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A Multi-Criteria Prioritization Framework (MCPF) to Assess Infrastructure Sustainability Objectives and Prioritize Damaged Infrastructure Assets in Developing Countries

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Abstract

This paper presents a Multi-Criteria Prioritization Framework (MCPF) that can assist decision-makers and government administrators in identifying and ranking infrastructure sustainability objectives in developing countries. The framework also helps governments of developing countries in assessing the priority of repair of damaged infrastructure assets, based on significant sustainability objectives. A Template of infrastructure sustainability objectives is developed through literature review and interviews with key experts. A questionnaire-based survey solicits experts' opinions to rate the sustainability objectives based on their relative importance to the public, using a five-point Likert rating scale. The quality of experts participating in the rating process is determined using the pair-wise comparison method of the analytical hierarchical process (AHP) that calculates a crisp importance weight value of each expert, based on his or her qualification criteria. The relative importance index (RII) method is adapted to prioritize the sustainability objectives, which integrates the rating scores assigned by experts and their relative importance weight factors. A crisp facility sustainability priority index (FSPI) is computed using a survey-based approach and a weighted sum technique in multi-criteria decision analysis that determines the priority of repair of damaged infrastructure facilities, based on significant sustainability objectives. In order to test the applicability of the prioritization framework, a case study is applied in Egypt to demonstrate how the model can assist governments of developing countries in prioritizing damaged infrastructure assets that need urgent repairs. The prioritization framework presented in this paper offers a simple yet efficient evaluation technique to decision-makers with limited budgets that accounts for sustainability objectives in deciding on the repair priorities of damaged facilities.

Keywords: infrastructure, sustainability, multi-criteria decision analysis

1. Introduction

In general, infrastructure assets, such as transportation and communications systems, water and power lines, and public services buildings provide the means for any society to survive. According to the World Bank Group (2008), infrastructure assets are the most critical components for the sustainable development of emerging countries, as they provide their communities with the necessary conditions to reach their economic, social, and environmental goals. Infrastructure assets are also fundamental to mitigate the effects of both natural and man-made catastrophic events. This is particularly important given the continuing growth of the global population and the global patterns of the migration of people (Cleveland, 2008). Similar to other types of facilities, infrastructure assets are subjected to deterioration, either due to aging or due to external sources of damage, such as fire, theft, or flooding that may necessitate conducting urgent repairs. As such, governments of developing countries are in need of a framework that can help them maintaining and restoring these facilities in the case of damage. However, damaged facilities do not necessarily share the same level of importance to the public welfare (Elbarkouky et al., 2012). Thus, the priority of repair should be given to the infrastructure facilities that most fit the strategic objectives of the decision-maker and the public, especially at times when decision-makers do not have enough budgets to perform the required repair. The same concept applies to constructing new infrastructure facilities in developing countries.

As a general rule, there is a group of factors that may impact the process of assigning priorities to the damaged infrastructure facilities. In contrast to the factors that can be easily quantified, such as the cost of repair, some factors are subjective in nature and cannot be easily assessed, such as safety, heritage, and renewable energy (Elbarkouky et al., 2012). Those factors are also referred to as "sustainability indicators" (Ugwu et al., 2006) that should be set as the basis for deciding on the priority of repair of any damaged infrastructure asset. However, the multidimensional perspectives of sustainability, such as economy, society, and environment (Ugwu & Haupt, 2007), and lack of sustainability research work in several developing countries may require the involvement of experts in the prioritization process of damaged facilities, which should be based on significant sustainability objectives to the citizens of those countries.

As such, this paper presents a prioritization framework that is based on expert judgment and multi-criteria decision analysis, which is capable of prioritizing damaged infrastructure assets that accounts for the significant sustainability objectives to the public welfare in developing countries. The major objectives of this paper can be summarized as follows:

1) To develop a template of infrastructure sustainability objectives that can be applied to developing countries.

2) To present a prioritization technique capable of identifying and ranking significant infrastructure sustainability objectives based on their relative importance to key decision-makers in developing countries.

3) To incorporate the quality of experts (Elbarkouky & Fayek, 2009; 2011) in the prioritization process, using the pair-wise comparison method of the analytical hierarchical process (AHP).

4) To consolidate the above objectives in a comprehensive multi-criteria prioritization framework (MCPF) that aids developing countries in prioritizing substantially damaged facilities based on their alignment degrees with significant infrastructure sustainability objectives.

2. Literature Review

The first definition of sustainability was given by the report from the Bruntland Commission, formally known as the World Commission on Environment and Development (WCED) in 1987 (Cleveland, 2008). In this report, sustainable development was defined as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*." Roseland (1998) summarized sustainable development as "*different kind of development…..that must be a proactive strategy to develop sustainability*", which contains at least three essential components: environmental considerations, equity, and qualitative and quantitative improvements. However, it was not until recently when the concept of sustainable development has been widely used in various applications of the construction industry, such as building construction and infrastructure projects. For example, Fernández-Sánchez and Rodríguez-López (2010), who defined sustainability as "*an opportunity for improvement*", presented several examples of different sustainable development applications in the construction industry.

