that takes into account of priorities of different dimensions of sustainability, risk factors and their interrelations. For this purpose first, a comprehensive literature survey was conducted to identify sustainability objectives and risks. Using the factors found from the literature, we developed a quantification method which is capable of assessing priorities, interrelations and cross-impacts. The proposed method, RAMSCOM (Risk Assessment Method for Sustainable Construction Objectives in Megaprojects) was applied to a real case project.

The selected megaproject for the implementation process of RAMSCOM is a hospital project with a capacity of 1000+ beds in an area of around 250.000 m^2. The project is in Turkey. The construction of the megaproject started in 2013 and was completed in 2020. The contract is based on FIDIC Red Book, and the payment type is the unit price. The contract price of the megaproject is around 400 million TL (approximately 0.02 % of the country's GDP). The data presented in the testing of RAMSCOM has been collected based on three volunteer experts' statements from different parties of the megaproject. The first expert is the client of this project, who has a BSc degree in civil engineering and more than twenty years of experience in the construction industry. The second expert is the contractor of the project, who has an MSc degree in civil engineering and more than ten years of experience in construction sites. The third expert is the architect of the project, who has a BSc degree in architecture and more than five years in construction design firms.

In the forthcoming parts of this paper, first, the findings from the literature survey on sustainability objectives and risks will be depicted as they form the basis of RAMSCOM. Then, the model development process will be explained using the data from the case project.

4. Sustainable Construction Objectives and Risks

A comprehensive literature review was performed to identify sustainable construction objectives and risks for megaprojects. Sustainable construction objectives were identified considering the time interval from 1994 (when sustainable construction first was introduced by Kibert) to 2023 in the Google Scholar database. The keywords for the initial screening were utilized as “sustainable construction objectives” or “sustainability objectives” and 17.800 publications were listed under the construction management field. Among the initial screening findings, a total of 45 papers cited more than ten times on average or relevance of the publication title were filtered, then nine papers referred specifically to one or more sustainable construction dimensions were selected to identify sustainable construction objectives for this study. Literature survey findings demonstrate that sustainable construction dimensions are usually categorized in terms of economic, environmental, and social aspects. Notwithstanding, there can be some dimensions categorized under more than one category; thus, it is hypothesized that categories such as economic-environmental, environmental-social, or economic-social are more relevant to organize these dimensions. Therefore, sustainable construction dimensions are divided into six main groups for the development of the proposed method, and a coding system is defined for the objectives. The identified sustainable construction dimensions and objectives utilized in the proposed method are presented in Table I.

Table I. Sustainable construction dimensions and objectives

Sustainable Construction Dimensions	ID	Code	Sustainable Construction Objectives	A	B	C	D	E	F	G	H	I
Economic Sustainability	1	EC-SO_1	Feasibility and financial affordability of the megaproject	*								
	2	EC-SO_2	Optimized long term economic value							*		
	3	EC-SO_3	Effective project management and management of resources				*					
Economic-Environmentally Sustainability	4	EC-EN-SO_1	Energy efficiency for all phases of the megaproject						*			
	5	EC-EN-SO_2	Utilization of local materials and supplies				*				*	
	6	EC-EN-SO_3	Reduction, reuse and recycling of the materials	*	*		*	*				
	7	EC-EN-SO_4	Optimization of site layout				*					
Environmentally Sustainability	8	EN-SO_1	Reduction of emissions, wastes, pollutants and noise	*	*	*	*	*	*	*	*	
	9	EN-SO_2	Choice of environmentally friendly materials and products	*	*		*	*				
	10	EN-SO_3	Natural resource conversation and preference of renewable resources							*	*	
	11	EN-SO_4	Enhancing biodiversity	*			*			*		
Environmentally-Social Sustainability	12	EN-S-SO_1	Preservation of cultural identity and reducing the impact on heritage due to the megaproject			*					*	
	13	EN-S-SO_2	Minimizing local nuisance and disruption				*					
	14	EN-S-SO_3	Providing a healthy and safety environment for all phases of the MCP				*					
Social Sustainability	15	S-SO_1	Delivering services that enhance the local environment		*							*
	16	S-SO_2	Provision of equal opportunities	*	*						*	*
	17	S-SO_3	Enhancing quality of life and providing customer and employee satisfaction	*	*		*	*		*		*
Economic-Social Sustainability	18	EC-S-SO_1	Supporting local economies		*							*
	19	EC-S-SO_2	Providing equal employment creation		*		*				*	*
	20	EC-S-SO_3	Zero defects policy				*					

References:
A: Hill and Bowen (1997), B: Sourani and Sohail (2005), C: Bragança *et al.* (2010), D: Akadiri *et al.* (2012), E: Hussin *et al.* (2013), F: Kim and Park (2013), G: Atombo *et al.* (2015), H: Enhassi *et al.* (2016), I: Fatourehchi and Zarghami (2020)

Risk factors that could be potential threats to achieving sustainability objectives for megaprojects were determined from the Google Scholar database considering the rise of interest in those concepts in the last decade (2010-2023). The initial search was performed considering the keywords “megaproject risks” or “sustainability risks”, and 5.180 publications were listed based on those keywords. Thereafter, publications cited more than 30 times were focused on among the initial screen findings. A total of ten papers were analysed based on the comprehensiveness and relevance of the publications for this study. In total, 38 risk factors that can threaten the achievement of sustainable construction objectives are identified through the literature review and classified under nine categories considering their risk types. The code numbers are assigned based on their risk categories. The risk factors for the proposed method have been presented in Table II.

