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# A model for the evaluation of environmental impact indicators for a sustainable maritime transportation systems

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**Abstract** Maritime shipping is considered the most efficient, low-cost means for transporting large quantities of freight over significant distances. However, this process also causes negative environmental and societal impacts. Therefore, environmental sustainability is a pressing issue for maritime shipping management, given the interest in addressing important issues that affect the safety, security, and air and water quality as part of the efficient movement of freight throughout the coasts and waterways and associated port facilities worldwide. In-depth studies of maritime transportation systems (MTS) can be used to identify key environmental impact indicators within the transportation system. This paper develops a tool for decision making in complex environments; this tool will quantify and rank preferred environmental impact indicators within a MTS. Such a model will help decision-makers to achieve the goals of improved environmental sustainability. The model will also provide environmental policy-makers in the shipping industry with an analytical tool that can evaluate tradeoffs within the system and identify possible alternatives to mitigate detrimental effects on the environment.

**Keywords** environmental sustainability, maritime transportation system, environmental impact indicators, fuzzy

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analytic hierarchy process, fuzzy TOPSIS, decision-making tool

## 1 Introduction

Maritime transportation systems (MTS) consist of ports and inter-modal land-side connections that allow various modes of transportation to move goods to, from, and on the water. MTS transport about 90% of global trade (United Nations Business, 2016). MTS are considered the most efficient and cost-effective method for the international transportation of goods, providing a dependable means of facilitating commerce among nations (UNCTAD, 2012; IMO, 2012). However, MTS are also a source of environmental pollution (Luo and Yip, 2013). According to the International Maritime Organization (IMO), maritime shipping was estimated to have accounted for 2.3% of global CO<sub>2</sub> emissions in 2012, and these emissions will increase by 50% in 2050 (OECD and PBL Netherlands Environmental Assessment Agency, 2012). The increasing demands on our MTS must be safely handled and balanced with environmental values to ensure that freights move efficiently to, from, and on our waterfronts.

As container traffic increases, ports continually increase in size and throughput to compete in the global trade. Ideally, this growth should transpire without imposing additional externalities that harm the environment. Thus, port authorities must find ways to lessen the environmental damage from their operations while enhancing performance (Melious, 2008). Hence, ports should adapt to 21st century concerns and implement best practices to reduce their environmental impact at both the local and global levels.

De Toni and Comello (2005) stated that complex systems and phenomena comprise numerous components that interact in a highly dependent manner. These researchers also reported that such interactions occur at different levels; both elements and hierarchical levels are

linked by a variety of nonlinear relationships, capable of exchanging stimuli with one another and with their environment. The management of MTS supply chain is a highly complex problem, that is, a complex phenomenon that cannot be understood analytically but it has to be looked at as a system that cannot be divided. Further, limited research address the sustainability of MTS (IMO, 2012). Experts must gain a more complete understanding of the environmental impact of the industry on local and global ecosystems to develop a sustainable protocol as MTS activity will grow significantly in the near future. If the preferred environmental performance measures lack understanding by the typical management reviewers in the marine industry, evaluation of the sustainability of the system will present difficulty (Johnson et al., 2013). For the efficient functioning of MTS, certain key performance environmental measures must be understood and addressed. These key performance measures will aid in the achievement of sustainability and enhancement of a system's competitiveness.

### 1.1 Environmental sustainability

Environmental sustainability is a global issue that has been gathering momentum over the last decade (Carter and Rogers, 2008; Mudgal et al., 2010). This condition is triggered by the growing needs of an expanding world population and increasing economic activity which deplete natural resources and impose considerable pressure on the environment. The increasing demands on our MTS must also be safely handled and balanced with environmental values to ensure that freights move efficiently to, from, and on our waterfronts. Coordination, leadership, and cooperation are essential to addressing the challenges faced by MTS. Information on safety, natural environment, and security must be shared among regional and local agencies and private sector owners and operators to effectively meet the needs of the MTS. As a consequence of this consensus, green concepts are important for the operation of marine activities to prevent environmental damage (Chiu et al., 2014). The green economy is considered a vital policy option that can address the growing economic, environmental, and social challenges.

A review of literature on sustainability in the maritime industry focused on the importance of comprehensive understanding of the concept of sustainability in MTS. A port is considered sustainable if it presents an optimal balance between its performance as a business entity and its environmental performance (Broesterhuizen et al., 2014).

Numerous studies published in recent years pointed out the importance of environmental sustainability as a topic among academic communities and the maritime industry (Chiu et al., 2014). The shipping industry continually increases its environmental awareness and requires their supply chain partners to also offer eco-efficient services

(Lee and Lam, 2012). Most studies considering maritime pollution suggested control measures and goals to mitigate the environmental impact of the ports under study (Johnson et al., 2013; Woo and Moon, 2013; Homsomba et al., 2013; Chang, 2013). From a supply chain perspective, key performance measures for the environmental performance of the system are crucial to a system's success and effectiveness. Therefore, green port strategies require further examination to prioritize their impacts on achieving environmentally sustainable status.

In theory, the MTS cannot implement all sustainable measures existing in literature (Bailey and Solomon, 2004; Darbra et al., 2005; Peris-Mora et al., 2005; Chiu and Lai, 2011; Lirn et al., 2013) without compromising their efficiency and associated costs. Hence, the most significant measures capable of attaining the most sustainable MTS must be prioritized.

A number of reasons limit the possibility of continuous improvement toward a more sustainable environment in the maritime transportation industry. Studies have shown that despite the necessity of identifying key performance indicators (KPIs), only 17% of the industry utilizes these KPIs (Konsta and Plomaritou, 2012). Studies have also revealed that among performance problems observed in the maritime industry, 8% are directly attributed to the lack of understanding of environmental aspects (Konsta and Plomaritou, 2012). Although the rank of these KPIs in uncertain environments must be determined to improve the quality of the sustainable performance of MTS, few studies focused on how port management can select the preferred environmental performance measures based on this type of ranking (Peris-Mora et al., 2005; Chiu & Lai, 2011; Park & Yeo, 2012; Lirn et al., 2013; Puig et al., 2015).

As expressed previously, limited research focused on developing indicators or frameworks that assess the MTS sustainability. Peris-Mora et al. (2005) proposed a system of sustainable environmental management indicators to be used by port authorities to analyze potential environmental impacts and risks with the use of multi-criteria analysis technique. Their research used the Port of Valencia as reference. Lirn et al. (2013) applied the analytic hierarchy process (AHP) to measure a port's green performance indicators and to determine the overall sustainable performance of three major ports in Asia: Shanghai, Hong Kong, and Kaohsiung. In their research, they studied the weight and degree of performance of 17 indicators under five dimensions: (1) air pollution management, (2) aesthetic and noise pollution management, (3) solid waste pollution management, (4) liquid pollution management, and (5) marine biology preservation. These dimensions were used to evaluate the greening of ports. Park and Yeo (2012) implemented factor analysis and the fuzzy approach to create the Green Criteria of Seaport, which consist of 15 indicators grouped into five main groups: (1) ease the environmental burden, (2) environment-friendly method and technology development of construction, (3) utiliza-

tion of resources and waste inside a port, (4) efficient planning and management of port operations, and (5) port redevelopment with introduction of the waterfront concept. These criteria were utilized to evaluate the greenness of five major Korean ports. Chiu and Lai (2011) formulated a fuzzy AHP (FAHP) model which comprises 5 dimensions and 13 factors as strategies for green port operations. Results from an evaluation of the operations of the ports of Kaohsiung, Taichung, and Keelung showed the top five attributes of green port operations: hazardous waste handling, air pollution, water pollution, port greenery, and habitat quality maintenance. Finally, Puig et al. (2015) developed a computer-based tool to assist port authorities in identifying and assessing the significant environmental aspects for implementing effective environmental management of port operations.