Gibson (2002) described the concept of sustainability in terms of seven principles: integrity, sufficiency and opportunity, equity, efficiency, democracy and civility, precaution and adaptation, and necessity for creating a broad and holistic interpretation of sustainability. The latter principle has been also supported by Ugwu et al. (2006) who developed a "holistic approach" to assess the sustainability of infrastructure projects at the various stages of a project life cycle. They developed sustainability indicators at the project level, and applied a multi-criteria decision-making (MCDM) model combined with the analytical hierarchy approach (AHP) to determine the priorities of infrastructure sustainability indicators to Africans. A three pillar approach: economical, societal, and environmental was adopted by Ugwu et al. (2006) in categorizing their proposed sustainability indicators. This approach is arguably the most popular approach in defining sustainable development (Goodland, 1995). However, a historical sustainability definition that was previously presented by Robinson, Francis, Legge, and Lerner (1990) included three additional pillars: political, institutional, and cultural. According to Rosenthal (2004), a problem with the pillar approach lies in the "*entrenchment of categories according to academic disciplines, implying competing objectives across various dimensions of human-ecological interests*" (Gibson, 2002). However, the pillar approach is valuable in that it provides a basic overview of important sustainability considerations, yet it is limited in integrating the different components of sustainability (Rosenthal, 2004).

In South Africa, Ugwa and Haupt (2007) added health and safety, resource utilization, and project management to the pillars of infrastructure sustainability. They further emphasized that "*the governments of developing countries are in need of a large number of infrastructure projects to encourage the economic growth of their countries and solve the problems of poverty and overpopulation through the strengthening of local institutions, and utilization of the capacities of their citizens*" (Elbarkouky et al., 2012). They also developed a generic

sustainable breakdown structure and prioritized infrastructure sustainability key indicators using an expert judgment matrix. They collected the data through questionnaires, using a five-point Likert (1931) scale, and applied a weighted sum technique in MCDM to aggregate the results numerically.

Similar to Ugwa and Haupt (2007), Lim and Yang (2009) identified critical sustainability criteria and indicators, using a Delphi study. However, the study was only concerned with Australian road infrastructure projects. The major contribution of that study was that it paved the way for further identification of solutions for each critical indicator, which can allow for developing consistent approaches to the sustainability strategy in road and highway infrastructure projects. Cleveland (2008) presented some examples of infrastructure assets that can benefit from the pillars concept, such as roads, bridges, rail and transit facilities, factories, communications networks, power generation facilities, residential and commercial buildings, airports, government buildings, schools, military bases, hospitals, electric and gas utilities, water and wastewater facilities, and pipelines. Specific studies of the various divisions of construction sustainability in developing countries were conducted by other researchers, such as Talukhaba et al. (2005), who incorporated socioeconomic sustainability criteria in the planning stage of a construction project; and Dalgleish et al. (1997), who studied the impact of environmental sustainability on the delivery of affordable housing in South Africa.

Researchers are continuously investigating new infrastructure sustainability indicators and establishing new methodologies that can be applied to infrastructure construction projects. For example, Fernández-Sánchez and Rodríguez-López (2010) discussed the need to establish a methodology to identify sustainability indicators from the project management point of view. They stated that "*there is no norm or standard model of identification of sustainability indicators that follows a technical-scientific methodology, except that a project is proven to be sustainable when it improves in the previously discussed triple bottom-line dimensions*" (Elbarkouky et al., 2012); an argument that has been scrutinized by Bell and Morse (2008) in their research study "*Sustainability Indicators, Measuring the Immeasurable?*"

Fernández-Sánchez and Rodríguez-López (2010) utilized the AHP method in MCDM to identify and prioritize sustainability indicators for infrastructure projects in Spain. They presented a procedure that considered sustainability indicators as positive risks during the project life cycle to obtain societal, economical, and environmental benefits. They also ranked infrastructure sustainability indicators, based on the Pareto principle that infers that "*80% of sustainability objectives could be represented by 20% of the identified sustainability indicators*." They recommended the analysis of lessons learned from previous projects to discover new sustainability objectives in construction projects and urban planning.

3. Detailed Steps of the Multi-Criteria Prioritization Framework (MCPF)

This paper utilizes the weighted sum technique of the multi-criteria decision analysis (Ugwu & Haupt, 2007) combined with the analytical hierarchical process (AHP) (Saaty, 1980) to develop Multi-criteria Prioritization Framework (MCPF) that computes a facility sustainability priority index (FSPI)—a crisp value for prioritizing damaged facilities in developing countries, based on significant sustainability objectives. The research utilizes a methodology that has been adapted from Elbarkouky et al. (2012) in prioritizing damaged infrastructure facilities for developing countries, and it tests the applicability of the framework, using a case study in Egypt that extends the results of pilot surveys that was previously conducted by Elbarkouky et al. (2012).

The weighted sum technique is used to calculate the *FSPI* because it is the most "*widely used*" and "*practically proven*" technique in MCDM analytical models for quantifying sustainability objectives (Ugwu et al., 2006; Elbarkouky et al., 2012), which sets a good mathematical base for the research at hand. The pair-wise comparison method of the AHP is used to determine the importance weights of experts because it is an "*efficient and practical technique*" that can "*resolve conflicts between a set of similar alternatives*" (Elbarkouky et al., 2012), which was previously applied by Fernández-Sánchez and Rodríguez-López (2010) to resolve a similar problem. Figure 1 illustrates the steps used in developing the Multi-criteria Prioritization Framework (MCPF), which is discussed in details in the following sections.

