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CO_2 Emission based prioritization of bridge maintenance projects using neutrosophic fuzzy sets based decision making approach

Ilgin Gokasar [a,*], Muhammet Deveci [b], Onur Kalan [c]

[a] Department of Civil Engineering, Faculty of Engineering, Bogazici University, 34342, Bebek, Istanbul, Turkey
[b] Department of Industrial Engineering, Turkish Naval Academy, National Defence University, 34940, Tuzla, Istanbul, Turkey
[c] New York, NY, USA

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ABSTRACT

Climate change is one of the most challenging problems for the world, which leads researchers to study on the decrease of its impact to the environment at several disciplines. One of the most adverse effects on environment can be observed in transportation area. Hence, in this paper, the impact of bridge maintenance on the environment is inquired in the bridge maintenance prioritization perspective. The aim of this paper is to rank the bridge maintenance projects using type-2 neutrosophic number (T2NN) based fuzzy WASPAS (Weighted Aggregated Sum Product Assessment) and TOPSIS (Technique For Order Preference By Similarity To An Ideal Solution) to test five alternative bridges, where a critical environmental criterion is introduced in this model, which addresses to additional CO_2 emission because of truck detours in the event of a bridge closures. The applicability of the proposed model is demonstrated in a case study in Turkey. The evaluation findings show that the ranking results are robust and the CO_2 emission criterion is found to be the dominant criterion in the multi-criteria decision-making model proposed in this paper.

1. Introduction

Climate change is one of the most challenging problems in today's world. As one of the most generated greenhouse gasses (GHG), carbon dioxide (CO_2) has an increasing effect on global warming (Ritchie & Roser, 2017). The USA has one of the highest CO_2 emissions per capita (Ritchie & Roser, 2017) and it continues to increase each year. Even though the U.S. Energy Information Administration (EIA) projects that total CO_2 emissions will decrease until 2020 because of the change from fuel to electricity [1] the world CO_2 emissions are expected to increase by the end of 2050 especially among non-OECD member countries (Marchal et al., 2011).

The construction sector is responsible for 39% of CO_2 emissions in 2018, including the manufacturing of the materials (Guggemos & Horvath, 2005). Besides, the substantial usage of nonrenewable energy makes the construction sector even more critical, and there is room for further improvements to reduce CO_2 emissions created by the construction industry (BIS, 2010; Levermore, 2008). Therefore, life cycle analysis (LCA) is an important concept for the construction industry and was investigated in recent years. Yet, the focus of LCA analysis in the sector is buildings rather than infrastructure facilities (Atmaca & Atmaca, 2015; Guggemos & Horvath, 2005; Kua & Maghimai, 2017; Levermore, 2008; Stephan & Stephan, 2016).

Here, another important source of CO_2 is the materials used that ranges from the substitution of the materials such as asphalt (Mladenovič et al., 2015), sand (Kua, 2013), and even cement (Crossin, 2015). In the US to minimize the environmental damages of bridge paints, new coating systems are developed (Itoh & Kitagawa, 2003). A study discusses the different CO_2 emissions of steel and concrete and found that reinforced concrete has lower embodied energy depending on the case (Kua & Maghimai, 2017). Another study investigates the usage of alternative structural systems extensively by considering many elements such as materials, transportation, and fuel emissions (Cole, 1998).

The concept of embodied energies is especially important for infrastructures such as roads, bridges, and tunnels because they are the reason for over 90% of life cycle emissions (Huang et al., 2015; Stephan & Stephan, 2016). The LCA studies test that infrastructure construction is mainly based on material use (Huang et al., 2015). The same applies to maintenance activities. The operational energy that includes the

* Corresponding author.
E-mail addresses: ilgin.gokasar@boun.edu.tr (I. Gokasar), muhammetdeveci@gmail.com (M. Deveci), dronurkalan@gmail.com (O. Kalan).

[1] https://www.eia.gov/energyexplained/.

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heating, cooling, etc. of the building covers most of the CO_2 emissions of a building. Yet, for a bridge, this stage does not include many aspects. Therefore, the major source of CO_2 emissions is the construction and maintenance of the bridges. In this paper, the CO_2 emission is much more tested as an additional fuel consumption because of truck detours.

Testing alternatives should not only base on traditional cost evaluation methods. Instead, it should consider environmental costs as an important parameter. In this perspective, this study aims to develop a multi-criteria decision-making (MCDM) methodology to assess the bridge maintenance projects based on their CO_2 emissions. Especially, in the analysis section of this paper, it is shown that the highest importance weight among the criteria is assigned to the CO_2 emissions by the decision-makers, which also supports the claim of this paper. One contribution of this paper is to propose a new model to assess different maintenance projects by taking the environment into the heart of the methodology.

This study proposes a new hybridizing type-2 neutrosophic number (T2NN) based fuzzy WASPAS (Weighted Aggregated Sum Product Assessment) and TOPSIS (Technique For Order Preference By Similarity To An Ideal Solution) model to prioritize the bridge maintenance projects. One of the major contributions of this study is to present a prioritizing tool using expert knowledge. Another contribution is to develop a hybrid MCDM model named fuzzy T2NN based WASPAS and TOPSIS that enables the alternative evaluation from qualitative and quantitative information and provides the best alternative for decision-makers.