Table II. Risk factors for megaprojects and sustainable construction objectives

Category	ID	Code	Risk Factors	A	B	C	D	E	F	G	H	I	J
Financial	1	FRF_1	Exchange rate fluctuation	*	*	*	*			*	*	*	
	2	FRF_2	Change in inflation rate	*	*	*	*			*	*	*	
	3	FRF_3	Change in interest rates	*	*	*	*			*	*	*	
	4	FRF_4	Change in taxation policies	*						*			
Policy and Law	5	$PLRF_1$	Instable political environment	*	*	*	*			*		*	
	6	$PLRF_2$	Emergence of civil strife, war and terrorism issues	*	*	*							
	7	$PLRF_3$	Difficulty in getting permits due to bureaucracy	*		*	*			*	*	*	
	8	$PLRF_4$	Vagueness of policies and regulations								*	*	
	9	$PLRF_5$	Change in laws and regulations	*	*	*	*			*		*	
Society	10	SRF_1	Public reaction towards the project (strike, rebellion etc.)			*	*			*	*		
	11	SRF_2	Vagueness of the needs of the community		*	*		*	*				
Physical	12	PRF_1	Unforeseen weather conditions	*	*	*				*			
	13	PRF_2	Unexpected physical conditions	*	*	*				*			
Technical	14	TRF_1	Design team's lack of experience on sustainable construction principles								*	*	
	15	TRF_2	Complexity of design	*		*	*			*		*	

	16	TRF_3	Low constructability			*				*		*	
	17	TRF_4	Inaccurate or incomplete design drawings	*	*	*	*						
	18	TRF_5	Changes in amount of work due to defective work, rework or poor quality of construction	*	*	*	*			*	*	*	
	19	TRF_6	Low productivity									*	
	20	TRF_7	Unavailability of labour		*	*							
	21	TRF_8	Unavailability of sub-contractor				*						
	22	TRF_9	Unavailability of construction materials							*	*	*	
	23	TRF_{10}	Defective construction materials										*
	24	TRF_{11}	Technology								*		
	25	TRF_{12}	Problems with the construction site	*		*				*	*	*	
Organizational and Managerial	26	$OMRF_1$	Inaccurate cost, time and resource allocation estimation	*	*	*	*			*	*	*	
	27	$OMRF_2$	Inexperienced or non-competitive contractor	*			*				*	*	
	28	$OMRF_3$	Lack of organization and coordination among project stakeholders		*	*				*			
	29	$OMRF_4$	Lack of audits on occupational health and safety procedures		*	*		*	*		*		
Client	30	$CLRF_1$	Client's reluctant attitude towards sustainable construction					*	*		*	*	
	31	$CLRF_2$	Client's lack of knowledge about sustainable construction					*	*		*	*	
	32	$CLRF_3$	Undocumented bill off quantities or change orders		*	*							
	33	$CLRF_4$	Inadequate funding or delay in progress payments		*	*	*				*		
Contractual	34	CRF_1	Ill-defined scope of the work and contract specification		*	*	*			*	*	*	
	35	CRF_2	Contractual dispute resolution process							*			
	36	CRF_3	Inappropriate contract type, project delivery system and bidding type	*	*	*							
Environmental	37	ERF_1	Ineffective waste management							*	*	*	
	38	ERF_2	No audits for poor waste management								*	*	

References:
A: Little (2011), B: Irimia-Diéguez *et al.* (2014), C: Sanchez-Cazorla *et al.* (2016), D: Park *et al.* (2016), E: Banihashemi *et al.* (2017), F: Hosseini *et al.* (2018), G: Chen *et al.* (2019), H: Javed *et al.* (2020), I: Qazi *et al.* (2021), J: Nguyen *et al.* (2022)

5. Development of RAMSCOM

This section presents the development and implementation of the risk assessment method RAMSCOM on the case project in three main steps. In each step, the methodology utilized for the development of RAMSCOM is described as well as demonstrating the implementation of the proposed method based on the experts' statements employed in a real megaproject.

The first step elaborates on the quantification process of the sustainable construction objectives to determine the importance of the objectives through the Analytical Hierarchy Process (AHP). AHP has been chosen for the prioritization process of sustainable construction objectives since it is a multicriteria decision-making method that allows pairwise comparisons among alternatives hierarchically (Gilani *et al.*, 2022). The second step assesses the expected influence values of the risk factors on the sustainable construction objectives by Cross-Impact Analysis (CIA). CIA has been utilized to determine the expected influence values of the risk factors, considering its effectiveness in analysing the factors' impact on future project decisions (Alarcón and Ashley, 1998). The third step visualises the overall findings regarding the outputs obtained from the first and second steps.