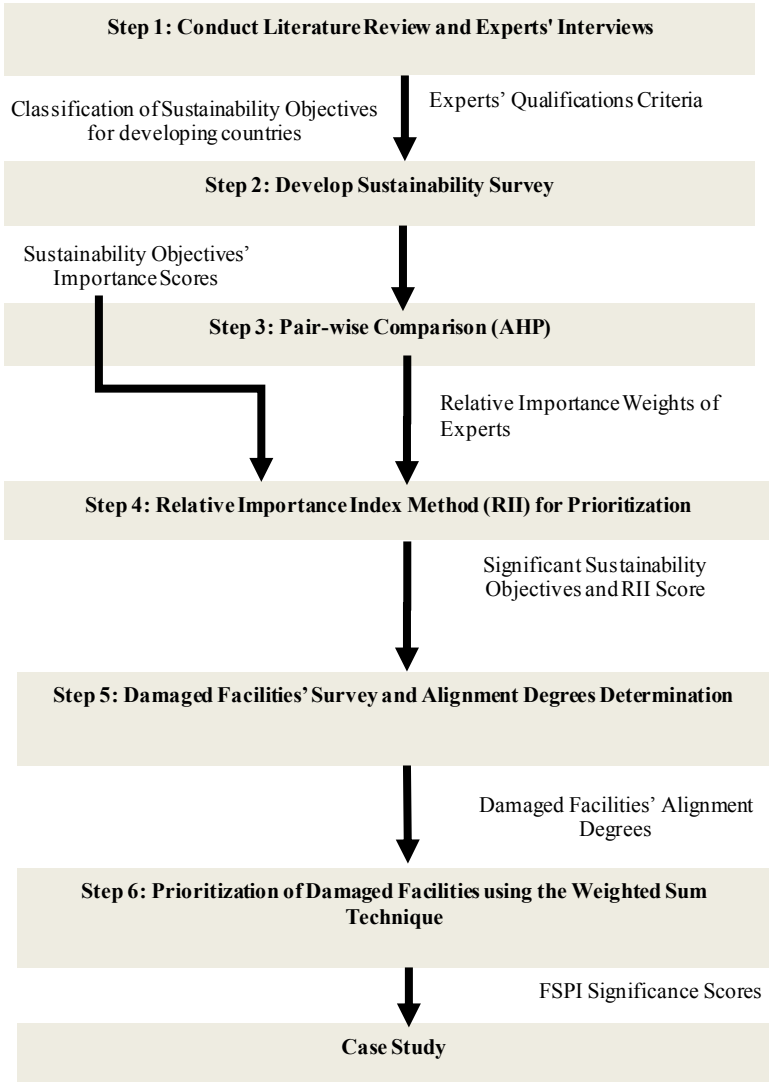

Figure 1. Multi-criteria Prioritization Framework (MCPF)

3.1 Conduct Literature Review and Experts' Interviews to Identify and Classify Sustainability Objectives

Based on the the work previously conducted by Fernández-Sánchez and Rodríguez-López (2010), Ugwu et al. (2006), Ugwu and Haupt (2007), and Elbarkouky et al. (2012), a list of sustainability indicators was prepared that simplified the classification of the factors into three criteria: economical, societal, and environmental. Then, structured interviews with experts resulted in modifying, amending, or eliminating some of these indicators to accommodate the requirements of developing countries. Then, the contexts of the indicators were modified to clearly emphasize the positive sustainability objectives that would result from applying each indicator; and to enable the experts to rate the sustainability objectives according to their level of importance to the public.

Table 1. Illustrates the template of the modified sustainability objectives

Environmental	Societal	Economical
E1: Reducing energy consumption	S1: Enhancing public safety and health	C1: Reflecting urgency of work (duration)
E2: Enhancing waste management	S2: Maximizing economical/ heritage benefits	C2: Reducing life cycle cost
E3: Widening ecological footprint	S3: Demonstrating public interest	C3: Minimizing material consumption
E4: Reducing CO_2 emissions	S4: Permitting public participation	C4: Motivating design for disassembly
E5: Encouraging renewable energy use	S5: Protecting human rights	C5: Reducing extent of traffic blockage
E6: Protecting water resources	S6: Respecting local customs	C6: Encouraging strategic management
E7: Mitigating disasters (earthquakes, floods)		C7: Encouraging tourism
E8: Controlling climate change		C8: Acquiring innovative elements
E9: Enhancing environmental management		C9: Reducing costs incurred to users
E10: Raising the ecological value of soil		C10: Allowing use of regional/local resources
E11: Minimizing noise pollution		C11: Possessing functional flexibility
E12: Minimizing visual impact		C12: Increasing environmental economic values

3.2 Develop Sustainability Survey

After developing the infrastructure sustainability template, a survey-based questionnaire is designed to help experts in ranking each sustainability objective based on its relative importance to the public, using a five-point Likert (1931) scale. The scale ranged between (1) Very Low Importance and (5) Very High Importance, while the term (3) Medium Importance was placed as a midterm value on the scale. Also, the questionnaire included a section that enquired about experts' demographic data that defined five qualification criteria of experts: (Q1) Type of Organization, (Q2) Position in the Organization, (Q3) Years of Experience, (Q4) Academic Qualifications, and (Q5) Involvement in Sustainability-Driven Projects. The key experts also assigned subjective weights (g) to the attributes of each quality criterion that ranged between 0 and 1, as illustrated in brackets in Table 2. The subjective weight (g) determines the significance of each attribute in computing the relative importance weight factor of each expert. For example, for the criterion (Q2) Position in the Organization, the higher the position of a given expert is, the higher the significance of his or her qualifications are on the value of his or her relative importance weight factor. The questionnaires can be distributed using a combination of internal circulation through contact persons, fax, and by email.