## 1.2 Purpose of study

Limited research address the environmental sustainability of MTS (IMO, 2012). This gap implies the lack of knowledge as to which performance metrics best evaluate environmental sustainability within MTS. Most existing studies (Peris-Mora et al., 2005; Chiu and Lai, 2011; Park and Yeo, 2012; Lirn et al., 2013) are port-specific and therefore feature limited applicability outside of the selected port.

In this paper, key environmental quality indicators are identified and used to develop a tool for decision making in complex environment (DCME) particularly with regard to energy efficiency and minimization of pollution. The indicators are identified by evaluation of green performance measures using the integration of fuzzy logic with a combination of AHP and techniques for order performance by similarity to ideal solution (FTOPSIS). The integration of fuzzy theory to the analysis provides a unique view to the uncertainties associated with the models.

## 2 Method

The evaluation of MTS sustainability becomes increasingly complicated. This condition is due in part to numerous inter-related variables that are used to define MTS models. Each variable results in potential consequences that must be predicted far into the future to quantify sustainability. Furthermore, considerable uncertainties are associated with both the measurements of these variables and their predicted consequences, making them eligible for fuzzy analyses. This situation leads to the development of multiple operational, organizational, and strategic management approaches to port systems, resulting in considerable discrepancies and uncertainties (Oguzitmur, 2011). These uncertainties may result from unquantifiable information or imprecise opinions and lead to the need to produce a comprehensive and structured

port management discipline. In effect, KPIs are ranked based upon the experience of port managers, maritime experts (Tadic, et al., 2016), or stakeholders in private industries. Such an ad hoc system makes the rankings extremely subjective and difficult to reproduce (Konsta and Plomaritou, 2012). Fuzzy, multi-criteria, and decision-making methods have been developed to more effectively handle such uncertain and subjective information than conventional multi-criteria decision-making methods. In multi-criteria decision analysis, the fuzzy set theory, introduced by Zadeh (1965), is considered the most common method when dealing with uncertainties (Demirel et al., 2008), particularly the uncertainty resulting from fuzziness in human judgment and preferences (Ding, 2011). Fuzzy analyses provide a documented approach for understanding vague or qualitative inputs and allow these valuable inputs to be considered a part of a system of systems approach for sustainable transportation systems (Paz et al., 2013). Fuzzy analyses are also useful in considering vulnerability to pollutants (Aydi, 2018). Decision-makers find more convenience and confidence dealing with interval judgments than with fixed crisp values.

Expert preferences are difficult to quantify with certainty, consequently resulting in the difficulty to use them as input to numerical models (Torfi et al., 2010). The fuzzy set theory provides a valuable tool by using linguistic variables that are translated into fuzzy numbers to generate decisions (Kaur & Chakraborty, 2007; Kahraman, 2009). The approach is particularly useful for the interdependent systems inherent in transportation networks (Paz et al., 2013). Fuzzy numbers stand for a range of possible values applied to a particular variable; in consequence, a variable that is expressed in vague and imprecise terms by the experts is treated by the fuzzy set theory as a triangular probability distribution to be effectively used in logical reasoning and assist in making decisions (Fig. 1). A single linguistic rating given by an expert will be transformed into a fuzzy number comprising multiple numbers that convey a range of possible values (Shukla et al., 2014). The mathematical concept, as presented by Hsieh et al. (2004) and Liou et al. (2008),

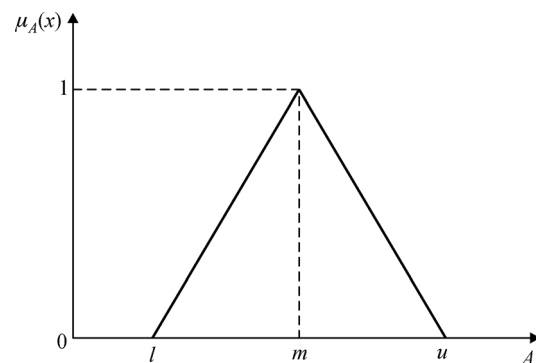


Fig. 1 Function of a TFN A

explains fuzzy number  $A$  to possess a triangular fuzzy number (TFN) distribution ( $\mu_A(x)$ ) calculated using Eq. (1) (Balli and Korukoglu, 2009), where TFN  $A$  is defined as a trio  $(l, m, u)$ , representative of the lower bound or smallest possible value, the modal or most favorable value, and the upper bound or largest possible value, respectively, to describe the fuzzy number,  $A$ .

$$\mu_A(x/A) = \begin{cases} 0 & x < l; \\ \frac{x-l}{m-l} & l \leq x \leq m; \\ \frac{u-x}{u-m} & m \leq x \leq u; \\ 0 & x > u. \end{cases} \quad (1)$$

Figure 1 shows a geometric representation of fuzzy number  $A$  from Eq. (1), as modified from the work of Balli and Korukoglu (2009).

Environmental port management is a component of port efficiency and competitiveness (Lai et al., 2011). Thus, shipping firms should find ways to lessen the environmental damages of their operations while enhancing their performance (Han, 2010) and identifying and satisfying the chief interests of the industry at the same time. In this paper, criteria are selected to evaluate operational alternatives in terms of their environmental performance within the MTS. Table 1 shows a list of literature studies that influenced the criteria upon which alternative performance will be evaluated.

**Table 1** Select heavily cited expert literature used for the evaluation of criteria and alternatives

Expert	Source(s)
E1	Duru et al. (2012)
E2	Gudmundsson (2001)
E3	Lai et al. (2011)
E4	Peris-Mora et al. (2005)
E5	Jeon & Amekudzi (2005), Rodrigue et al. (2013)
E6	Lister (2015), Lun et al. (2016)

The six criteria and four alternatives used to evaluate the sustainability of MTS are selected based on a synthesis of numerous green port metrics and KPIs (Gudmundsson, 2001; Jeon & Amekudzi, 2005; Peris-Mora et al., 2005; Lai et al., 2011; Shimin and Diew, 2012; Schinas and Stefanakos, 2012; UNCTAD, 2012; Duru et al., 2013; Rodrigue et al., 2013; Yang et al., 2013; InterManager and MARINTEK, 2015; Kavakeb et al., 2015; Lam, 2015; Lister, 2015; Lun et al., 2016). Table 2 presents the criteria identified in literature and have been repeated most often and given the highest weight of importance with respect to environmentally sustainable MTS. These criteria permit the evaluation of alternatives that are selected to lead to a more sustainable MTS (Table 3).