5.1 Step 1: Prioritization of Sustainable Construction Objectives

Sustainable construction objectives within the scope of a megaproject may differ from one megaproject to another due to the unique nature of the megaprojects. Therefore, it is important to prioritize the sustainable construction objectives of a megaproject, considering the project characteristics and expectations from the project. Prioritization of objectives is necessary to assess risks depending on their impacts on several objectives. AHP is one of the most common multi-criteria decision-making methods (MCDM) that enable pairwise comparisons among multiple factors (Santos *et al.*, 2019). Implementing AHP is simple while offering a high level of consistent results with a smaller data size (Darko *et al.*, 2019). According to Behl *et al.* (2023), the results obtained from the AHP are better than other MCDM methods such as ANP, ELECTRE and TOPSIS. AHP can quantify and establish decision makers' opinions, and address the decision problem in a rational and organized way (Han *et al.*, 2023). The decision problem, the main decision criteria, and alternatives to the decision problems are presented at the level of hierarchies, and the factors in each level are compared in pairwise comparison matrices. The best alternative regarding the decision problem is determined based on the weights obtained from each level (Yap *et al.*, 2019). For instance, Ugwu and Haupt (2007) identified key performance indicators for computing sustainability index in infrastructure projects by the "weighted sum model" technique in multi-criteria decision analysis (MCDA) and the "additive utility model" technique in AHP. Figueiredo *et al.* (2021) proposed a decision-making framework to address subjectivity, uncertainty, and ambiguity problems in choosing sustainable construction materials based on Fuzzy-AHP. In the AHP method, the best alternative is selected by assigning input values to the pairwise comparison matrices based on the experts' views. According to Saaty and Özdemir (2014), the number of experts shall not exceed 7 or 8 due to the consistency limits of the matrices. Additionally, they even argue that one expert can be sufficient if the expert has both knowledge and practical experience about the selection criteria. Furthermore, Erol *et al.* (2022) also underline the experiences of the experts as more important than the number of experts. There are several studies obtained the findings from comparison matrices with a limited number of experts such as three professionals (Dikmen *et al.*, 2010), three experts (Yu *et al.*, 2010), four decision-makers (Ennaceur *et al.*, 2017), five experts (Kil *et al.*, 2016).

Prioritization of the sustainable construction objectives is performed by AHP, taking into account the multiple sustainable construction objectives potentially having different levels of importance considering the expectations of project stakeholders in this study. The hierarchical relationship between sustainable construction objectives is structured, and codes are assigned to the related category in the literature review section previously. In this part, pairwise comparison matrices among sustainable construction objectives are constructed for the first and second levels of hierarchies using the numerical scale from 1 (equal significance of the two elements) to 9 (absolute dominance of one element over another) with an integer increment. Then, global weights for the sustainable construction dimensions (first-level hierarchy) and local weights for the sustainable construction objectives (second-level hierarchy) in the corresponding hierarchy can be estimated considering the consistency of the matrix. Finally, global weights for each sub-factor among other sustainable construction objectives can be calculated by multiplication of the local weight and the global weight of the related category.

The implementation process of the first step is carried out as follows. The experts assigned values to the first and second levels of pairwise comparison matrices considering the numerical scale from 1 to 9. Each expert filled a total of seven pairwise comparison matrices. Consistency ratios for seven matrices were checked, and the ratios were found as less than 10%, wherefore matrices were consistent based on the numerical values assigned by the experts. The global weight for each sustainable construction dimension and local weight for each sustainable construction objective is calculated individually considering the experts' statements. The local and global importance weights presented in Table III are the percentages of the mean values obtained from each expert.

Table III. Local and global importance weights for the sustainable construction objectives

ID	Code	Local Weight	Global Weight
1	$EC\text{-}SO_1$	26.06%	4.34%
2	$EC\text{-}SO_2$	63.35%	10.56%
3	$EC\text{-}SO_3$	10.59%	1.77%
4	$EC\text{-}EN\text{-}SO_1$	62.21%	10.37%
5	$EC\text{-}EN\text{-}SO_2$	8.68%	1.45%
6	$EC\text{-}EN\text{-}SO_3$	22.23%	3.70%
7	$EC\text{-}EN\text{-}SO_4$	6.88%	1.15%
8	$EN\text{-}SO_1$	45.00%	7.50%
9	$EN\text{-}SO_2$	45.00%	7.50%
10	$EN\text{-}SO_3$	5.00%	0.83%
11	$EN\text{-}SO_4$	5.00%	0.83%
12	$EN\text{-}S\text{-}SO_1$	7.14%	1.19%
13	$EN\text{-}S\text{-}SO_2$	74.82%	12.47%
14	$EN\text{-}S\text{-}SO_3$	18.04%	3.01%
15	$S\text{-}SO_1$	24.31%	4.05%
16	$S\text{-}SO_2$	8.82%	1.47%
17	$S\text{-}SO_3$	66.87%	11.14%
18	$EC\text{-}S\text{-}SO_1$	60.00%	10.00%
19	$EC\text{-}S\text{-}SO_2$	20.00%	3.33%
20	$EC\text{-}S\text{-}SO_3$	20.00%	3.33%