2. Related works

2.1. Bridge maintenance studies

In the literature, most of the studies focus on the economic evaluation of bridge maintenance projects by ignoring the environmental costs (Liu & Frangopol, 2005; Miyamoto et al., 2000). There are different techniques to manage bridge maintenance such as Markovian models (Scherer & Glagola, 1994) and genetic algorithms (Liu et al., 1997; Liu & Frangopol, 2004; Neves et al., 2006). However, using multi-attribute decision-making (MCDM) techniques is highly preferred to test different alternatives (Bai et al., 2008, 2013; Li & Sinha, 2004; Zayed et al., 2007). The investigation for the bridge maintenance projects is conducted by their risk, certainty, and uncertainty conditions based on the goals and weights that are given accordingly (Bai et al., 2008; Jeon, 2010; Li & Sinha, 2004). Maintaining the level of service (LOS) is also a goal for the maintenance projects, especially for urban areas (Kim et al., 2016).

In bridge management area, one of the most common MCDM techniques is the Utility model. The utility model allows the decision-makers to prioritize different project alternatives according to a given set of criteria by considering the decision-makers' tendencies towards risk-taking attitudes, such as being risk-averse. The utility model considers the Weighted Sum Model (WSM) approach that sums up the derived utility values for each criterion for each project alternative by multiplying them with the corresponding criterion's weight (Patidar, Labi, Sinha, & Thompson, 2007). However, in this paper, the WASPAS method is considered, which is an aggregation of the Weighted Sum Model (WPM) and Weighted Product Model (WPM). According to https://eejournal.ktu.lt/index.php/elt/article/view/1810's study, it is found that the accuracy of the WASPAS method increases up to 1.6 times compared to WSM. Due to its high reliability, WASPAS is selected as the MCDM technique used in this paper.

In a study, identifying the performance measures is accepted as one of the most important efforts to choose the best action (Patidar, Labi, Sinha, Thompson, et al., 2007). The goals to satisfy those measures are defined as preservation, traffic safety, and cost minimization as most of the studies already suggest. Apart from the identification of the performance measures, the proper combination and trade-off evaluation are also important. Therefore, many methodologies convert different units into one unit to compare all criteria by weighting through MCDM proven very effective for network-level decision making (Bai et al., 2008; Li and Sinha, 2004, 2009; Matos & Sein, 2017; Sun et al., 2017; Zayed et al., 2007). Network-level performance is an important comparison element in the evaluation procedure because it considers the effects of a single project for the entire network which will affect the traffic situation (Bai et al., 2013; Sun et al., 2017).

Few studies consider sustainability as a parameter (Jeon, 2010; Padgett & Tapia, 2013). A study considers CO_2 emissions as an environmental sustainability criteria to minimize the greenhouse effect and air pollution. In the sensitivity analysis, it is found that over 40% weight must be given to the CO_2 emissions so that the final decision would be effected (Jeon, 2010). Even though Life Cycle Analysis was gaining popularity around the world and was considered in the construction industry (Carreras et al., 2016; Kendall et al., 2008; Silvestre et al., 2013; Wang et al., 2015), in the literature, the effects of environmental cost are not investigated broadly for bridge maintenance (Estes & Frangopol, 2001; van Noortwijk & Frangopol, 2004). According to a study by the New Jersey Department of Transportation (DOT), only 12.5% of the states apply LCA on bridges (Ozbay et al., 2004). Yet, it is highly necessary for the bridges to test the whole life-cycle by including environmental costs to be successful (Matos & Sein, 2017).

A study conducts a life cycle cost analysis (LCCA) to assess the pavement maintenance strategy by using a multi-attribute approach (Giustozzi et al., 2012). The maintenance should be applied at the proper time while the pavement still has high serviceability. The study includes not only CO_2 emissions but also other parameters (quality, cost, etc.) into the decision process by considering materials and traffic situations. Traffic situation should be one consideration in the LCA analysis, as suggested in some studies that CO_2 emissions mostly derived from the traffic on the road (Huang et al., 2009). Yet, the pollution damage costs are difficult to estimate only by adding the cost per metric ton of carbon. Therefore, a study used Monte Carlo simulation to address the uncertainty (Kendall et al., 2008).

A study (Itoh & Kitagawa, 2003) categorizes the maintenance components of a bridge as pavement, deck, painting, expansion joint, and support. It compares two different bridges by considering CO_2 emissions throughout their life cycle. Conventional bridges (CB) resulted in having more CO_2 emissions and costs compared to minimized girder bridges (MGB). The same results are also approved in another study that compares different bridge designs (Tsubouchi et al., 2006). The comparison of different bridge types in terms of life cycle costs is relatively common in the literature (Chandler, 2004; Kendall, 2004; Keoleian et al., 2005; Keoleian et al., 2005, 2005).