With the increasing environmental concerns with regard to maritime activity, the shipping industry must find solutions to attain environmental sustainability in their operations and the system as a whole. Along with regulatory requirements from institutions such as IMO, customers and stakeholders of shipping services demand for environmental sustainability from maritime services. Hence, the importance of this research concerns the selection of the criteria and alternatives to be considered and evaluated in order to ensure that environmental concerns and practices are integrated into industry activities. In the search for environmental sustainability of MTS, the expectations and requirements of shipping managers and stakeholders from the system in environmental dimensions must be understood. How such requirements can be translated into specific processes must also be determined. For these reasons, in this research, criteria are defined as the preferred environmental management requirements that allow meeting of a goal, that is, the set of preferred feasible solutions to the environmental sustainability performance issue. Alternatives are defined as the desired objectives that fit best with the goal of attaining environmental sustainability in the MTS or improving its environmental performance. To select the competitive alternatives and the determining criteria to be used for evaluation and to better support the decision-making process in the complex real-world of the maritime industry, a survey of literature related to the maritime industry is evaluated to detect patterns in discussed preferences among different reports and/or

**Table 2** Criteria from the FAHP that are most connected to improved environmental performance of MTS

Notations	Environmental Performance Criteria
C1	Use of green design in ships, engines and machinery
C2	Use of clean technologies such as, low sulfur fuel and option to alternate energy (fuel type)
C3	Reuse and recycle of resources used in shipping
C4	Ballast water treatment and residue/waste/spill control
C5	Logistic and scheduling efficiency for such as reduction of idle and waiting times
C6	Use of environmentally friendly shipping equipment and facilities

**Table 3** Environmental performance alternatives determined by FTOPSIS for environmentally sustainable MTS

Notations	Environmental performance alternatives
A1	Reduction of release of substances as defined by MARPOL Annex 1-6
A2	Management of water ballast violations
A3	Contained spill of hazardous materials
A4	Reduction of environmental deficiencies

studies (Table 1).

The criteria from Table 2 are described in detail. (C1) The use of green design ships, engines, and machinery is considered a vital step for the shipping industry to address technical and economic aspects of using environment-friendly shipping equipment and facilities. For example, a new vessel design includes a waste-heat recovery system that reduces fuel consumption and CO<sub>2</sub> emissions by 9% along with a newly designated space to accommodate sulfur-cleaning scrubbers and remove SO<sub>2</sub> before its release into the atmosphere. The SO<sub>2</sub> captured in the scrubber is a recyclable product that can later be used as soil amendment in agriculture and in construction applications including cement (Romeo, 2013). (C2) The use of clean technologies, such as low-sulfur fuel or alternate energy sources to fuel container ships, leads to high fuel consumption efficiency and reduced CO<sub>2</sub> emissions (Peris-Mora et al., 2005). Alternatives to the heavy fuel oil, which is presently used in maritime transport, are needed to address environmental concerns and develop more stringent government regulations (Bengtsson et al., 2012). For instance, studies have evaluated whether hybrid fuels, biofuels, or nuclear energy can be applied in shipping operations (Bengtsson et al., 2012; Dedes et al., 2012). (C3) Reuse and recycling of shipping-related wastes involve the development and implementation of recycling programs. These programs can include the storage of waste during transit and use of green packing materials. Lai et al. (2011) suggested the sale or reuse of shipping materials and used oil as an incentive for implementing such sustainability programs. (C4) Ballast water treatment and residue/waste/spill control includes the management of ship wastes during voyage to prevent waste disposal at sea. Installation of ballast water treatment systems on future ships will minimize the introduction of invasive species that threaten local ecosystems (Department of Homeland Security, 2012). (C5) Logistics and scheduling efficiency for the reduction of idle and waiting times is also attributed to the environmental sustainability of an MTS (Lam, 2015) because it minimizes environmental impacts and improves the environmental performance of the system. For example, optimized voyage planning can result in fuel savings, and identifying the most fuel-efficient route and engaging in a steady running strategy contribute to the reduction of emissions and the environmental performance

of the system (Lai et al., 2011; Xin et al., 2014). Also, reducing idle and wait times at the port results in reduced gaseous and particulate emissions from vessels, thus improving air quality (Eyring, et al., 2010; Fagerholt et al., 2015). The last criterion is the usage of environmentally friendly shipping equipment and facilities (C6), which include green practices adopted by the industry to improve environmental performance and economic competitiveness. For example, MTS engage in green practices, such as the use of non-toxic paint (Gudmundsson, 2001; Yang et al., 2013).

Table 3 depicts the four alternatives for a sustainable MTS, namely (A1) reduction of release of substances as defined by International Convention for the Prevention of the Pollution from Ships (MARPOL) Annex 1 through 6, (A2) management of ballast water violations, (A3) containment of spills of hazardous materials, and (A4) reduction of environmental deficiencies (Duru et al., 2013; Lam, 2015). These alternatives are specifically related to environmental sustainability and are considered herein as major pathways that promote improved performance in MTS. The first alternative (A1) focuses on the pollution aspect of environmental sustainability, including air and water pollution, with specific emphasis on reducing the release of waste substances as defined by the International Convention for the Prevention of Pollution from Ships or MARPOL in Annex 1 through 6 (IMO, 1978).

1. MARPOL Annex I – Prevention of Pollution by Oil
2. MARPOL Annex II – Control of Pollution by Noxious Liquid Substance in Bulk
3. MARPOL Annex III – Prevention of Pollution by Harmful Substances Carried by Sea in Packaged Form
4. MARPOL Annex IV – Prevention of Pollution by Sewage from Ships
5. MARPOL Annex V – Prevention of Pollution by Garbage from Ships
6. MARPOL Annex VI – Prevention of Air Pollution from Ships

The second alternative (A2), the management of ballast water violations, considers the discharges from ships that have a negative impact on the marine environment because discharge typically contains a variety of biological materials, such as plants, viruses, and bacteria, often non-native, that can cause extensive ecological and economic damage along with serious human health problems (Darbra et al., 2005; Eyring, et al., 2010). The

third alternative (A3), the containment of spills of hazardous materials, can have devastating effects on the environment. Such spills can be toxic to marine life and stored for a long time in marine sediments, given that natural bioremediation is typically a slow process and anthropogenic remediation is costly (Eyring, et al., 2010). The fourth alternative (A4), the reduction of environmental deficiencies, is another requirement on environmental performance and contributes to the improvement of social performance and human health conditions at local and global levels (Eyring, et al., 2010; Chiu et al., 2014; Lam, 2015).

The first step of a DMCE protocol is to set up a hierarchy system, such as the one shown in Fig. 2. This system is composed of multiple hierarchies and includes the goal of evaluating the preferred KPIs for a sustainable MTS criteria, as shown in Table 2, with the decision alternatives to determine the preferred choice, as shown in Table 3.

The model proposed in this work is developed in two main steps: (1) the prioritization of weights for criteria using FAHP and (2) the prioritization of alternatives using FTOPSIS technique with the use of the weights of criteria attained from FAHP. Basically, the DMCE tool consists of the integration of two methods. The intent of using FAHP is to compute the importance weight of the criteria that will be used in the FTOPSIS method. In this work, an adaptation of Chang’s (1992; 1996) analysis on FAHP is used.

2.1 Fuzzy AHP

The following steps explain the process of determining the priority weights for the decision criteria:

Step 1: The collection of literature that will be used as the voice of the experts is selected, as depicted in Table 1.

Step 2: The criteria are identified, as shown in Table 2.

Step 3: The opinions and voice of experts are utilized to provide the relative weight to each criterion that conforms to the linguistic variables shown in Table 4, as defined by Tolga et al. (2005). The criteria are evaluated according to the experts by the selection of the related linguistic variables according to Table 4. The experts’ comparisons of criteria according to linguistic variable (by comparing which is the more important of each two criteria) as presented in journal articles and are herein interpreted as illustrated in Table 5. Furthermore, to proceed with the calculation of the pairwise comparison of criteria, the linguistic variables in Table 5 are converted into their corresponding TFNs, which are found in Table 4, resulting in Table 6 after combining Tables 4 and 5.

Step 4: The fuzzy importance weight of criteria is calculated by employing the geometric mean of the experts’ opinions. To calculate the geometric mean, Buckley’s (1985) geometric mean method is used. Results are shown in Table 7.

Step 5: The fuzzy relative importance weight of the criteria is calculated using an adaptation of Chang’s (1996) extent analysis method (Eqs. (2)–(5)).