5.2 Step 2: Risk Assessment of Sustainable Construction Objectives

Each construction project objective exposes to threats, so it is critical to determine and evaluate the threats to the objectives. Risk matrices based on probability and impact rating are traditional methods still utilized in construction management and decision-makers (Qazi *et al.*, 2020). CIA is a risk assessment method that enables determining the relationships between events and dealing with future uncertainties (Salo *et al.*, 2022). He and Chen (2021) determined the most influential critical factors for implementing sustainable construction projects in environmentally fragile regions with the contribution of cross-impact matrix multiplication. Kuru (2015) suggested CIA as an alternative way of qualitative data analysis of the repertory grid technique to construct a hierarchy of the factors to assess the importance of the factors more visually. In that study, two characteristics of the cross-impact factors obtained from the impact values assigned for each factor are mentioned. Active sum refers to the sums of each row of the impact matrix, which indicate the level of effect on other factors. The passive sum represents the sums of each column of the impact matrix that demonstrate the level of being affected by other factors.

The risk assessment of sustainable construction objectives for the proposed method is performed by integrating the probability-impact matrix into CIA. First, the cross-impact matrix has been constructed by placing identified sustainable construction objectives on the horizontal axis and identified risk factors on the vertical axis. Secondly, the cross-impact of each risk factor on each sustainable construction objective shall be assigned considering the numerical scale from 0 (no impact) to 5 (very high impact), considering an integer increment. The dependency values for each sustainable construction objective can be calculated by the sum of each column, and the influence values of each risk factor can be calculated by the sum of each row based on the assigned cross-impact values of the risk factors. Third, the probability of occurrences of each risk factor shall be determined according to the probability scale from 0 (rare) to 1 (almost certain), considering a 0.1 decimal increment.

Finally, the expected dependency values for each sustainable construction objective and the expected influence values for each risk factor can be calculated by multiplication of the cross-impact values and probability values of each risk factor. Expected dependency values for each sustainable construction objective are calculated by the sum of each column which represents the level of being affected by the risk factors. Expected influence values for each risk factor are calculated by the sum of each row which refers to the level of effect on sustainable construction objectives.

In the testing process of the proposed method, experts determine the cross-impact values on each sustainable construction objective by considering the cross-impact scale from 0 to 5, as well as the initial probability of occurrence for each risk factor based on the probability scale between 0 and 1. The finalized results obtained from the assignment of the cross-impact and probability values are calculated considering the mean values of each parameter assigned by each expert. The results of this process will be presented in the following step.

5.3 Step 3: Visualization of the Overall Findings

Two outputs can be obtained from the RAMSCOM based on the values assigned by the experts. The first one is the vulnerability chart that enables observing the level of dependency of the sustainable construction objectives regarding their importance. The chart's horizontal axis represents the weights of the sustainable construction objectives obtained from AHP pairwise comparison matrices. Expected dependency values obtained from CIA are on the chart's vertical axis. This chart defines each sustainable construction objective by its global weight and expected dependency value. The vulnerability chart is divided into four dependency regions to visualize the dependency levels of the sustainable construction objectives. The regions are determined with the contribution of a probability-impact matrix based on the cross-impact values and probability values. The constituted probability-impact matrix is demonstrated in Table IV, and each risk factor is categorized considering values obtained from the matrix as low (0.00-0.60), medium (0.61-1.20), high (1.21-2.99) and critical (3.00-5.00).

Table IV. Probability-impact matrix

Impact

Probability

	1	2	3	4	5
0.2	0.2	0.4	0.6	0.8	1.0
0.4	0.4	0.8	1.2	1.6	2.0
0.6	0.6	1.2	1.8	2.4	3.0
0.8	0.8	1.6	2.4	3.2	4.0
1.0	1.0	2.0	3.0	4.0	5.0

The intervals for dependency regions are determined by considering all risk factors. The results obtained from the probability-impact matrix (Table IV) are multiplied by the total number of the identified risk factors, which is provided in Table II. As a consequence, dependency regions are obtained as low (7.60-22.80), medium (22.81-45.60), high (45.61-91.20), and critical (91.21-190.00). Dependency regions for the vulnerability chart represent the level being affected by the sustainable construction objectives by the risk factors.

The vulnerability chart with dependency regions based on the information provided above is presented in Figure 1.