Table 2. Qualifications criteria and their respective weights as proposed by experts, adapted (Elbarkouky et al., 2012)

(Q1) Type of Organization	(Q3) Years of Experience
Owner (1.0)	>20 Years (1.0)
Consultant (0.8)	15-20 Years (0.8)
Contractor (0.4)	10-15 Years (0.6)
(Q2) Position in the Organization	5-10 Years (0.4)
Prinicipal (1.0)	<5 Years (0.2)
PM (0.9)	(Q4) Academic Qualifications
Designer (0.8)	Ph.D. (1.0)
CM (0.7)	MSc. (0.8)
Tech. Manager (0.6)	BSc. (0.6)
HSE Manager (0.5)	Diploma (0.4)
Senior Engineer (0.4)	(Q5) Involvement in Sustainability-Driven Projects
Estimator (0.3)	Yes (1.0)
Engineer (0.2)	No (0.5)

* The weights of the attributes (g) of each criterion are illustrated between brackets

3.3 AHP Approach to Calculate Experts' Importance Weight Factor

The analytical hierarchical process (AHP) in MCDM (Saaty, 1980) was utilized in this step to compute the relative importance weight factor (wi) of the experts, based on the weights of their respective qualifications. The AHP approach was implemented because "*it is a simple and widely used approach in MCDM that allows subjective and objective assessments of multiple factors, while offering a systematic thinking environment*" (Elbarkouky et al., 2012).

Four specialists in the field of human resource management and recruitment in three different developing countries (Egypt, Iran, and Turkey) helped conducting the pair-wise comparison method to determine the relative importance weight (r_k) of each of the five qualification criteria. A five-point preference scale was introduced to the experts to rank the factors relative to each other, using a standard preference matrix. The cardinality values of the scale ranged between (1) Equal Preference and (5) Extremely Preferred. The terms: (2) Slightly Preferred, (3) Preferred, and (4) Very Much Preferred were used as intermediate values. Table 3 illustrates the values computed using the n^{th} root method (Saaty, 1980) that has been utilized to compute the eigenvector elements of the matrix that represents the average ratings of the four experts, where n is the number of rows or columns of the matrix.

Table 3. Values of the eigenvectors of the AHP method

Criteria	(Q1)	(Q2)	(Q3)	(Q4)	(Q5)	nth root of product	Eigenvector
(Q1)	1.000	3.500	0.286	0.286	0.250	0.590	0.096
(Q2)	0.333	1.000	0.400	0.400	0.250	0.422	0.069
(Q3)	3.500	2.500	1.000	0.400	0.333	1.031	0.168
(Q4)	3.500	2.500	2.500	1.000	0.500	1.614	0.262
(Q5)	4.000	4.000	3.000	2.000	1.000	2.491	0.405
Total						6.148	1

This method takes the n^{th} root of the product of the entries in each row of the matrix. The n^{th} roots are summed and that sum is used to normalize the eigenvector elements to add to 1.000, using Equation 1.

$$rk = Rk / \sum_{k=1}^{n} Rk \quad (1)$$

Where r_k is an element of the eigenvector that represents the relative importance weight of a given criteria (k), R_k is the n^{th} root of product of each criteria, and n is the number of criteria in the matrix. For example, the 5th root for the first row is $R_1 = 0.590$, which is divided by the sum of the n^{th} roots (6.148) to give 0.096 that is the first element in the eigenvector that denotes the relative importance weight (r_1) of the criteria (Q_1) Type of Organization.

The elements of the eigenvector shown in Table 3 illustrate that the criteria (Q_5) Involvement in Sustainability-Driven Projects is assigned the highest relative importance weight by the expert ($r_5 = 0.405$), followed by (Q_4) Academic Qualifications ($r_4 = 0.262$), (Q_3) Years of Experience ($r_3 = 0.168$), (Q_1) Type of Organization ($r_1 = 0.096$), and (Q_2) Position in the Organization ($r_2 = 0.069$).

Finally, the consistency ratio (CR) (Saaty, 1980) is computed, which is designed so that the values of the ratio exceeding 0.1 are indicative of inconsistent judgments. This ratio can support the decision-maker so he or she can judge the level of consistency in the experts' judgment and reach a more reliable analysis.