Let  $G = \{g_1, g_2, \dots, g_n\}$  be a goal set. Each criterion is utilized, and the extent analysis for each goal  $g_i$  is performed. Then,  $m$  extent analysis values for each criterion are attained using the following notation (Kahraman et al., 2004);  $M_{g_i}^1, M_{g_i}^2, \dots, M_{g_i}^m$ , where  $g_i$  is the goal set ( $i = 1, 2, \dots, n$ ) and  $M_{g_i}^j$  ( $j = 1, 2, \dots, m$ ), where all are TFNs.

The value of the fuzzy synthetic extent value ( $S_i$ ) with respect to the  $i$ th criteria is defined as seen in Eq. (2)

$$S_i = \sum_{j=1}^m M_{g_i}^j \otimes \left[ \sum_{i=1}^n \sum_{j=1}^m M_{g_i}^j \right]^{-1} \quad (2)$$

Then, to obtain equation  $\sum_{j=1}^m M_{g_i}^j$ , the fuzzy addition

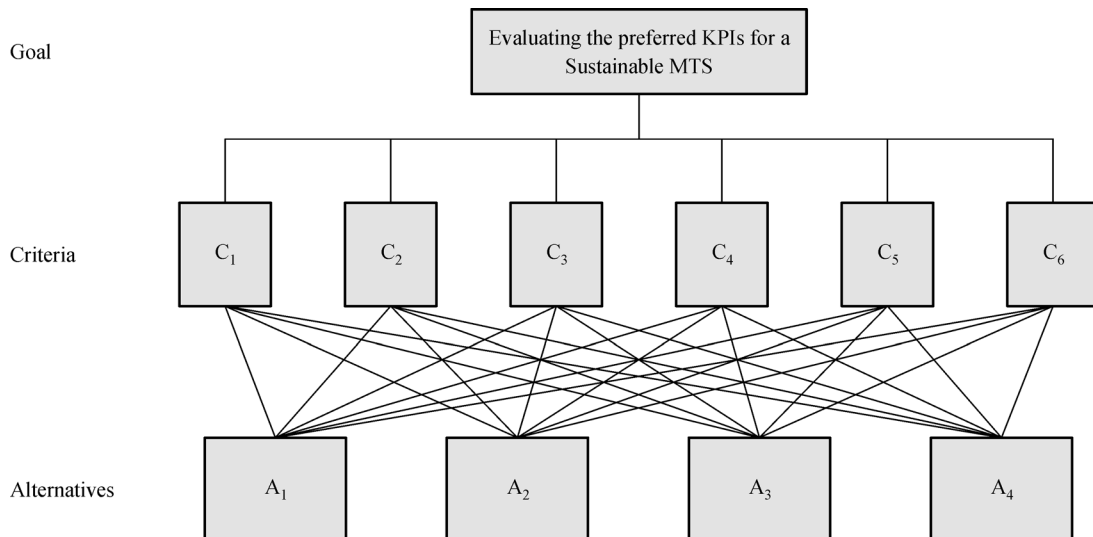


Fig. 2 DMCE model framework

**Table 4** Values of TFNs (Tolga et al., 2005)

Linguistic Variables	Triangular Fuzzy Numbers	Reciprocal Triangular Fuzzy Numbers
Absolute (A)	(7/2, 4, 9/2)	(2/9, 1/4, 2/7)
Very Strong (VS)	(5/2, 3, 7/2)	(2/7, 1/3, 2/5)
Fairly Strong (FS)	(3/2, 2, 5/2)	(2/5, 1/2, 2/3)
Weak (W)	(2/3, 1, 3/2)	(2/3, 1, 3/2)
Equal (E)	(1, 1, 1)	(1, 1, 1)

**Table 5** Pairwise comparisons of criteria via linguistic variables

Criteria	Experts	C1	C2	C3	C4	C5	C6
C1	E1	E	E	FS	VS	E	VS
	E2	E	W	W	W	VS	E
	E3	E	FS	FS	FS	A	E
	E4	E	E	E	W	FS	FS
	E5	E	W	E	W	E	E
	E6	E	W	W	E	W	E
C2	E1	E <sup>-1</sup>	E	W	E	E	A
	E2	W <sup>-1</sup>	E	VS	FS	VS	FS
	E3	FS <sup>-1</sup>	E	FS	E	FS	E
	E4	E <sup>-1</sup>	E	VS	FS	FS	VS
	E5	W <sup>-1</sup>	E	FS	W	E	FS
	E6	W <sup>-1</sup>	E	VS	VS	W	E
C3	E1	FS <sup>-1</sup>	W <sup>-1</sup>	E	E	W <sup>-1</sup>	W
	E2	W <sup>-1</sup>	VS <sup>-1</sup>	E	E	W	E
	E3	FS <sup>-1</sup>	FS <sup>-1</sup>	E	W	E	E
	E4	E <sup>-1</sup>	VS <sup>-1</sup>	E	E	FS	FS
	E5	E <sup>-1</sup>	FS <sup>-1</sup>	E	W	E	E
	E6	W <sup>-1</sup>	VS <sup>-1</sup>	E	W	W	W
C4	E1	VS <sup>-1</sup>	E <sup>-1</sup>	E <sup>-1</sup>	E	E	FS
	E2	W <sup>-1</sup>	FS <sup>-1</sup>	E <sup>-1</sup>	E	E	E
	E3	FS <sup>-1</sup>	E <sup>-1</sup>	W <sup>-1</sup>	E	FS	E
	E4	W <sup>-1</sup>	FS <sup>-1</sup>	E <sup>-1</sup>	E	VS	FS
	E5	W <sup>-1</sup>	W <sup>-1</sup>	W <sup>-1</sup>	E	FS	E
	E6	E <sup>-1</sup>	VS <sup>-1</sup>	W <sup>-1</sup>	E	E	E
C5	E1	E <sup>-1</sup>	W <sup>-1</sup>	W <sup>-1</sup>	E <sup>-1</sup>	E	A
	E2	VS <sup>-1</sup>	W <sup>-1</sup>	W <sup>-1</sup>	E <sup>-1</sup>	E	E
	E3	A <sup>-1</sup>	E <sup>-1</sup>	E <sup>-1</sup>	FS <sup>-1</sup>	E	E
	E4	FS <sup>-1</sup>	FS <sup>-1</sup>	FS <sup>-1</sup>	VS <sup>-1</sup>	E	VS
	E5	E <sup>-1</sup>	E <sup>-1</sup>	E <sup>-1</sup>	FS <sup>-1</sup>	E	FS
	E6	W <sup>-1</sup>	W <sup>-1</sup>	W <sup>-1</sup>	E <sup>-1</sup>	E	E
C6	E1	VS <sup>-1</sup>	A <sup>-1</sup>	W <sup>-1</sup>	FS <sup>-1</sup>	A <sup>-1</sup>	E
	E2	E <sup>-1</sup>	FS <sup>-1</sup>	E <sup>-1</sup>	E <sup>-1</sup>	E <sup>-1</sup>	E
	E3	E <sup>-1</sup>	E <sup>-1</sup>	E <sup>-1</sup>	E <sup>-1</sup>	E <sup>-1</sup>	E
	E4	FS <sup>-1</sup>	VS <sup>-1</sup>	FS <sup>-1</sup>	FS <sup>-1</sup>	VS <sup>-1</sup>	E
	E5	E <sup>-1</sup>	FS <sup>-1</sup>	E <sup>-1</sup>	E <sup>-1</sup>	FS <sup>-1</sup>	E
	E6	E <sup>-1</sup>	E <sup>-1</sup>	W <sup>-1</sup>	E <sup>-1</sup>	E <sup>-1</sup>	E