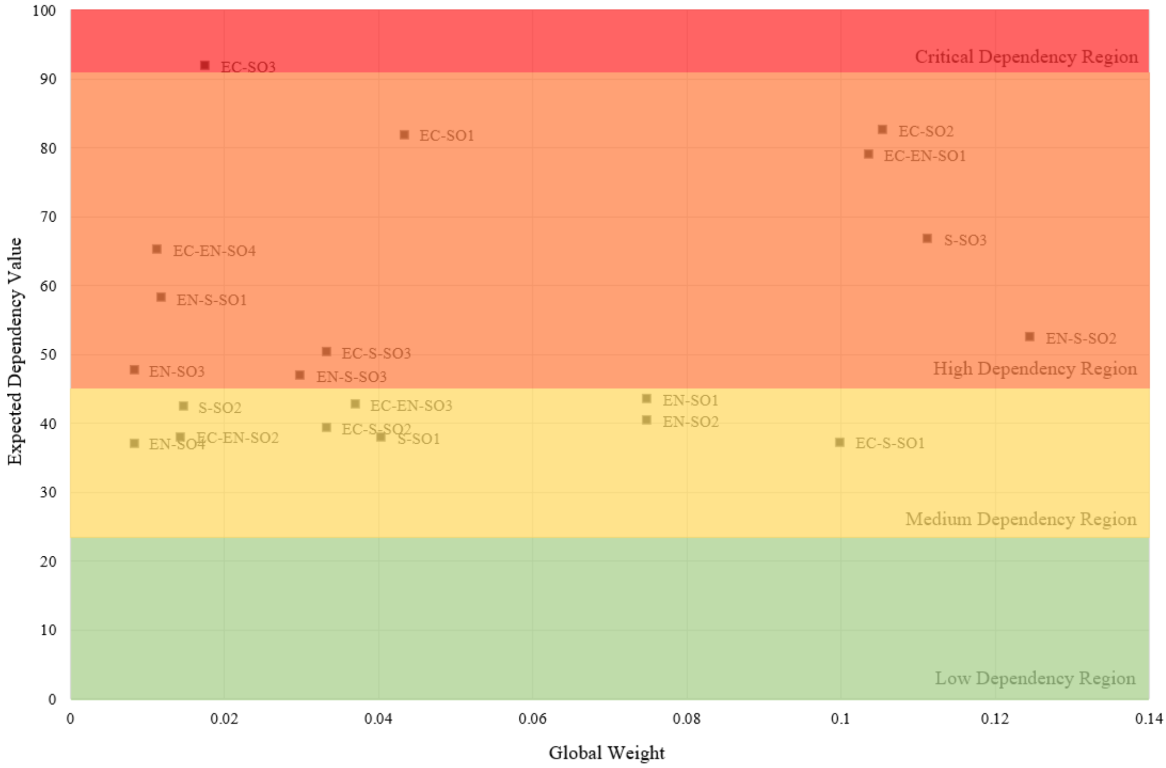

Figure 1. Vulnerability chart

The heat map is the second output, enabling risk monitoring and control for sustainable construction objectives. It is generated by multiplying the mean cross-impact values of each risk factor on the sustainable construction objectives and the mean initial probability of occurrence values of the risk factors obtained from the experts. The expected dependency value of each sustainable construction objective can be analysed by tracking the individual contribution of each risk factor from the heat map. There are four colours in the heat map, and each colour represents the risk categories for each risk factor based on the multiplication of probability and cross-impact values. The intervals for the risk categories are determined considering the values provided in Table IV. Thus, each risk factor can be analysed independently, considering their risk categories and types that directly affect the achievement of the sustainable construction objectives can be monitored and controlled by the utilization of four coloured heat map.

The heat map includes the average initial probability of occurrences of the risk factors, the average expected dependency values of the sustainable construction objectives, and the average expected influence values with the risk factors provided in Table V.