If the CO_2 emissions are considered as a criterion, the primary focus in the literature is given to the entire life cycle of a bridge or just the construction phase. A study aims to test different maintenance projects based on LCA to show operators how to standardize the procedure and how to manage more efficiently and sustainability (Matos & Sein, 2017). Another study offers a decision support system to optimize the maintenance of RC girder bridge superstructures by minimizing life-cycle cost and environmental impact. Even though the study evaluates a single bridge, it can be broadened for multiple projects. Yet, the CO_2 emission data is still restricted as suggested in the study (Sun et al., 2015).

A study creates a bridge management strategy based on the risks arising from climate change events (flood, sea-level rise, and hurricanes). It proposes a framework that tests possible conclusions of a transportation network and investigates different climate change scenarios. Yet, CO_2 emissions are not considered as a parameter to assess the bridge maintenance (Liu et al., 2020).

As a result, there are many approaches to consider the environmental costs, especially based on the materials used, and most studies gather around the LCA analysis or construction phase by focusing on buildings rather than bridges. So, there is still a gap in the literature for bridge maintenance assessment. None of the existing studies considers CO_2 emissions because of additional fuel consumption as a dominant criterion to assess different maintenance project options.

2.2. Fuzzy MCDM studies using neutrosophic sets

There have been studies investigating neutrosophic fuzzy sets for different MCDM problems over the last decade. The studies on fuzzy MCDM using neutrosophic fuzzy sets are presented in Table 1.

The nature of the assessment of bridge maintenance projects possesses uncertain and imprecise data. This study uses the neutrosophic sets which specialize in processing unclear, unpredictable, and indeterminate information since they have been proved to be an efficient tool to handle an expert's impreciseness or incompleteness (Abdel--Basset, Saleh, et al., 2019). It has not yet been implemented to the assessment of bridge maintenance problems.

In addition, MCDM-based studies have been conducted in various applications such as some determining criteria weight coefficients using CRITIC method (Žižović et al., 2020), soft multi-set topology with applications in MCDM method (Riaz et al., 2020), ranking of the listed failure causes using intuitionistic fuzzy based failure mode effect analysis and TOPSIS (Kushwaha et al., 2020), evaluating criteria importance in selecting reach stackers by fuzzy PIPRECIA (Vesković et al., 2020), selecting an airport ground access mode using fuzzy LBWA-WASPAS (Pamucar et al., 2020), prioritizing the alternatives of the hydrogen bus development usinf fuzzy MCDM (Pamucar et al., 2020), and locating an authorized dismantling center using intuitionistic fuzzy MCDM-based CODAS method (Karagoz et al., 2020).

3. Problem definition

From the literature, we find that different approaches are applied in many types of research for understanding the impact of a decision-making process on bridge asset management practices. However, there is still a gap in addressing the impact of environmental effects precisely, especially CO_2 emission because of additional fuel consumption. In this paper, we consider a hybrid model in a dataset of five bridges in Northwestern Turkey. This paper aims to illustrate the impact of different criteria set on the prioritization of these given bridges. Notably, the impact of the CO_2 emission-based criterion is tested separately after the results are achieved. The result of the decision-making model indicates a significant effect of CO_2 emission criterion on the approach of the decision-makers towards the rankings of the bridges. One contribution of this paper is considering the additional CO_2 emission of the trucks detouring in case of a closure of a bridge with adverse physical conditions. The main added value of this paper is the use of fuzzy T2NN based WASPAS and TOPSIS approach to eliminate the uncertainty and lack of information from conflicting opinions.

3.1. Definition of alternatives

In this study, five different bridge alternatives are selected in Turkey. These bridges and their information are obtained from the study (Masoumi, 2014). These bridges are in the same region of Turkey, the Marmara Region, and they all are in highways. The summary of these five different alternatives is provided in Table 2. The alternatives in the study region are illustrated in Fig. 1.

3.2. Determination of decision-making criteria

The criteria selection process is performed based on the discussion between the decision-makers among several goals, several of them are already in bridge management literature (Patidar, Labi, Sinha, & Thompson, 2007), to be achieved by prioritizing the different project alternatives. That said, the most appropriate criteria set for the existing project dataset are given below.

3.2.1. Cost criteria

- *Cost Effectiveness (C_1):* It is a criterion measured by an index where the ratio of needed funds for a bridge to its rehabilitation cost is scaled into a utility score where a similar method is provided in VDOT Bridge Prioritization Guide (Structure and Bridge Maintenance Program Area, 2018). Fig. 2 illustrates the Cost-Effectiveness score regarding Fund Needs for a bridge maintenance per this bridge's Rehabilitation cost amount. As it is shown in this figure, the larger ratio of fund needs for the maintenance of a bridge to rehabilitation cost of the same bridge leads to fewer cost-effectiveness scores. For example, if the funds for bridge maintenance equals to the rehabilitation cost amount of the same bridge, then it means the current condition of this bridge is not cost effective. Hence, to increase its cost-effectiveness, this bridge should get the first rank in maintenance planning.
- *Additional Fuel Consumption Cost (C_2):* It is a mobility-based index criterion, which considers the additional fuel consumption cost once traffic is interrupted by either maintenance or replacement. Therefore, the amount of average daily traffic passes on the roadway of this bridge is affected–the same formulation in the VDOT Bridge Prioritization document used in the analysis in this paper.