**Table 6** Pairwise comparisons of criteria via TFNs

Criteria	Experts	C1	C2	C3	C4	C5	C6
C1	E1	(1,1,1)	(1,1,1)	(3/2, 2, 5/2)	(5/2, 3, 7/2)	(1,1,1)	(5/2, 3, 7/2)
	E2	(1,1,1)	(2/3, 1, 3/2)	(2/3, 1, 3/2)	(2/3, 1, 3/2)	(5/2, 3, 7/2)	(1,1,1)
	E3	(1,1,1)	(3/2, 2, 5/2)	(3/2, 2, 5/2)	(3/2, 2, 5/2)	(7/2, 4, 9/2)	(1,1,1)
	E4	(1,1,1)	(1,1,1)	(1,1,1)	(2/3, 1, 3/2)	(3/2, 2, 5/2)	(3/2, 2, 5/2)
	E5	(1,1,1)	(2/3, 1, 3/2)	(1,1,1)	(2/3, 1, 3/2)	(1,1,1)	(1,1,1)
	E6	(1,1,1)	(2/3, 1, 3/2)	(2/3, 1, 3/2)	(1,1,1)	(2/3, 1, 3/2)	(1,1,1)
C2	E1	(1,1,1)	(1,1,1)	(2/3, 1, 3/2)	(1,1,1)	(1,1,1)	(7/2, 4, 9/2)
	E2	(2/3, 1, 3/2)	(1,1,1)	(5/2, 3, 7/2)	(3/2, 2, 5/2)	(5/2, 3, 7/2)	(3/2, 2, 5/2)
	E3	(2/5, 1/2, 2/3)	(1,1,1)	(3/2, 2, 5/2)	(1,1,1)	(3/2, 2, 5/2)	(1,1,1)
	E4	(1,1,1)	(1,1,1)	(5/2, 3, 7/2)	(3/2, 2, 5/2)	(3/2, 2, 5/2)	(5/2, 3, 7/2)
	E5	(2/3, 1, 3/2)	(1,1,1)	(3/2, 2, 5/2)	(2/3, 1, 3/2)	(1,1,1)	(3/2, 2, 5/2)
	E6	(2/3, 1, 3/2)	(1,1,1)	(5/2, 3, 7/2)	(5/2, 3, 7/2)	(2/3, 1, 3/2)	(1,1,1)
C3	E1	(2/5, 1/2, 2/3)	(2/3, 1, 3/2)	(1,1,1)	(1,1,1)	(2/3, 1, 3/2)	(2/3, 1, 3/2)
	E2	(2/3, 1, 3/2)	(2/7, 1/3, 2/5)	(1,1,1)	(1,1,1)	(2/3, 1, 3/2)	(1,1,1)
	E3	(2/5, 1/2, 2/3)	(2/5, 1/2, 2/3)	(1,1,1)	(2/3, 1, 3/2)	(1,1,1)	(1,1,1)
	E4	(1,1,1)	(2/7, 1/3, 2/5)	(1,1,1)	(1,1,1)	(3/2, 2, 5/2)	(3/2, 2, 5/2)
	E5	(1,1,1)	(2/5, 1/2, 2/3)	(1,1,1)	(2/3, 1, 3/2)	(1,1,1)	(1,1,1)
	E6	(2/3, 1, 3/2)	(2/7, 1/3, 2/5)	(1,1,1)	(2/3, 1, 3/2)	(2/3, 1, 3/2)	(2/3, 1, 3/2)
C4	E1	(2/7, 1/3, 2/5)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(3/2, 2, 5/2)
	E2	(2/3, 1, 3/2)	(2/5, 1/2, 2/3)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)
	E3	(2/5, 1/2, 2/3)	(1,1,1)	(2/3, 1, 3/2)	(1,1,1)	(3/2, 2, 5/2)	(1,1,1)
	E4	(2/3, 1, 3/2)	(2/5, 1/2, 2/3)	(1,1,1)	(1,1,1)	(5/2, 3, 7/2)	(3/2, 2, 5/2)
	E5	(2/3, 1, 3/2)	(2/3, 1, 3/2)	(2/3, 1, 3/2)	(1,1,1)	(3/2, 2, 5/2)	(1,1,1)
	E6	(1,1,1)	(2/7, 1/3, 2/5)	(2/3, 1, 3/2)	(1,1,1)	(1,1,1)	(1,1,1)
C5	E1	(1,1,1)	(2/3, 1, 3/2)	(2/3, 1, 3/2)	(1,1,1)	(1,1,1)	(7/2, 4, 9/2)
	E2	(2/7, 1/3, 2/5)	(2/3, 1, 3/2)	(2/3, 1, 3/2)	(1,1,1)	(1,1,1)	(1,1,1)
	E3	(2/9, 1/4, 2/7)	(1,1,1)	(1,1,1)	(2/5, 1/2, 2/3)	(1,1,1)	(1,1,1)
	E4	(2/5, 1/2, 2/3)	(2/5, 1/2, 2/3)	(2/5, 1/2, 2/3)	(2/7, 1/3, 2/5)	(1,1,1)	(5/2, 3, 7/2)
	E5	(1,1,1)	(1,1,1)	(1,1,1)	(2/5, 1/2, 2/3)	(1,1,1)	(3/2, 2, 5/2)
	E6	(2/3, 1, 3/2)	(2/3, 1, 3/2)	(2/3, 1, 3/2)	(1,1,1)	(1,1,1)	(1,1,1)
C6	E1	(2/7, 1/3, 2/5)	(2/9, 1/4, 2/7)	(2/3, 1, 3/2)	(2/5, 1/2, 2/3)	(2/9, 1/4, 2/7)	(1,1,1)
	E2	(1,1,1)	(2/5, 1/2, 2/3)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)
	E3	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)	(1,1,1)
	E4	(2/5, 1/2, 2/3)	(2/7, 1/3, 2/5)	(2/5, 1/2, 2/3)	(2/5, 1/2, 2/3)	(2/7, 1/3, 2/5)	(1,1,1)
	E5	(1,1,1)	(2/5, 1/2, 2/3)	(1,1,1)	(1,1,1)	(2/5, 1/2, 2/3)	(1,1,1)
	E6	(1,1,1)	(1,1,1)	(2/3, 1, 3/2)	(1,1,1)	(1,1,1)	(1,1,1)

operation (Sun, 2010) of  $m$  extent analysis values for a certain matrix is performed, as seen in Eq. (3)

$$\sum_{j=1}^m M_{g_i}^j = \left( \sum_{j=1}^m l_j, \sum_{j=1}^m m_j, \sum_{j=1}^m u_j \right), \quad (3)$$

where  $l$  is the lower bound value,  $m$  is the most promising value, and  $u$  is the upper bound value. Then, to obtain

$[\sum_{i=1}^n \sum_{j=1}^m M_{g_i}^j]^{-1}$ , the fuzzy addition operation of  $M_{g_i}^j$  ( $j = 1,2,3,4,5,\dots,m$ ) values is executed using Eq. (4)

$$\sum_{i=1}^n \sum_{j=1}^m M_{g_i}^j = \left( \sum_{j=1}^n l_j, \sum_{j=1}^n m_j, \sum_{j=1}^n u_j \right). \quad (4)$$