Table V. Heat map

				Initial Probability of Occurence	Sustainable Construction Objectives																				Expected Influence Value
					Economic			Economic-Environmental				Environmental				Environmental-Social			Social			Economic-Social			
					1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
					EC-SO$_1$	EC-SO$_2$	EC-SO$_3$	EC-EN-SO$_1$	EC-EN-SO$_2$	EC-EN-SO$_3$	EC-EN-SO$_4$	EN-SO$_1$	EN-SO$_2$	EN-SO$_3$	EN-SO$_4$	EN-S-SO$_1$	EN-S-SO$_2$	EN-S-SO$_3$	S-SO$_1$	S-SO$_2$	S-SO$_3$	EC-S-SO$_1$	EC-S-SO$_2$	EC-S-SO$_3$	
Risk Factors	F	1	FRF$_1$	0.90	4.50	4.50	3.60	2.70	0.00	0.00	2.70	0.00	1.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.80	1.80	2.70	0.00	26.10
		2	FRF$_2$	0.90	4.50	4.50	3.60	2.70	0.00	0.00	2.70	0.00	1.80	0.00	0.00	0.00	0.00	0.00	0.00	0.90	2.70	2.70	3.60	0.00	29.70
		3	FRF$_3$	0.90	2.70	3.60	3.60	2.70	0.00	0.00	2.70	0.00	1.80	0.00	0.00	0.00	0.00	0.00	1.80	1.80	3.60	1.80	2.70	0.00	28.80
		4	FRF$_4$	0.70	2.10	2.10	1.40	2.10	0.00	0.00	2.10	0.00	1.40	0.00	0.00	0.00	0.00	0.00	1.40	1.40	2.10	2.10	2.10	0.00	20.30
	PL	5	PLRF$_1$	0.80	4.00	4.00	4.00	1.60	1.60	0.00	1.60	0.00	0.00	1.60	1.60	4.00	0.00	0.00	2.40	2.40	2.40	0.00	1.60	0.00	32.80
		6	PLRF$_2$	0.40	1.60	1.60	2.00	0.80	1.20	0.40	1.20	1.60	0.00	0.80	0.80	2.00	2.00	2.00	1.60	1.20	2.00	1.20	1.20	0.80	26.00
		7	PLRF$_3$	0.80	1.60	2.40	4.00	2.40	0.00	0.00	4.00	0.00	0.00	0.80	0.00	4.00	1.60	1.60	0.00	0.00	0.00	0.00	0.00	0.00	22.40
		8	PLRF$_4$	0.40	1.20	1.20	2.00	2.00	1.20	1.60	1.60	2.00	2.00	2.00	2.00	2.00	1.60	2.00	0.80	0.80	1.20	0.80	1.60	1.20	30.80
		9	PLRF$_5$	0.50	1.50	2.00	1.50	2.50	1.00	1.00	2.00	2.50	2.50	2.50	2.50	2.50	2.00	2.50	1.00	1.00	1.50	1.00	2.00	1.50	36.50
	S	10	SRF$_1$	0.20	0.60	0.40	1.00	0.60	0.00	0.00	0.60	0.00	0.00	0.00	0.00	0.00	1.00	1.00	0.00	0.00	0.60	0.00	0.00	0.20	6.00
		11	SRF$_2$	0.20	0.20	0.40	0.60	0.40	0.60	0.60	1.00	1.00	0.80	0.80	0.40	0.80	0.80	0.80	1.00	1.00	1.00	0.80	1.00	0.00	14.00
	P	12	PRF$_1$	0.50	1.50	2.00	1.50	2.00	1.00	0.50	2.00	1.00	1.00	1.50	1.00	2.00	1.00	1.00	2.00	1.00	1.00	1.50	1.00	1.50	27.00
		13	PRF$_2$	0.85	3.40	3.40	4.25	3.40	1.70	0.00	4.25	2.55	0.00	2.55	1.70	4.25	3.40	3.40	0.85	1.70	2.55	0.85	0.00	2.55	46.75
	T	14	TRF$_1$	0.10	0.40	0.40	0.40	0.50	0.40	0.40	0.30	0.20	0.50	0.50	0.40	0.50	0.10	0.20	0.30	0.30	0.30	0.30	0.10	0.30	6.80
		15	TRF$_2$	0.90	3.60	2.70	3.60	2.70	2.70	2.70	3.60	2.70	2.70	1.80	1.80	2.70	3.60	1.80	0.00	0.00	1.80	0.00	1.80	3.60	45.90
		16	TRF$_3$	0.70	3.50	2.10	3.50	3.50	2.10	2.10	1.40	0.70	0.70	0.70	0.00	0.70	2.10	1.40	0.70	2.10	2.10	0.00	0.00	2.80	32.20
		17	TRF$_4$	0.40	1.60	1.60	2.00	2.00	2.00	1.60	1.60	0.80	2.00	1.20	1.20	1.60	0.00	0.80	0.80	0.80	1.60	0.00	0.80	2.00	26.00
		18	TRF$_5$	0.70	3.50	3.50	3.50	2.80	0.70	2.10	1.40	2.10	0.00	2.10	0.70	2.10	2.10	1.40	0.70	0.00	2.10	0.00	0.00	3.50	34.30
		19	TRF$_6$	0.70	2.80	2.10	3.50	2.80	0.70	0.70	2.10	0.00	0.00	2.10	0.00	0.00	1.40	0.70	2.80	3.50	0.00	0.00	0.00	2.10	27.30
		20	TRF$_7$	0.10	0.30	0.20	0.40	0.50	0.40	0.00	0.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.20	0.30	0.40	0.40	0.30	0.20	4.10
		21	TRF$_8$	0.20	0.60	0.40	0.80	0.80	1.00	0.00	0.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.40	0.60	0.60	0.80	0.60	0.40	7.80
		22	TRF$_9$	0.60	1.80	1.80	1.80	1.80	3.00	2.40	2.40	2.40	3.00	2.40	0.00	1.80	0.60	1.20	1.80	1.20	0.60	1.80	0.00	1.20	33.00
		23	TRF$_{10}$	0.80	3.20	2.40	4.00	2.40	1.60	2.40	0.00	0.00	2.40	1.60	0.00	0.00	3.20	3.20	0.00	0.00	2.40	0.00	0.00	4.00	32.80
		24	TRF$_{11}$	0.80	4.00	3.20	4.00	3.20	1.60	2.40	2.40	3.20	1.60	2.40	2.40	2.40	2.40	2.40	0.80	0.80	2.40	1.60	1.60	4.00	48.80
		25	TRF$_{12}$	0.80	4.00	4.00	3.20	4.00	3.20	1.60	4.00	1.60	0.00	2.40	2.40	4.00	4.00	2.40	2.40	2.40	1.60	2.40	1.60	1.60	52.80
	OM	26	OMRF$_1$	0.80	4.00	4.00	4.00	4.00	2.40	3.20	2.40	1.60	1.60	1.60	1.60	0.00	2.40	1.60	2.40	4.00	3.20	1.60	2.40	2.40	50.40
		27	OMRF$_2$	0.70	3.50	2.10	3.50	2.80	0.70	1.40	2.10	1.40	0.70	2.10	2.10	2.10	3.50	2.10	1.40	2.80	2.10	1.40	1.40	3.50	42.70
		28	OMRF$_3$	0.60	2.40	1.80	3.00	3.00	0.00	2.40	3.00	1.80	1.80	1.20	1.20	1.80	1.20	1.20	0.00	0.00	1.20	1.20	1.20	2.40	31.80
		29	OMRF$_4$	0.40	1.20	1.20	2.00	1.20	0.00	0.00	1.20	1.60	0.00	0.00	0.80	1.20	2.00	2.00	0.00	0.00	2.00	0.40	0.00	1.20	18.00
	CL	30	CLRF$_1$	0.30	1.50	1.50	1.20	1.20	1.20	1.50	0.90	1.50	1.50	1.50	1.50	1.50	0.60	0.60	0.90	0.90	1.20	1.50	1.50	0.00	23.70
		31	CLRF$_2$	0.30	0.90	1.20	0.90	0.90	1.20	0.90	0.60	0.60	0.90	0.90	1.50	1.50	0.60	0.60	0.60	0.60	0.30	0.60	0.90	0.30	16.50
		32	CLRF$_3$	0.80	4.00	2.40	4.00	1.60	0.00	2.40	1.60	0.80	0.80	0.00	0.00	1.60	0.00	0.00	0.00	2.40	4.00	2.40	2.40	3.20	33.60
		33	CLRF$_4$	0.40	2.00	1.60	2.00	1.20	0.00	1.20	1.60	1.20	1.20	1.20	0.00	1.20	0.00	0.00	1.20	1.20	2.00	0.80	0.40	1.60	21.60
	C	34	CRF$_1$	0.20	0.80	1.00	1.00	1.00	1.00	1.00	0.80	0.60	1.00	1.00	1.00	1.00	0.60	0.60	0.80	1.00	1.00	0.80	0.80	1.00	17.80
		35	CRF$_2$	0.60	1.80	1.80	3.00	1.80	0.00	0.00	1.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.40	1.20	1.20	1.20	15.60
		36	CRF$_3$	0.20	1.00	1.00	1.00	1.00	0.60	0.60	0.80	0.00	0.00	0.40	0.40	0.80	0.60	0.40	0.40	1.00	1.00	1.00	0.80	0.00	12.80
	E	37	ERF$_1$	0.80	0.00	3.20	2.40	4.00	1.60	4.00	0.00	4.00	2.40	4.00	4.00	4.00	4.00	4.00	3.20	0.00	4.00	1.60	0.00	0.00	50.40
		38	ERF$_2$	0.80	0.00	3.20	0.00	2.40	1.60	1.60	0.00	4.00	2.40	4.00	4.00	4.00	4.00	4.00	3.20	3.20	4.00	0.80	0.00	0.00	46.40
Expected Dependency Value					81.80	82.50	91.75	79.00	38.00	42.70	65.15	43.45	40.30	47.65	37.00	58.05	52.40	46.90	37.85	42.30	66.75	37.15	39.30	50.25	