In order to compute the consistency ratio, the maximum eigenvector (δmax) is first calculated, which is given by multiplying on the right the matrix of judgments by the eigenvector, obtaining a new vector. For example, the calculation for the first row in the matrix is show in Equation 2.

$$1.000*0.096+3.500*0.069+0.286*0.168+0.286*0.262+0.250*0.405 = 0.560 \quad (2)$$

The remaining four rows give 0.374, 0.915, 1.392 and 2.092. This vector of five elements (0.560, 0.374, 0.915, 1.392, 2.092) can now get the five estimates of (δmax) by dividing each component of (0.560, 0.374, 0.915, 1.392, and 2.092) by the corresponding eigenvector elements in Table 3 (0.096, 0.069, 0.168, 0.262, and 0.405). This gives 0.560/0.096=5.833 together with 5.420, 5.446, 5.312, and 5.165, approximately. The mean of these values is 5.435 and that would be the average estimate of (δmax). If any of the individual estimates of (δmax) turns out to be less than n (or 5 in this case), there has been an error in the calculation, which is a useful sanity check for the matrix calculations. The consistency index is then computed based on the formulae illustrated in Equation 3.

$$C1 = (\delta max - n)/(n-1) \quad (3)$$

Where CI is the consistency index of the matrix, (δmax) is the maximum eigenvector, and n is the number of criteria in the matrix. Equation 4 illustrates the calculation of the CI that gives a CI of 0.108.

$$C1 = (5.435 - 5)/4 = 0.108 \quad (4)$$

Then, the consistence ratio (CR) is calculated (Equation 5) by dividing the consistency index by a random consistency index (RI). The RI is the random index representing the consistency of a randomly generated pairwise comparison matrix. It is derived as average random consistency index calculated from a sample of 500 of randomly generated matrices based on the AHP scale, which is equal to 1.120 for the case of 5 criteria (Saaty, 1980).

$$CR = CI / RI = 0.108 / 1.120 = 0.097 \quad (5)$$

The consistency ratio (CR) of the matrix is computed as 0.097, which is less than 0.1 that signifies that the expert judgment was consistent.

Finally, in order to calculate the relative importance weight factor (w_i) of an expert (i), the subjective weights (g_i) of his or her attribute values are multiplied by the relative importance weights (r_k) of each respective criterion and the sum of the products is normalized to determine w_i, which ranges between 0 and 1. For example, the importance weight (W_i) of a project manager (0.900) who works in a consultant's office (0.800) who has a Ph.D. (1.000) and more than 20 years of experience in the construction industry (1.000) and has adequate number of years of experience in sustainability driven projects (1.000), could be calculated using Equation 6.

$$W_i = \sum gj \bullet rk \quad (6)$$

Where g_j is the subjective weight of his individual attributes (j) and r_k is the relative importance weight of each respective criterion. Equation 7 illustrates the calculations of W_i of that expert.

$$W_i = 0.800x0.096+0.900x0.069+1.000x0.168+1.000x0.262+1.000x0.405 = 0.973 \quad (7)$$

This value is normalized within the W_i values of any set of experts participating in the evaluation process of sustainability objectives to give a relative importance weight value w_i of each of these experts.

3.4 Relative Importance Index Method to Prioritize the Sustainability Objectives

In this step, the relative importance index (RII) (Kometa et al., 1994, and Sambasivan & Soon, 2007) is adapted to determine the relative importance of each sustainability objective (*j*) (Equation 8).

$$RIIj = \sum_{i=1}^{n} y_j w_i / z \quad (8)$$

Where, y_i is the rating score assigned to each sustainability objective (*j*) by each expert (*i*) on the Likert scale from 1 to 5, w_i is the relative importance weight factor (w_i) of the expert (*i*), and *z* is the highest possible rating value of the Likert scale, which is 5 in this case. The *RII* value has a range between 0 to 1 (0 not inclusive), such that the higher its value, the more important the sustainability objective is.

Based on the (20/80) Pareto principle, only significant sustainability objectives, i.e., the ones ranked with an *RII* value of 80% or more, are used for evaluating damaged facilities (Fernández-Sánchez & Rodríguez-López, 2010).

3.5 Damaged Facilities' Survey

In this step, a thorough review of the database of the damaged infrastructure assets should be made by the government officials of a developing country to determine the type, ownership status, age, location, source of damage, severity of damage, cost of repair, and repair duration of each. Also, the assets should be classified into the categories recommended by Cleveland (2008), such as roads, bridges, rail and transit facilities, residential and commercial buildings, airports, government buildings, schools, etc.

Then, a survey is conducted with experts who have previous knowledge with sustainability-driven projects in order to assign a rating score to only the infrastructure facilities whose degree of damage may hinder their ability to serve the public properly, using a five-point Likert scale.

The scale measures the degree of alignment of each facility to the government strategy to accomplish each of the significant sustainability objectives. The cardinality values of the scale range between (1) Very Low Alignment and (5) Very High Alignment degrees. The degrees (2) Low Alignment, (3) Medium Alignment, and (4) High Alignment are intermediate values. In this step, an average alignment degree (a_{ij}) of each facility (*i*), respective to each significant sustainability objective (*j*), is computed on the scale, using the average scores assigned by the experts on the scale.

3.6 Prioritization of Damaged Facilities Using the Weighted Sum Technique

In this step, the weighted sum technique in MCDM (Equation 9) is used to compute an infrastructure facility sustainability priority index (*FSPI*)—a crisp value that prioritizes each facility (*i*) in terms of its urgency for repair by taking the summation of the product of its average alignment degree and the relative importance index of each sustainability objective (*j*).

$$FSPI_i = \sum_{i=1}^{n} a_{ij} \bullet RII_j \qquad (\text{for i} = 1,2\ ,3\ ,4\ldots..\text{m}) \quad (9)$$

Where, a_{ij} is the average alignment degree of each facility (*i*) respective to each significant sustainability objective (*j*), and RII_j is the relative importance index of the significant sustainability objectives (*j*).