To calculate the inverse of the vector, Eq. (5) is used

**Table 7** Fuzzy geometric mean of pairwise comparison

Criteria	C1	C2	C3	C4	C5	C6
C1	(1,1,1)	(0.874,1.122,1.427)	(1,1.260,1.554)	(1.018,1.348,1.758)	(1.435,1.698,1.973)	(1.246,1.348,1.435)
C2	(0.701,0.891,1.145)	(1,1,1)	(1.692,2.182,2.717)	(1.246,1.513,1.789)	(1.246,1.513,1.789)	(1.643,1.906,2.149)
C3	(0.644,0.794,1)	0.368,0.458,0.591)	(1,1,1)	(0.816,1,1.225)	(0.874,1.122,1.427)	(0.935,1.122,1.334)
C4	(0.569,0.742,0.983)	(0.559,0.661,0.802)	(0.816,1,1.225)	(1,1,1)	(1.334,1.513,1.672)	(1.145,1.260,1.357)
C5	(0.507,0.589,0.697)	(0.701,0.891,1.145)	(0.701,0.891,1.145)	(0.598,0.661,0.750)	(1,1,1)	(1.536,1.698,1.844)
C6	(0.697,0.742,0.802)	(0.465,0.525,0.609)	(0.750,0.891,1.070)	(0.737,0.794,0.874)	(0.542,0.589,0.651)	(1,1,1)

$$\left[ \sum_{i=1}^n \sum_{j=1}^m M_{g_i}^j \right]^{-1} = \left( \frac{1}{\sum_{j=1}^n u_j}, \frac{1}{\sum_{j=1}^n m_j}, \frac{1}{\sum_{j=1}^n l_j} \right). \tag{5}$$

The resulting fuzzy synthetic extent with respect to its criteria is presented in Table 8.

**Table 8** Fuzzy synthetic extent with respect to its criteria

Criteria	Weight Low	Weight Med	Weight Upper
C1	0.146	0.201	0.274
C2	0.168	0.233	0.317
C3	0.103	0.142	0.197
C4	0.121	0.159	0.211
C5	0.112	0.148	0.197
C6	0.093	0.117	0.150

Step 6: The defuzzification method presented in Eq. (6) from Sun (2010) is applied to find the best non-fuzzy priority (BNP) or crisp weight value of the criteria. After calculating the BNP value, the criteria can then be ranked in order of preference as presented in Table 9.

**Table 9** Best BNP or crisp values of criteria

Criteria	BNP	Rank
C1- Green design	0.207	2
C2- Clean technologies	0.239	1
C3- Reuse and recycle	0.147	5
C4- Residue, waste and spill control	0.164	3
C5- Logistic and scheduling efficiency	0.152	4
C6- Green equipment and facilities	0.120	6

$$BNP_{S_i} = \frac{[(u_{s_i} - l_{s_i}) + (m_{s_i} - l_{s_i})]}{3} + l_{s_i}$$

where  $i = 1,2,3,\dots,6$ . (6)

To determine the fuzzy combination expansion for each

criterion, first, we calculate  $\sum_{j=1}^m M_{g_i}^j$  value for each row of the matrix. For example, for C<sub>1</sub>

$$\begin{aligned} C_1 &= (1 + 0.874 + 1 + 1.018 + 1.435 + 1.246, 1 \\ &\quad + 1.122 + 1.260 + 1.348 + 1.698 + 1.348, 1 \\ &\quad + 1.427 + 1.554 + 1.758 + 1.973 + 1.435) \\ &= (6.573, 7.777, 9.147). \end{aligned}$$

Then, the  $\sum_{i=1}^n \sum_{j=1}^m M_{g_i}^j$  value is calculated as  $(6.573, 7.777, 9.147) \otimes (7.529, 9.006, 10.589) \otimes (4.636, 5.497, 6.576) \otimes \dots \otimes (4.191, 4.540, 5.005)$

$$= (33.394, 38.725, 44.937).$$

Then, the  $[\sum_{i=1}^n \sum_{j=1}^m M_{g_i}^j]^{-1}$  value is calculated

$$\begin{aligned} & \left[ \sum_{i=1}^n \sum_{j=1}^m M_{g_i}^j \right]^{-1} \\ &= (1/44.937, 1/38.725, 1/33.394) \\ &= (0.022, 0.026, 0.030) \end{aligned}$$

The value of the fuzzy synthetic extent ( $S_i$ ) with respect to  $i$ th criteria ( $i = 1,2,3,4,5,6$ ) is calculated as seen in the example for criteria 1

$$\begin{aligned} S_1 &= (6.573, 7.777, 9.147) \otimes (0.022, 0.026, 0.030) \\ &= (0.146, 0.201, 0.274) \end{aligned}$$

Lastly, the BNP value of the fuzzy weights of each criterion is calculated for all six criteria. This is calculated as shown for criteria 1:

$$\begin{aligned} BNP_{S_1} &= \frac{[(0.274 - 0.146) + (0.201 - 0.146)]}{3} + 0.146 \\ &= 0.207 \end{aligned}$$

After determining the BNP value of the fuzzy weights of each criterion or the criteria weight, the second main step of this DMCE tool is to apply the prioritization of alternatives by using FTOPSIS technique using these BNP weights of criteria attained from FAHP.

2.2 Fuzzy TOPSIS

The TOPSIS technique was initially suggested by Hwang and Yoon (1981). Subsequently, the FTOPSIS method was presented by Chen and Hwang (1992). Its basic concept is to prioritize the alternatives to the identified preferred criteria for improving the sustainable performance of MTS. After determining the important weights of the criteria (BNP), FTOPSIS is used to rank the alternatives based on the closeness coefficients (CC). The method is based on the concept of selecting the best alternative, which has the shortest distance from the fuzzy positive-ideal solution (FPIS) and the longest distance from the fuzzy negative-ideal solution (FNIS). The result is a method of selecting the alternatives based on maximum similarity to the FPIS (Hwang & Yoon, 1981; Chen & Hwang, 1992). Related applications of the FTOPSIS are discussed in Cayir Ervural et al. (2018) and Awasthi et al. (2018). The algorithm of the proposed FTOPSIS method is explained in the following steps, as proposed by Chen (2000) and Chen et al. (2006):

Step 1: The alternatives are identified, as shown in Table 3.

Step 2: The opinions and voice of the experts are subjectively evaluated to give the relative weight to each alternative on the basis of the linguistic variables shown in Table 10. The experts' comparisons of alternatives according to linguistic variable (by comparing which is the more important of each two alternatives) are illustrated in Table 11. To proceed with calculations, the linguistic variables in Table 11 are converted into their corresponding TFNs found in Table 10, as defined by Shukla et al. (2014), and the results are presented in Table 12 after combining Tables 10 and 11.

**Table 10** Linguistic variables for rating (Shukla et al., 2014).

Linguistic Variables	Triangular Fuzzy Numbers
Very Poor (VP)	(0 ,0, 2)
Poor (P)	(1, 2, 3)
Medium Poor (MP)	(2, 3.5, 5)
Fair (F)	(4, 5, 6)
Medium Good (MG)	(5, 6.5, 8)
Good (G)	(7 ,8, 9)
Very Good (VG)	(8, 10, 10)

Step 3: The fuzzy decision matrix (FDM) depicted in Table 13 is constructed by determining the aggregated weight of alternatives with respect to each criterion by using Eq. (7) as presented by Shukla et al. (2014)

$$FDM_E = (l_E, m_E, u_E) \quad E = 1,2,3,\dots,6$$

$$l = \min_E(l_E), m = \frac{1}{E} \sum_{E=1}^E m, u = \max_E(u_E) \quad (7)$$

where E represents the experts, as a trio (l,m,u), representing of the lower bound or smallest possible value, the modal or most favorable value, and the upper bound or largest possible value, respectively, that describe the TFN rating of all the experts. The resulting FDM is presented in Table 13.