It can be summarized as the vulnerability chart (Figure 1) enables the experts to guide to examine and analyse the sustainable construction objectives in terms of their importance and vulnerability level, whereas the heat map (Table V) enables to track and analyse the threats for the achievement of the objectives beforehand. Correspondingly, RAMSCOM assists in foreseeing the probable country and project-related threats on the project objectives and taking action plans to minimize the effect of threats in advance. Interpretation of findings and experts' opinions are given under the forthcoming section on the discussion of case study findings.

6. Discussion of Case Study Findings

Decision-makers can use RAMSCOM to give risk-based decisions. For the vulnerability chart (Figure 1), critical and high-dependency regions encompass the most vulnerable sustainable construction objectives that may prevent achieving a sustainable outcome from the megaproject. Among the most vulnerable sustainable construction objectives, the major contributors to achieving a sustainable outcome from the megaproject can be determined by the higher global weight value, so it is essential to track the critical risk factors individually on the objectives with higher global weights. Considering both the expected dependency value and global weight of the objective EN-S-SO_2 (Minimizing local nuisance and disruption), the case megaproject will be more prone to fail the overall project sustainability objective if critical risks are not mitigated on that objective.

The vulnerability of the sustainable construction objectives is calculated by the sum of the expected influence value of each risk factor from the heat map given in Table V. Since the expected influence value of the risk factors is obtained from the multiplication of initial probability of occurrence and cross-impact value of the risk factors, it is essential to control those two parameters in order to reduce the expected dependency value of the most vulnerable sustainable construction objectives. As mitigation of the risks on EN-S-SO_2 (Minimizing local nuisance and disruption) plays a significant role in achieving a sustainable outcome, critical risks can be tracked from the heat map given Table V. There are seven critical risk factors (PRF_2 (Unexpected physical conditions), TFR_2 (Complexity of design), TRF_{10} (Defective construction materials), TRF_{12} (Problems with the construction site), $OMRF_2$ (Inexperienced or non-competitive contractor), ERF_1 (Ineffective waste management) and ERF_2 (No audits for poor waste management)) that affect the level of the expected dependency level of this objective directly. In this sense, the vulnerability level of EN-S-SO_2 (Minimizing local nuisance and disruption) can be decreased by focusing on the probability of the occurrence of critical risk factors. For instance, a comprehensive site visit can be held to foresee the possible future problems due to the megaproject in advance. Since the megaproject was constructed in the city center, it is important to take active construction noise management plans to improve the workplace and surrounding conditions (Mir *et al.*, 2022). Besides, the construction waste problems can be addressed by enforcing strict waste audits (Hill *et al.*, 2023).