4. Case Study: Application of the MCPF to Asses Egyptian Sustainability Objectives and Prioritize Damaged Facilities

In Egypt, several essential infrastructure and public services facilities have been exposed to different types of damage due to acts of violence resulting from the current state of unrest associated with the Egyptian revolution, which has started on the 25th of January 2011. The current objective of the Egyptian government is to maintain essential quality services to the public by salvaging the significantly damaged facilities. A thorough review of the database of the facilities that suffered damages or losses during the Egyptian revolution, coupled with structured interviews with government officials and construction experts resulted in preparing a comprehensive list of the facilities that need repair.

The list comprised the type, ownership status, age, location, source of damage, severity of damage, cost of repair, and repair duration of each damaged facility. Based on the results of the work by Elbarkouky et al. (2012), forty-seven damaged facilities have been classified into six groups (counts are indicated between brackets): Infrastructure (5), Public Services (4), Commercial (4), Police (20), Prisons (5), and Banks (9). The sources of damages or losses, such as theft, vandalism, explosion, partial destruction, and fire were identified for each facility using police reports, archived photographs, and site investigations. The severity of damage and repair costs were assessed by experts, subjectively, using three linguistic terms (high, medium, and low). The duration

periods to complete repair works were assessed by contractors that ranged between few weeks and more than 12 months. Finally, experts determined whether the severity of damage of each facility might disrupt any of its services, which helped in screening the facilities that did not need urgent repairs. The detailed information of the damaged facilities could be found in the work by Elbarkouky et al. (2012).

Ten facilities suffered severe damages, leading to the disruption of public services: a Wastewater plant in Gharbia Governorate, a Traffic Control CCTV system in Tahrir Square in Cairo, a Natural Gas Pump Station in Sinai Governorate, a Potable Water Disinfection Plant in Alexandria Governorate, a Multi-Courts Facility in Cairo City Centre, a Bank Branch, a Police Station, a Prison, a Mall, and a Government Building in Cairo.

One of the key steps of applying the MCPF to the case study was to prioritize the sustainability objectives based on their level of importance to the Egyptian citizens. It is important to mention that there have been no prior attempts by the Egyptian government to use sustainability objective in initiating its construction projects in Egypt.

Table 4. Experts' qualifications and corresponding relative importance weights, adapted (Elbarkouky et al., 2012)

Criteria	(Q1)	(Q2)	(Q3)	(Q4)	(Q5)	Importance	Relative Importance
Expert (*i*)	Attribute Values					Weight (*Wi*)	*Weight Factor (wi)*
E1	Consultant	PM	Ph.D.	>20 Years	Yes	0.974	0.048
E2	Contractor	PM	BSc.	10-15 Years	No	0.561	0.028
E3	Contractor	Engineer	MSc.	<5 Years	Yes	0.644	0.032
E4	Owner	Tech. Manager	MSc.	5-10 Years	Yes	0.782	0.039
E5	Owner	Senior Engineer	MSc.	5-10 Years	No	0.565	0.028
E6	Consultant	Principal	Ph.D.	>20 Years	Yes	0.981	0.049
E7	Contractor	Estimator	MSc.	5-10 Years	No	0.501	0.025
E8	Consultant	PM	Ph.D.	>20 Years	Yes	0.974	0.048
E9	Owner	Principal	MSc.	>20 Years	No	0.764	0.038
E10	Owner	CM	BSc.	>20 Years	Yes	0.912	0.045
E11	Contractor	HSE Manager	BSc.	15-20 Years	No	0.586	0.029
E12	Consultant	Designer	MSc.	5-10 Years	No	0.573	0.028
E13	Contractor	Engineer	BSc.	<5 Years	No	0.408	0.020
E14	Owner	PM	MSc.	>20 Years	Yes	0.960	0.048
E15	Consultant	Tech. Manager	MSc.	>20 Years	Yes	0.920	0.046
E16	Contractor	CM	BSc.	10-15 Years	No	0.547	0.027
E17	Consultant	PM	MSc.	15-20 Years	Yes	0.888	0.044
E18	Consultant	PM	MSc.	15-20 Years	Yes	0.888	0.044
E19	Contractor	CM	BSc.	10-15 Years	Yes	0.750	0.037
E20	Consultant	Tech. Manager	BSc.	15-20 Years	No	0.631	0.031
E21	Consultant	PM	Ph.D.	>20 Years	Yes	0.974	0.048
E22	Contractor	PM	MSc.	15-20 Years	Yes	0.850	0.042
E23	Contractor	PM	MSc.	15-20 Years	Yes	0.850	0.042
E24	Owner	PM	MSc.	15-20 Years	Yes	0.907	0.045
E25	Consultant	PM	MSc.	>20 Years	Yes	0.927	0.046
E26	Contractor	PM	BSc.	15-20 Years	Yes	0.816	0.041
Total						20.131	1.000

As such, the sustainability objectives template was introduced to experts and thirty experts were asked to provide a rating score (y_j) of 1 to 5 against each sustainability objective to determine the level of importance of each objective to the Egyptian public. The work by Elbarkouky et al (2012) was extended, and more experts have responded. A total of twenty-six valid questionnaires were returned—collection rate of 86%. The respondents' qualifications encompassed wide spectrum of academic and professional experience; diversified levels of expertise; and different types of institutions, which improved the quality of data. The relative importance weights of experts were computed based on the five qualification criteria that have been determined for each expert (Table 4).