Step 4: The weighted normalized FDM (WNFDM) is calculated by using the criteria weights (BNP) attained from the FAHP by using Eq. (8) according to Shukla et al. (2014).

$$WNFDM = [fdm_{ij} * BNP]_{m \times n} \quad i = 1,2,\dots,m$$

$$\text{and } j = 1,2,\dots,n$$

where  $fdm_{ij}$

$$= \left( \frac{l_{ij}}{C_j}, \frac{m_{ij}}{C_j}, \frac{u_{ij}}{C_j} \right) \text{ and } C_j = \max_i(FDM) \quad (8)$$

The resulting WNFDM is presented in Table 14.

Step 5: The FPIS and the FNIS are calculated by using Eqs. (9) and (10), respectively, as presented by Chen et al. (2006)

$$FPIS = (WFNDM_1^+, WFNDM_2^+, \dots, WFNDM_n^+)$$

where  $WFNDM_j^+ = \max_i\{wfnm_{ij}\}$  (9)

$$FNIS = (WFNDM_1^-, WFNDM_2^-, \dots, WFNDM_n^-)$$

where  $WFNDM_j^- = \min_i\{wfnm_{ij}\}$

$$i = 1,2,\dots,m; j = 1,2,\dots,n \quad (10)$$

The resulting FPIS and FNIS for each criterion are presented in Table 15.

Step 6: The distance of each alternative from the FPIS and the FNIS is calculated as described by Shukla et al. (2014) by using Eqs. (11) and (12), respectively.

$$d_i^+ = \sum_{j=1}^n d_v(wfnm_{ij} * wfnm_j^+); \quad i = 1,2,\dots,m \quad (11)$$

$$d_i^- = \sum_{j=1}^n d_v(wfnm_{ij} * wfnm_j^-); \quad i = 1,2,\dots,m \quad (12)$$

where  $d_v$  is the distance between two fuzzy numbers.

The resulting distances from the alternatives to the ideal solutions are provided in Table 16 for FPIS and Table 17 for FNIS.

Step 7: The alternatives are ranked according to the CCs, where the CC can be calculated for each alternative by using Chen's (2000) equation, as presented in Eq. (13).

$$CC_i = \frac{d_i^-}{d_i^- + d_i^+}; \quad i = 1,2,\dots,m. \quad (13)$$

**Table 11** Rating the alternatives in linguistic terms

Criteria	Alternatives	Experts Rating					
		E1	E2	E3	E4	E5	E6
C1	A1	VG	VG	G	G	G	VG
	A2	F	P	MP	MP	P	F
	A3	G	G	MP	VG	F	F
	A4	VG	G	VG	VG	G	G
C2	A1	VG	VG	VG	VG	G	VG
	A2	G	G	VG	VG	F	G
	A3	G	F	G	G	VG	G
	A4	VG	VG	G	G	G	VG
C3	A1	G	VG	VG	G	G	F
	A2	G	G	VG	G	VG	G
	A3	VG	G	MP	G	G	G
	A4	G	G	G	VG	G	MP
C4	A1	G	VG	G	G	MG	VG
	A2	VG	VG	G	VG	G	VG
	A3	VG	G	G	G	VG	G
	A4	G	G	VG	G	VG	G
C5	A1	VG	G	G	VG	VG	G
	A2	VP	P	MG	F	F	MG
	A3	G	G	MG	F	G	F
	A4	VG	G	G	MG	VG	MG
C6	A1	VG	G	VG	VG	G	VG
	A2	MP	F	P	P	F	MP
	A3	G	MP	MP	MP	G	MP
	A4	VG	G	G	MG	VG	G

The ranks based on each alternative's CC are shown in Table 18. The CC represents the distance from each alternative to the FPIS and the FNIS.

### 3 Discussion of results

The activities in MTS are sources of environmental pollution, creating new and critical challenges to port managers. One such challenge is the need to reduce environmental damage while enhancing system performance. Although multi-criteria decision methods have been implemented to assess these externalities, these methods have limitations in dealing with the imprecise nature of linguistic assessment. Decision-makers face uncertainties from subjective perceptions and experiences in the decision-making process. To overcome these limitations, fuzzy multi-criteria decision-making methods have been implemented in this research.

The need to understand which alternative strategies would most significantly enhance the sustainability of an

MTS led to the integration of the FAHP and FTOPSIS methods. FAHP was used to calculate the relative weights of each criterion in Table 2, and then FTOPSIS was used to prioritize the MTS's sustainable alternatives in Table 3 based on these selection criteria.

This research ranked four alternative methodologies to promote sustainability based on six criteria. As a result, FAHP determined the most important criteria as C2, the use of clean technologies such as low-sulfur fuel or an alternative energy source, because it had the highest weight or BNP (0.239). C1, the use of green design ships, engines and machinery, was ranked as the second highest criteria with a close weight or BNP of 0.207. C1 was followed by C4, ballast water treatment and residue/water/spill control, with a BNP of 0.164; C5, logistics and scheduling efficiency for reduction of idle and waiting times, with a BNP of 0.152; C3, reuse and recycle of resources on board, with a BNP of 0.147; and C6, the usage of environmentally friendly shipping equipment and facilities, with a BNP of 0.120. The results for C2 and C1 are not surprising given that one of the main targeted issues for improving

**Table 12** Translating linguistic terms into fuzzy terms

Criteria	Alternatives	Experts Rating					
		E1	E2	E3	E4	E5	E6
C1	A1	(8,10,10)	(8,10,10)	(7,8,9)	(7,8,9)	(7,8,9)	(8,10,10)
	A2	(4,5,6)	(1,2,3)	(2,3,5,5)	(2,3,5,5)	(1,2,3)	(4,5,6)
	A3	(7,8,9)	(7,8,9)	(2,3,5,5)	(8,10,10)	(4,5,6)	(4,5,6)
	A4	(8,10,10)	(7,8,9)	(8,10,10)	(8,10,10)	(7,8,9)	(7,8,9)
C2	A1	(8,10,10)	(8,10,10)	(8,10,10)	(8,10,10)	(7,8,9)	(8,10,10)
	A2	(7,8,9)	(7,8,9)	(8,10,10)	(8,10,10)	(4,5,6)	(7,8,9)
	A3	(7,8,9)	(4,5,6)	(7,8,9)	(7,8,9)	(8,10,10)	(7,8,9)
	A4	(8,10,10)	(8,10,10)	(7,8,9)	(7,8,9)	(7,8,9)	(8,10,10)
C3	A1	(7,8,9)	(8,10,10)	(8,10,10)	(7,8,9)	(7,8,9)	(8,10,10)
	A2	(7,8,9)	(7,8,9)	(8,10,10)	(7,8,9)	(8,10,10)	(7,8,9)
	A3	(8,10,10)	(7,8,9)	(2,3,5,5)	(7,8,9)	(7,8,9)	(7,8,9)
	A4	(7,8,9)	(7,8,9)	(7,8,9)	(8,10,10)	(7,8,9)	(2,3,5,5)
C4	A1	(7,8,9)	(8,10,10)	(7,8,9)	(7,8,9)	(5,6,5,8)	(8,10,10)
	A2	(8,10,10)	(8,10,10)	(7,8,9)	(8,10,10)	(7,8,9)	(8,10,10)
	A3	(8,10,10)	(7,8,9)	(7,8,9)	(7,8,9)	(8,10,10)	(7,8,9)
	A4	(7,8,9)	(7,8,9)	(8,10,10)	(7,8,9)	(8,10,10)	(7,8,9)
C5	A1	(8,10,10)	(7,8,9)	(7,8,9)	(8,10,10)	(8,10,10)	(7,8,9)
	A2	(0,0,2)	(1,2,3)	(5,6,5,8)	(4,5,6)	(4,5,6)	(5,6,5,8)
	A3	(7,8,9)	(7,8,9)	(5,6,5,8)	(4,5,6)	(7,8,9)	(4,5,6)
	A4	(8,10,10)	(7,8,9)	(7,8,9)	(5,6,5,8)	(8,10,10)	(5,6,5,8)
C6	A1	(8,10,10)	(7,8,9)	(8,10,10)	(8,10,10)	(7,8,9)	(8,10,10)
	A2	(2,3,5,5)	(4,5,6)	(1,2,3)	(1,2,3)	(4,5,6)	(2,3,5,5)
	A3	(7,8,9)	(2,3,5,5)	(2,3,5,5)	(2,3,5,5)	(7,8,9)	(2,3,5,5)
	A4	(8,10,10)	(7,8,9)	(7,8,9)	(5,6,5,8)	(8,10,10)	(7,8,9)