3.2.2. Technical criteria

- *Physical Condition (C_3):* Bridge Condition Rating (BCR) is used as scaling for bridge's overall physical condition that extends from 1 to 4.1 and 4 represent best and the worst condition values, respectively (Masoumi, 2014).
- *Exposure to Fatigue (C_4):* It is a criterion that shows the level of fatigue exposure in a bridge by considering average daily truck amount passes over the bridge and the age of the bridge.

3.2.3. Social criteria

- *Appropriateness for Maintenance (C_5):* This criterion provides insight for decision-makers to let them test a bridge according to its geometric and traffic based capabilities to allow both maintenance and traffic flow at the same time. Because of this, road width and deck length information of each bridge is provided to decision-makers as proxy variables for this criterion.
- *Social Impact for Travelers (C_6):* This criterion helps decision-makers to test each bridge concerning detouring of the vehicles passing over it in the event of closure of this bridge. The longer detours may have more adverse social impacts on the travelers, therefore, community. Hence, this criterion is provided to decision-makers to help them in their evaluation of the bridges for detours.
- *Importance factor (C_7):* It is a criterion where the decision-makers measure a bridge's importance in a logistics perspective. Once a bridge is closed, therefore the trucks pass on this bridge will be affected adversely, and logistics. That being said, the decision-makers are asked to test each bridge regarding logistics perspective in this criterion.

3.2.4. Environmental criteria

- *CO_2 Emission (C_8):* It is an environmental-based sustainability criterion which calculates the CO_2 emission amount of the trucks on a bridge because of the additional detour length led by the bridge maintenance.

The fuel consumption formula is obtained from the study (Kellner, 2016) as given below: $FC = \left(a + b^*v + c^*v^2 + \frac{d}{v}\right) \Big/ (e + f^*v + g^*v^2)$

In our analysis, it is supposed that the trucks are Rigid 20–26 tons (max. payload is 12 tons), and the load factor is assumed as 50%. Thus,

Table 1
Overview of the neutrosophic sets studies on fuzzy MCDM.

Author(s) and Year	Main-criteria	Sub-criteria	Alternatives	MCDM Problem	Fuzzy Sets	AHP	TOPSIS	VIKOR	DEMATEL	PROMETHEE	MABAC	ELECTRE	QFD	MULTIMOORA	TODIM	MAIRCA
Tiwari and Kumar (2020)	–	10	6	Cloud service selection	Yes		x									
Supciller and Toprak (2020)	4	22	6	Wind turbine selection	Yes		x									
Pamucar et al. (2020)	4	13	6	Prioritizing the energy storage technologies selection	Yes											X
Hezam et al. (2020)	4	15	–	Determining the priority groups for COVID-19 Vaccine	No	x	x									
Başhan et al. (2020)	–	–	23	Maritime risk evaluation	Yes		x									
Abdel-Basset, Saleh, et al. (2019)	–	6	4	Fighter aircraft selection	Yes		x		x							
Abdel-Basset, Manogaran, and Mohamed (2019)	–	3	5	Security service selection	Yes					x						
Kilic and Yalcin (2020)	–	8	–	Environmental dimensions evaluation	Yes		x		x							
Ji et al. (2018)	–	3	5	Outsourcing provider selection	Yes						x	x				
Abdel-Basset et al. (2018)	5	7	5	Supplier selection	Yes	x							x			
Liang et al. (2017)	4	22	6	E-commerce website evaluation	Yes				x							
Zavadskas et al. (2017)	–	21	5	Material selection	No									x		
Şahin and Yiğider (2014)	–	5	5	Supplier selection	Yes		x									
Ji et al. (2018)	–	3	4	Personnel selection	Yes										x	

Table 2
Characteristics of the alternatives for evaluation.

Code	Bridge Name	Roadway	Province	BCR[a]	ADT (veh)	Optimal Repair Cost (TL)	Rehabilitation Cost (TL)	Detour Length (km)
A	BAYRAMDERE	BEYCAYIRI-IL SN.	CANAKKALE	1.68	3,191	10,986.00	13,047.00	0.35
B	KINALI KAV. KARAYOLU	CORLU-ISTANBUL	ISTANBUL	1.19	13,329	1,770.00	4,061.00	5.40
C	SEREFLI CIFTLIGI	SILIVRI-LULEBURGAZ	TEKIRDAG	1.19	13,329	3,860.00	3,860.00	0.05
D	MUDURNU	KOCAELI-DUZCE	KOCAELI	1.12	17,487	7,334.00	9,430.00	30.00
E	KARAHISAR	KESAN-ENEZ	EDIRNE	1.40	840	12,791.00	12,791.00	30.00

[a] BCR: Bridge Condition Rating.

Table 3
The values of coefficient.