Table 5. Prioritization of the sustainability objectives based on the RII

ID	Sustainability Objective	Average Score	RII	Rank
S2	Maximizing economical values or heritage benefit	4.547	0.909	1
S1	Enhancing public safety and health	4.465	0.893	2
C9	Reducing costs incurred to users	4.339	0.868	3
C5	Reducing extent of traffic blockage	4.204	0.841	4
E1	Reducing energy consumption	4.198	0.84	5
C7	Encouraging tourism	4.174	0.835	6
C10	Encouraging use of regional/local resources	4.148	0.83	7
C1	Signifying Urgency of work (e.g., shorter repair duration)	4.132	0.826	8
C2	Reducing life cycle cost	4.087	0.817	9
S6	Respecting local customs	4.083	0.817	10
E2	Enhancing waste management function	4.037	0.807	11
E6	Protecting water resources	4.03	0.806	12
C3	Reducing material consumption	3.872	0.774	13
C6	Encouraging strategic management	3.822	0.764	14
C8	Acquiring innovative elements	3.803	0.761	15
E4	Reducing CO2 emissions	3.71	0.742	16
E5	Encouraging renewable energy use	3.692	0.738	17
E10	Raising the ecological value of soil	3.649	0.73	18
S3	Demonstrating public interest	3.643	0.729	19
S5	Protecting human rights	3.581	0.716	20
C12	Increasing the economic value of the environment	3.549	0.71	21
E9	Enhancing environmental management	3.516	0.703	22
S4	Allowing public participation	3.493	0.699	23
C11	Possesing functional flexibility	3.222	0.644	24
C4	Motivating design for disassembly	2.839	0.568	25
E11	Minimizing noise pollution	2.795	0.559	26
E3	Widening ecological footprint	2.759	0.552	27
E12	Minimizing visual impact	2.541	0.508	28
E8	Controling climate change	2.1	0.42	29
E7	Mitigating disasters (quakes, floods)	1.88	0.376	30

Table 5 illustrates the average scores given by experts and the *RII* values that have been computed for each sustainability objective, which combined experts' ratings and their relative importance weights, using Equation 8.

From Table 5 and based on the Pareto principle, the first twelve significant sustainability objectives in the table, those of an *RII* value of 0.800 or more, were used to prioritize the damaged facilities, which extended the preliminary work by Elbarkouky et al. (2012) who only incorporated the first six factors in the prioritization process of the facilities. Subsequently, a survey was conducted with eight experts who had previous knowledge with sustainability-driven projects to assign a rating score to each of the top ten ranked facilities, using a five-point Likert scale. The scale measured the degree of alignment of each facility to the government strategy to accomplish each of the twelve significant sustainability objectives (*j*). Table 6 summarizes the average alignment degrees (a_{ij}) as well as the standard deviation calculated for each facility, respective to the twelve significant sustainability objectives.

Table 6. Average alignment degrees of the damaged facilities, adapted (Elbarkouky et al., 2012)

Sustainability Objective (*j*)	S2	S1	C9	C5	E1	C7	C10	C1	C2	S6	E2	E6
Relative Importance Index (*RIIj*)	0.909	0.893	0.868	0.841	0.840	0.835	0.830	0.826	0.817	0.817	0.806	0.807
Facility (i)	Average Alignment Degree (*ai*j) (Standard Deviation)											
1. Wastewater Plant	4.500 (0.756)	4.625 (0.518)	3.875 (1.126)	1.375 (0.744)	4.500 (0.535)	1.500 (0.756)	2.625 (1.302)	4.000 (0.926)	4.625 (0.518)	2.75 (1.035)	2.625 (1.302)	2.625 (1.302)
2. Traffic Control CCTV System	2.875 (0.641)	3.250 (0.463)	2.875 (1.126)	4.750 (0.463)	1.875 (0.835)	2.375 (0.744)	1.375 (0.518)	4.125 (0.835)	1.875 (0.835)	4.000 (0.756)	1.375 (0.518)	1.375 (0.518)
3. Natural Gas Pump Station	3.250 (1.069)	3.250 (1.488)	3.250 (1.035)	3.375 (1.408)	3.265 (0.916)	2.750 (1.753)	4.500 (0.535)	3.875 (0.641)	3.625 (1.061)	3.250 (0.707)	2.625 (0.744)	1.250 (0.463)
4. Potable Water Disinfection Plant	3.875 (1.356)	4.125 (0.835)	3.500 (0.756)	2.125 (1.808)	1.875 (0.835)	2.375 (1.302)	2.500 (0.535)	3.875 (0.835)	4.000 (0.756)	4.125 (0.641)	4.375 (0.518)	4.625 (0.518)
5. Multi-Courts Facility	3.750 (0.886)	4.125 (0.991)	2.750 (1.035)	2.0000 (1.414)	1.750 (0.886)	3.000 (1.773)	2.250 (0.463)	4.000 (1.195)	3.500 (1.069)	4.750 (0.463)	2.000 (0.756)	1.750 (0.463)
6. Bank Branch	3.125 (0.991)	2.875 (0.835)	2.500 (1.195)	2.875 (0.886)	1.750 (0.926)	3.375 (0.641)	1.750 (0.707)	4.750 (0.518)	1.750 (0.756)	3.625 (0.641)	2.875 (0.535)	1.125 (0.916)
7. Police Station	2.500 (0.756)	5.000 0.000	2.375 (1.061)	3.500 (1.246)	3.000 (1.165)	1.333 (1.061)	1.333 (0.886)	1.333 (0.463)	1.333 (0.463)	1.333 (0.916)	1.333 (0.641)	1.333 (0.354)
8. Prison	3.250 (1.282)	4.250 (0.886)	2.625 (0.916)	3.000 (1.512)	2.250 (1.753)	3.125 (1.356)	1.875 (0.835)	4.250 (0.707)	3.750 (0.886)	3.875 (0.835)	3.250 (1.165)	2.750 (1.282)
9. Mall	3.750 (1.282)	2.875 (0.641)	3.625 (1.061)	1.875 (1.126)	1.125 (0.354)	3.500 (1.414)	1.500 (0.535)	1.500 (0.535)	1.625 (0.518)	1.875 (0.835)	3.625 (0.744)	1.250 (0.463)
10. Government Building	1.875 (1.126)	2.625 (0.916)	2.750 (0.707)	2.125 (1.246)	1.500 (0.756)	3.250 (1.035)	4.375 (0.518)	1.625 (0.744)	3.875 (0.991)	3.375 (0.916)	3.125 (0.641)	1.375 (0.518)