**Table 13** FDM

Criteria	Alternatives			
	A1	A2	A3	A4
C1	(7,8,9)	(1,3.500,6)	(2,6.583,10)	(7,9,10)
C2	(7, 9.667,10)	(4,8.167,10)	(4,7.833,10)	(7,9,10)
C3	(7,9,10)	(7,8.667,10)	(2,7.583,10)	(2,7.583,10)
C4	(5,8.417,10)	(7,9.333,10)	(7,8.667,10)	(7,8.667,10)
C5	(7,9,10)	(0,4.167,8)	(4,6.750,9)	(5,8.167,10)
C6	(7,9.33,10)	(1,3.500,6)	(2,5,9)	(5,8.417,10)

environmental sustainability is the reduction and control of pollution due to emissions. Furthermore, such pollution reduction and control are mainly driven by reducing water pollution, which directly relates to the third ranked criteria, C4.

Once the criteria weights had been established, the alternatives could then be evaluated by using FTOPSIS. The ranking order of the four evaluated alternatives is as

follows:  $A1 > A4 > A3 > A2$ . A1, the reduction of release of substances as defined by MARPOL Annex 1-6, received a CC of 0.765. A4, the reduction of environmental deficiencies, attained a CC of 0.702. A3, the controlled spills of hazardous materials, and A2, the management of ballast water violations, received the lowest CC values of 0.561 and 0.489, respectively. A1 was the preferred alternative, presumably because it reduces air and water

**Table 14** WNFDM

Alternatives	Criteria					
	C1	C2	C3	C4	C5	C6
A1	(0.145,0.186,0.207)	(0.167,0.231,0.239)	(0.103,0.133,0.147)	(0.082,0.138,0.164)	(0.107,0.137,0.152)	(0.084,0.112,0.120)
A2	(0.021,0.072,0.124)	(0.096,0.195,0.239)	(0.103,0.128,0.147)	(0.115,0.153,0.164)	(0,0.064,0.122)	(0.012,0.042,0.072)
A3	(0.041,0.136,0.207)	(0.096,0.187,0.239)	(0.029,0.112,0.147)	(0.115,0.142,0.164)	(0.061,0.103,0.137)	(0.024,0.060,0.108)
A4	(0.145,0.186,0.207)	(0.167,0.215,0.239)	(0.029,0.112,0.147)	(0.115,0.142,0.164)	(0.076,0.124,0.152)	(0.060,0.101,0.120)

**Table 15** FPIS and FNIS per criterion

Criteria	FPIS	FNIS
C1	0.207	0.021
C2	0.239	0.096
C3	0.147	0.029
C4	0.164	0.082
C5	0.152	0.000
C6	0.120	0.012

pollution simultaneously. A1 represents a broader scope in terms of the assessment of environmental externalities resulting from maritime activities that are detrimental to the environment. The second alternative (A4) represents a system's environmental performance by measuring the number of environment-related deficiencies recorded

relative to the total number of external inspections and audits. This alternative measures the importance of complying with regulations and policies when attempting to increase the environmental performance of MTS.

The determination of which alternatives have the most influence on the environmental performance of the maritime industry is recorded in their relative ranking. This determination would allow decision-makers and managers in the industry to develop a plan that improves the sustainable environmental performance of an MTS.

## 4 Conclusions and future work

This research develops a DMCE tool that quantifies and ranks preferred environmental impact indicators within an MTS. The model helps decision-makers achieve environmental sustainability and also provides environmental

**Table 16** Distance between the alternatives and the FPIS with respect to each criterion

Distance	C1	C2	C3	C4	C5	C6	Sum
$d(A1 \text{ to FPIS})$	0.033	0.036	0.023	0.043	0.024	0.018	0.178
$d(A2 \text{ to FPIS})$	0.122	0.075	0.024	0.025	0.090	0.071	0.407
$d(A3 \text{ to FPIS})$	0.090	0.076	0.062	0.027	0.053	0.057	0.364
$d(A4 \text{ to FPIS})$	0.033	0.038	0.062	0.027	0.041	0.032	0.231

**Table 17** Distance between the alternatives and the FNIS with respect to each criterion

Distance	C1	C2	C3	C4	C5	C6	Sum
$d(A1 \text{ to FNIS})$	0.139	0.105	0.087	0.050	0.116	0.082	0.578
$d(A2 \text{ to FNIS})$	0.058	0.087	0.085	0.057	0.069	0.034	0.389
$d(A3 \text{ to FNIS})$	0.110	0.085	0.072	0.053	0.091	0.054	0.465
$d(A4 \text{ to FNIS})$	0.139	0.100	0.072	0.053	0.106	0.074	0.544

**Table 18** CC of alternatives and their respective ranking

Alternative	d+	d-	$d^+ + d^-$	CC	Rank
A1- Reduction release of substances: MARPOL	0.178	0.578	0.755	0.765	1
A2- Manage of water ballast violations	0.407	0.389	0.796	0.489	4
A3- Contained spill of hazardous materials	0.364	0.465	0.830	0.561	3
A4- Reduction of environmental deficiencies	0.231	0.544	0.775	0.702	2

policy-makers in the shipping industry with an analytical tool that can evaluate tradeoffs within the system and identify possible alternatives to mitigate detrimental effects on the environment. The integrated evaluation tool developed in this research uses FAHP and FTOPSIS methodologies and can provide marine decision-makers with a fuzzy analysis of a traditional performance evaluation model that includes the uncertainty and imprecision that comes with DMCE. The proposed method enables decision analysts in the maritime industry to better understand the complete evaluation process of alternatives and criteria for a sustainable system.

This study models the environmental effects of various green performance measures and their uncertainties by integrating fuzzy logic into the combination of AHP and the TOPSIS methods. Effective ranking of these performance measures is the result. With the use of these effective performance measures, this research developed a DMCE tool for evaluating the preferred green measures in an MTS. The DMCE tool helps eliminate model complexity that reduces an MTS's performance and provides a better understanding of beneficial elements and performance measures in terms of a system's environmental performance.

For future work, we propose to expand the model and evaluate the alternatives with respect to more detailed criteria. Also, given that the results of this research are based on the criteria and alternatives identified through an examination and survey of related literature, the testing and validation of the DMCE tool are limited to the experiences and knowledge of those who were chosen as experts. The incorporation of a greater number of experts could yield more accurate results with respect to the preferred green performance measures in the maritime industry to attain an environmentally sustainable system.

Moreover, the comprehensive methodology developed in this research can be implemented to evaluate other systems and infrastructures. This methodology will allow decision-makers to identify preferred performance indicators and make strategic decisions that will enhance the efficiency and the environmental performance of an MTS.

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