Coefficients	Values
A	−465.38
B	155.18
C	5.93
D	1888.82
E	1
F	−0.22
G	0.05
V	75 km/h

the coefficients are:

By using this FC formula, it is achieved that how much fuel a truck consumes per one kilometer. This additional unit fuel consumption emits 3.1643 g CO_2 (Kellner, 2016). Therefore, the total CO_2 emission value due to detour of trucks can be calculated as:

4. Preliminaries

4.1. Type-1 neutrosophic set

The neutrosophic sets (NSs) was introduced by Smarandache (1999). The NSs are extension of intuitionistic fuzzy sets (IFSs) theory. IFSs were proposed by Atanassov (1986) as an extension of Zadeh's fuzzy sets theory known as type-1 fuzzy sets (Zadeh, 1965). Although IFS can only successful in processing incomplete information, the NSs can handle both indeterminate and inconsistent information in decision making systems (Smarandache, 1998). Fig. 3 illustrates geometric representation of various fuzzy extensions including NSs, IFSs, PFSs (Pythagorean fuzzy sets) and SFSs (Spherical fuzzy sets) and the differences among these extensions. It can be concluded from Fig. 3 that NSs are a generalization of all fuzzy set extensions.

A neutrosophic set can be characterized by three independent degree such as a truth membership function T, an indeterminacy membership function I and a falsity membership function F (Mohamed et al., 2017), where the new parameter "indeterminacy" was incorporated to IFS definition (Smarandache, 1999).

Definition 1. (Pawlak, 1982). Let $\widetilde{P}$ be an initial universe of discourse,

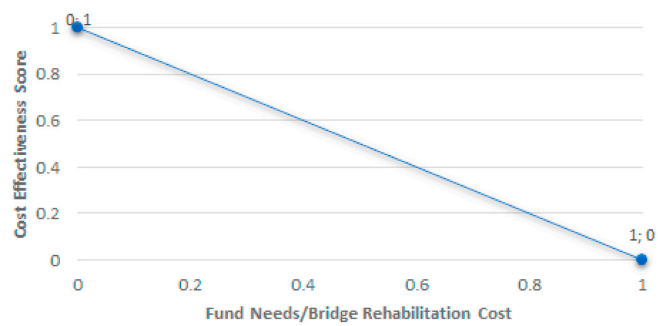

Fig. 2. Cost effectiveness score.

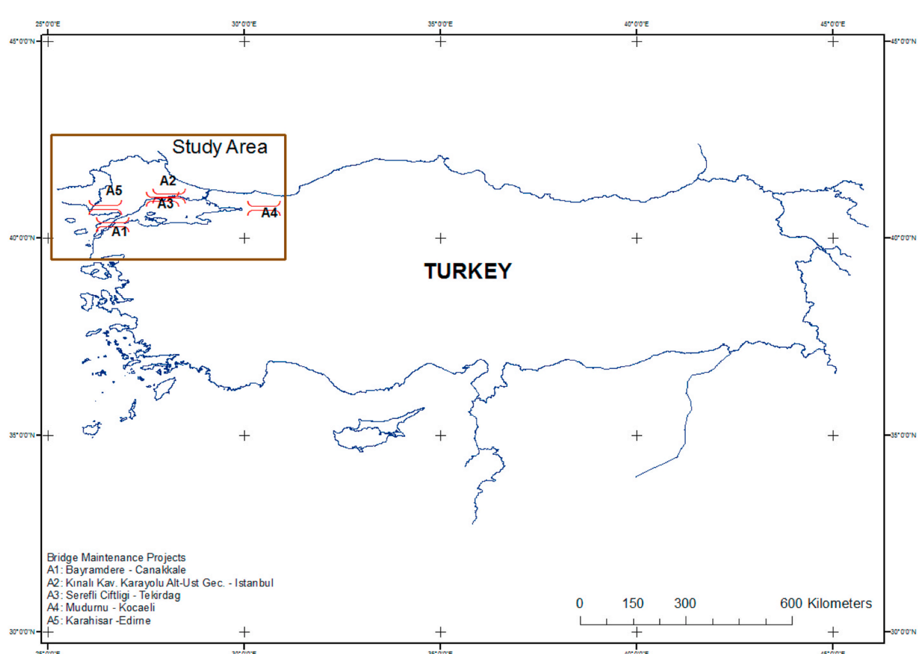

Fig. 1. Study region in the Marmara Region of Turkey.

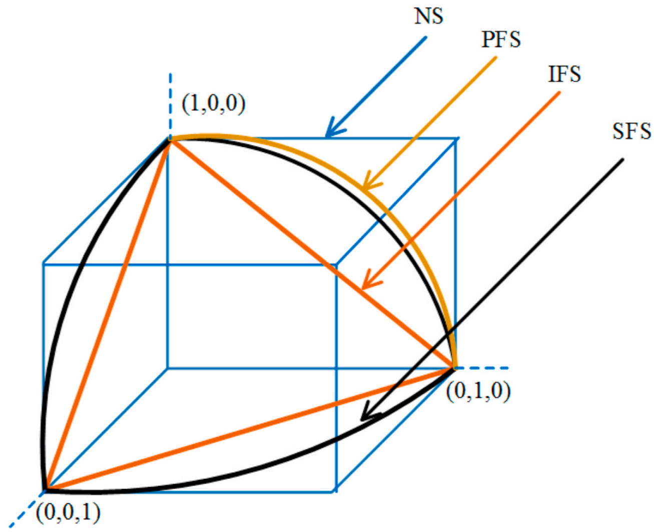

Fig. 3. Geometric representation of various fuzzy set extensions and neutrosophic sets.