Finally, the *FSPI* was calculated for each facility, using Equation 9, and then the facilities were prioritized accordingly. As illustrated in Table 7, the wastewater plant was the most aligned facility with the most significant sustainability objective S_2: maximizing economical/heritage benefits (a_{11} = 4.500), followed by the potable water disinfection plant (a_{41} = 3.875). The police station (a_{72}= 5.000), wastewater plant (a_{12} = 4.625), prison (a_{82} = 4.250), potable water plant (a_{42} = 4.125), and multi-court (a_{52} = 4.125) were the most aligned facilities with the objective S_1: enhancing public safety and health. The wastewater plant was the most aligned facility with the objectives C_9: reducing costs incurred to users (a_{13} = 3.875), followed by the potable water disinfection plant (a_{43} = 3.500). The potable water disinfection plant was the most aligned facility with the objectives E_2: enhancing waste management function (a_{411} = 4.375) and E_6: protecting water resources (a_{412} = 4.625). The traffic control

CCTV system was the most aligned facility with the objective C_5: reducing the extent of traffic blockage (a_{24} = 4.750), while the mall was the most aligned facility with the objective C_7: encouraging tourism (a_{96} = 3.500). Table 7 illustrates the prioritized facilities based on their *FSPIs*, while Equation 10 demonstrates a sample calculation of $FSPI_1$ of the wastewater plant facility.

$$FSPI_1=4.500x0.909+4.625x0.893+3.875x0.868+1.375x0.841+4.500x0.840+1.500x0.835+2.625x0.830+4.000x0.826+4.625x0.817+2.750x0.817+2.625x0.806+2.625x0.807=33.515 \quad (10)$$

Table 7. Prioritization and ranking of damaged facilities, adapted (Elbarkouky et al., 2012)

Facility (i)	FSPI	Rank	Facility (i)	FSPI	Rank
4. Potable Water Disinfection Plant	34.752	1	7. Police Station	28.491	6
1. Wastewater Plant	33.515	2	2. Traffic Control CCTV System	27.12	7
3. Natural Gas Pump Station	32.75	3	6. Bank Branch	26.714	8
8. Prison	32.176	4	10. Government Building	26.713	9
5. Multi-Courts Facility	30.064	5	9. Mall	23.837	10

Based on the *FSPI* calculations (Table 7), the potable water disinfection plant ($FSPI_4$ = 34.752) was assigned the highest priority rank to undergo repairs, followed by the wastewater plant ($FSPI_1$ = 33.515), and the natural gas pump station ($FSPI_3$ = 32.176). The potable water disinfection plant and wastewater plant were highly ranked because they were most aligned with the three most significant sustainability objectives S_2, S_1, and C_9 of the highest relative importance indices, 0.909, 0.893, and 0.868 respectively.

5. Conclusion and Future Research

This paper presented a Multi-Criteria Prioritization Framework (MCPF) to assess infrastructure sustainability objectives and prioritize damaged infrastructure assets in developing countries. The framework aids government officials of limited budgets in ranking damaged facilities that urgently need repair, using an infrastructure facility sustainability priority index (*FSPI*), which is a crisp value that prioritizes damaged facilities in terms of their urgency for repair. The paper classified thirty essential sustainability objectives based on three sustainability pillars: economical, societal, and environmental that emphasized the concept of achieving sustainable construction environments in developing countries. The study applied expert judgment, multi-criteria decision analysis, and the pairwise comparison method of the analytical hierarchal process (AHP) to integrate the quality of experts and their opinions in the prioritization process. The *FSPI* presents a simple crisp numerical indicator that ranks damaged infrastructure facilities, based on a transparent classification structure of sustainability objectives. It is efficient in capturing the knowledge of the experts in an integrated framework that incorporates significant sustainability objectives and qualifications of experts in the decision-making process of assessing damaged facilities. A case study is applied in Egypt to test the applicability of the model in a developing country whose infrastructure assets were subjected to damage due to the public unrest that occurred during the Egyptian revolution period that started on the 25th of January 2011.

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