When the outputs from the proposed method were discussed with the experts involved in the case project, it was evident that visual outputs were useful for the formulation of strategies and developing risk mitigation plans. On the other hand, implementing the proposed risk assessment method has some shortcomings. For example, the proposed method can be time-consuming. At the beginning of the interview, experts were informed about the proposed method. Then, experts assigned numerical values to the pairwise comparison matrices and risk factors. Finally, outputs were created manually based on the values assigned by experts, and the results were discussed with each expert. The whole process took approximately 1.5 hours. Implementing the proposed risk assessment should be optimized to obtain faster and more reliable results.

7. Novelty of This Study and RAMSCOM

The novelty of this study and the proposed method can be summarised as follows:

- Achievement of a sustainable outcome is crucial, especially for megaprojects considering their long-term impacts on the economy, environment, and society. For this purpose, RAMSCOM is developed to assess and mitigate threats to sustainability objectives. The scope of RAMSCOM is presently developed for superstructure projects that cost more than a billion dollars or 0.01% of the country's GDP. It is believed that sustainability dimensions, objectives, and risks used in RAMSCOM can be helpful for other researchers aiming to develop similar models/methods. The objectives and factors defined in RAMSCOM can be modified and customised according to different types of projects and their specific priorities.
- Previous research on construction mega project risk assessment mainly concentrates on project time, cost, and quality aspects (Dorfeshan *et al*. (2022)), or generalizes sustainability risks without taken account the megaproject characteristics (Okoye *et al*. (2022)). The main methodological contribution of this study is that it integrates a sustainability perspective into the project risk management process and proposes a quantitative method for showing a long-term picture of project performance rather than traditional performance indicators based on cost, time, and quality.

- Recent studies in the literature generally scrutinize sustainability risks in megaprojects by focusing on one dimension of sustainability (Tang *et al.* (2022), Lu *et al.* (2023)). The proposed method, RAMSCOM, differs from the other risk assessment methods in the literature since it addresses sustainable construction objectives in six main dimensions of sustainability (economic, economic-environmental, environmental, environmental-social social, economic-social), and considers risk factors' impacts on sustainability objectives by taking into account their priorities and cross-impacts.
- RAMSCOM combines two prevailing risk assessment approaches, AHP and CIA, to present a widescale interpretation of the sustainable project objectives, and it quantifies the vulnerability of sustainable construction objectives based on two parameters simultaneously; priority and dependency. This is a methodological novelty which can be used by other researchers while developing similar risk assessment methods for different purposes.
- Megaprojects involve various stakeholders with different concerns regarding the project outcomes (Travaglini *et al.*, 2016), so it is important to retain effective communication to evade undesirable project failures (Li *et al.*, 2018). In this sense, RAMSCOM can guide construction practitioners from various parties (client, contractor, designer, subcontractor) to assess and visualize relationships among sustainability objectives and risk factors, easily track the most vulnerable sustainable objectives in advance, and develop risk mitigation plans, which is one of the practical contributions of this study.

8. Concluding Remarks and Limitations

The main contribution of this study is that it facilitates decision-making processes regarding the sustainable construction of megaprojects. In this study, sustainable construction objectives are associated with the risk factors to foresee the possible threats to the objectives and develop action plans by focusing on the importance of project objectives. As the primary aim of the proposed method is to assess and mitigate threats to the sustainability objectives, the proposed method addresses all types of construction megaprojects regardless of the green building certification criteria. Although the proposed method endeavours to integrate the sustainability concept into the risk management field and provides decision support for decision-makers regarding managing vulnerability and risk, applying the proposed method in a real project revealed that the implementation process could be time-consuming and ineffective without assistance.

Moreover, there are some methodological limitations. The proposed method prioritises sustainable construction objectives by AHP, considering the numerical scale from 1 to 9 where numerical values are assigned by the experts making the prioritisation process subjective. For the CIA, only the initial probability of occurrences of the risk factors has been considered in the proposed method. However, the cross-impact of the risk factors should have been analysed under different scenarios like conditional occurrence and conditional non-occurrence of the risk factors. There are also limitations regarding the generalizability of findings. Three experts from different parties determined the values for the prioritization and risk assessment of sustainability objectives. The obtained results based on the experts' opinions are not generic, so the findings from the case project may not be applicable to the assessment of sustainability risks in other megaprojects.

As a further study, the proposed method can be developed as a decision-support system with a more user-friendly interface. With this decision-support system, awareness about the sustainability concept among construction practitioners can be increased, and they may be encouraged to integrate a sustainability perspective by mitigating threats to ensure long-term sustainability of megaprojects. Further studies are needed to validate the added value of a decision support system based on RAMSCOM for developing risk mitigation plans on sustainability objectives in mega construction projects.

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