with a generic element in $\widetilde{P}$ denoted by $\widetilde{p}$, a neutrosophic set can be denoted as follow:

$$\widetilde{C} = \left\{ \langle \widetilde{p} : T_{\widetilde{C}}(\widetilde{p}), I_{\widetilde{C}}(\widetilde{p}), F_{\widetilde{C}}(\widetilde{p}) \rangle \middle| \widetilde{p} \in \widetilde{P} \right\} \tag{1}$$

where the functions $T, I, F : \widetilde{P} \rightarrow]^{-}0, 1^{+}[$ define respectively the degree of membership (or Truth), the degree of indeterminacy, and the degree of nonmembership (or Falsehood) of the element $\widetilde{p} \in \widetilde{P}$ to the set $\widetilde{C}$ with the condition $0^{-} \leq T_{\widetilde{C}}(\widetilde{p}), I_{\widetilde{C}}(\widetilde{p}), F_{\widetilde{C}}(\widetilde{p}) \leq 3^{+}$.

4.2. Type-2 neutrosophic set

In this section, the some basic concepts and operators of type-2 neutrosophic number set are introduced. It represents expansions of single-valued neutrosophic sets using triangular fuzzy numbers.

Definition 1. (Abdel-Basset, Saleh, et al., 2019). Let P be the universe of discourse. A neutrosophic set C in P are characterized by a truthy T_C, indeterminacy I_C, and falsity F_C membership functions (Smarandache, 2005). The type-2 fuzzy neutrosophic set $\widetilde{C}$ in P is defined as follows. $\widetilde{C} = \{\langle p, T_{\widetilde{C}}(p), I_{\widetilde{C}}(p), F_{\widetilde{C}}(p)\rangle | p \in P\}$, where $T_{\widetilde{C}}(p) : P \rightarrow T[0,1]$, $I_{\widetilde{C}}(p) : P \rightarrow I[0,1]$, and $F_{\widetilde{C}}(p) : P \rightarrow F[0,1]$. The elements of type-2 neutrosophic number set (T2NNS) can be stated as $T_{\widetilde{C}}(p) = (T_{T_{\widetilde{C}}}(p), T_{I_{\widetilde{C}}}(p), T_{F_{\widetilde{C}}}(p))$, $I_{\widetilde{C}}(p) = (I_{T_{\widetilde{C}}}(p), I_{I_{\widetilde{C}}}(p), I_{F_{\widetilde{C}}}(p))$, and $F_{\widetilde{C}}(p) = (F_{T_{\widetilde{C}}}(p), F_{I_{\widetilde{C}}}(p), F_{F_{\widetilde{C}}}(p))$, respectively.$C = ((T_T, T_I, T_F), (I_T, I_I, I_F), (F_T, F_I, F_F) | p \in P)$ can be also represented as a T2NNS.

$T_{\widetilde{C}}(p) = (T_{\widetilde{C}}^{1}(p), T_{\widetilde{C}}^{2}(p), T_{\widetilde{C}}^{3}(p))$, $I_{\widetilde{C}}(p) = (I_{\widetilde{C}}^{1}(p), I_{\widetilde{C}}^{2}(p), I_{\widetilde{C}}^{3}(p))$, and $F_{\widetilde{C}}(p) = (F_{\widetilde{C}}^{1}(p), F_{\widetilde{C}}^{2}(p), F_{\widetilde{C}}^{3}(p))$, where $T_{\widetilde{C}}(p), I_{\widetilde{C}}(p)$ and $F_{\widetilde{C}}(p)$ are $P \rightarrow [0,1]$. For every $p \in P : 0 \leq T_{\widetilde{C}}^{1}(p) + I_{\widetilde{C}}^{1}(p) + F_{\widetilde{C}}^{1}(p) \leq 3$ are stated.

Definition 2. (Abdel-Basset, Saleh, et al., 2019). Let $\widetilde{C}_1 = \langle (T_{T_{\widetilde{C}_1}}(p), T_{I_{\widetilde{C}_1}}(p), T_{F_{\widetilde{C}_1}}(p)), (I_{T_{\widetilde{C}_1}}(p), I_{I_{\widetilde{C}_1}}(p), I_{F_{\widetilde{C}_1}}(p)), (F_{T_{\widetilde{C}_1}}(p), F_{I_{\widetilde{C}_1}}(p), F_{F_{\widetilde{C}_1}}(p)) \rangle$ and $\widetilde{C}_2 = \langle (T_{T_{\widetilde{C}_2}}(p), T_{I_{\widetilde{C}_2}}(p), T_{F_{\widetilde{C}_2}}(p)), (I_{T_{\widetilde{C}_2}}(p), I_{I_{\widetilde{C}_2}}(p), I_{F_{\widetilde{C}_2}}(p)), (F_{T_{\widetilde{C}_2}}(p), F_{I_{\widetilde{C}_2}}(p), F_{F_{\widetilde{C}_2}}(p)) \rangle$ be two type-2 neutrosophic numbers in the set of real numbers.

Some definitions are given as follows (Abdel-Basset, Saleh, et al., 2019; Biswas et al., 2016):

(1) The addition between two type-2 fuzzy neutrosophic numbers are given as follows:

$$\begin{aligned}\widetilde{C}_1 \oplus \widetilde{C}_2 = \langle & \Big(T_{T_{\widetilde{C}_1}}(p) + T_{T_{\widetilde{C}_2}}(p) - T_{T_{\widetilde{C}_1}}(p) \cdot T_{T_{\widetilde{C}_2}}(p), T_{I_{\widetilde{C}_1}}(p) + T_{I_{\widetilde{C}_2}}(p) - \\ & T_{I_{\widetilde{C}_1}}(p) \cdot T_{I_{\widetilde{C}_2}}(p), T_{F_{\widetilde{C}_1}}(p) + T_{F_{\widetilde{C}_2}}(p) - T_{F_{\widetilde{C}_1}}(p) \cdot T_{F_{\widetilde{C}_2}}(p) \Big) \\ & \Big(I_{T_{\widetilde{C}_1}}(p) \cdot I_{T_{\widetilde{C}_2}}(p), I_{I_{\widetilde{C}_1}}(p) \cdot I_{I_{\widetilde{C}_2}}(p), I_{F_{\widetilde{C}_1}}(p) \cdot I_{F_{\widetilde{C}_2}}(p) \Big), \\ & \Big(F_{T_{\widetilde{C}_1}}(p) \cdot F_{T_{\widetilde{C}_2}}(p), F_{I_{\widetilde{C}_1}}(p) \cdot F_{I_{\widetilde{C}_2}}(p), F_{F_{\widetilde{C}_1}}(p) \cdot F_{F_{\widetilde{C}_2}}(p) \Big) \rangle \end{aligned} \tag{2}$$

(2) The multiplication between two type-2 fuzzy neutrosophic numbers are given as follows:

$$\begin{aligned}\widetilde{C}_1 \otimes \widetilde{C}_2 = \langle & \Big(\Big(T_{T_{\widetilde{C}_1}}(p) \cdot T_{T_{\widetilde{C}_2}}(p), T_{I_{\widetilde{C}_1}}(p) \cdot T_{I_{\widetilde{C}_2}}(p), T_{F_{\widetilde{C}_1}}(p) \cdot T_{F_{\widetilde{C}_2}}(p) \Big), \\ & \Big(I_{T_{\widetilde{C}_1}}(p) + I_{T_{\widetilde{C}_2}}(p) - I_{T_{\widetilde{C}_1}}(p) \cdot I_{T_{\widetilde{C}_2}}(p) \Big), \Big(I_{I_{\widetilde{C}_1}}(p) + I_{I_{\widetilde{C}_2}}(p) - I_{I_{\widetilde{C}_1}}(p) \cdot I_{I_{\widetilde{C}_2}}(p) \Big), \\ & \Big(I_{F_{\widetilde{C}_1}}(p) + I_{F_{\widetilde{C}_2}}(p) - I_{F_{\widetilde{C}_1}}(p) \cdot I_{F_{\widetilde{C}_2}}(p) \Big) \Big) \\ & \Big(F_{I_{\widetilde{C}_1}}(p) + F_{I_{\widetilde{C}_2}}(p) - F_{I_{\widetilde{C}_1}}(p) \cdot F_{I_{\widetilde{C}_2}}(p) \Big), \Big(F_{F_{\widetilde{C}_1}}(p) + F_{F_{\widetilde{C}_2}}(p) - F_{F_{\widetilde{C}_1}}(p) \cdot F_{F_{\widetilde{C}_2}}(p) \Big) \Big) \end{aligned} \tag{3}$$

(3) The arithmetic operation for a type-2 fuzzy neutrosophic number is given as follows:

$$\theta\widetilde{C} = \langle \left(1-\left(1-T_{T_{\widetilde{C}_1}}(p)\right)^{\theta}, 1-\left(1-T_{I_{\widetilde{C}_1}}(p)\right)^{\theta}, 1-\left(1-T_{F_{\widetilde{C}_1}}(p)\right)^{\theta}\right), \left(\left(I_{T_{\widetilde{C}_1}}(p)\right)^{\theta}, \left(I_{I_{\widetilde{C}_1}}(p)\right)^{\theta}, \left(I_{F_{\widetilde{C}_1}}(p)\right)^{\theta}\right), \left(\left(F_{T_{\widetilde{C}_1}}(p)\right)^{\theta}, \left(F_{I_{\widetilde{C}_1}}(p)\right)^{\theta}, \left(F_{F_{\widetilde{C}_1}}(p)\right)^{\theta}\right)\rangle \tag{4}$$

where $\theta > 0$

(4) The exponentiation of a type-2 fuzzy neutrosophic number is given as follows:

$$\widetilde{C}^{\theta} = \langle \left(\left(T_{T_{\widetilde{C}_1}}(p)\right)^{\theta}, \left(T_{I_{\widetilde{C}_1}}(p)\right)^{\theta}, \left(T_{F_{\widetilde{C}_1}}(p)\right)^{\theta}\right), \left(1-\left(1-I_{T_{\widetilde{C}_1}}(p)\right)^{\theta}, 1-\left(1-I_{I_{\widetilde{C}_1}}(p)\right)^{\theta}, 1-\left(1-I_{F_{\widetilde{C}_1}}(p)\right)^{\theta}\right), \left(1-\left(1-F_{T_{\widetilde{C}_1}}(p)\right)^{\theta}, 1-\left(1-F_{I_{\widetilde{C}_1}}(p)\right)^{\theta}, 1-\left(1-F_{F_{\widetilde{C}_1}}(p)\right)^{\theta}\right)\rangle \tag{5}$$

where $\theta > 0$

Definition 3. (Abdel-Basset, Saleh, et al., 2019). Suppose that $\widetilde{C}_1 = \langle (T_{T_{\widetilde{C}_1}}(p), T_{I_{\widetilde{C}_1}}(p), T_{F_{\widetilde{C}_1}}(p)), (I_{T_{\widetilde{C}_1}}(p), I_{I_{\widetilde{C}_1}}(p), I_{F_{\widetilde{C}_1}}(p)), (F_{T_{\widetilde{C}_1}}(p), F_{I_{\widetilde{C}_1}}(p), F_{F_{\widetilde{C}_1}}(p)) \rangle$ are type-2 neutrosophic number sets. The score function of $S(\widetilde{C}_1)$ of $\widetilde{C}_1$ is stated as follows:

$$S\left(\widetilde{C}_1\right) = \frac{1}{12}\langle 8 + \left(T_{T_{\widetilde{C}_1}}(p) + 2\left(T_{I_{\widetilde{C}_1}}(p)\right) + T_{F_{\widetilde{C}_1}}(p)\right) - \left(I_{T_{\widetilde{C}_1}}(p) + 2\left(I_{I_{\widetilde{C}_1}}(p)\right) + I_{F_{\widetilde{C}_1}}(p)\right) - \left(F_{T_{\widetilde{C}_1}}(p) + 2\left(F_{I_{\widetilde{C}_1}}(p)\right) + F_{F_{\widetilde{C}_1}}(p)\right)\rangle \tag{6}$$

Definition 4. (Abdel-Basset, Saleh, et al., 2019). Suppose that $\widetilde{C}_1 = \langle (T_{T_{\widetilde{C}_1}}(p), T_{I_{\widetilde{C}_1}}(p), T_{F_{\widetilde{C}_1}}(p)), (I_{T_{\widetilde{C}_1}}(p), I_{I_{\widetilde{C}_1}}(p), I_{F_{\widetilde{C}_1}}(p)), (F_{T_{\widetilde{C}_1}}(p), F_{I_{\widetilde{C}_1}}(p), F_{F_{\widetilde{C}_1}}(p)) \rangle$ are type-2 neutrosophic number sets. The accuracy function of $A(\widetilde{C}_1)$ of $\widetilde{C}_1$ is stated as follows:

$$A\left(\widetilde{C}_1\right) = \frac{1}{4}\langle \left(T_{T_{\widetilde{C}_1}}(p) + 2\left(T_{I_{\widetilde{C}_1}}(p)\right) + T_{F_{\widetilde{C}_1}}(p)\right) - \left(F_{T_{\widetilde{C}_1}}(p) + 2\left(F_{I_{\widetilde{C}_1}}(p)\right) + F_{F_{\widetilde{C}_1}}(p)\right)\rangle \tag{7}$$

Definition 5. (Abdel-Basset, Saleh, et al., 2019). Let $\widetilde{C}_1 = \langle (T_{T_{\widetilde{C}_1}}(p), T_{I_{\widetilde{C}_1}}(p), T_{F_{\widetilde{C}_1}}(p)), (I_{T_{\widetilde{C}_1}}(p), I_{I_{\widetilde{C}_1}}(p), I_{F_{\widetilde{C}_1}}(p)), (F_{T_{\widetilde{C}_1}}(p), F_{I_{\widetilde{C}_1}}(p), F_{F_{\widetilde{C}_1}}(p)) \rangle$ and $\widetilde{C}_2 = \langle (T_{T_{\widetilde{C}_2}}(p), T_{I_{\widetilde{C}_2}}(p), T_{F_{\widetilde{C}_2}}(p)), (I_{T_{\widetilde{C}_2}}(p), I_{I_{\widetilde{C}_2}}(p), I_{F_{\widetilde{C}_2}}(p)), (F_{T_{\widetilde{C}_2}}(p), F_{I_{\widetilde{C}_2}}(p), F_{F_{\widetilde{C}_2}}(p)) \rangle$ be two type-2 neutrosophic numbers. $S(\widetilde{C}_i)$ and $A(\widetilde{C}_i)$ denote the score and accuracy functions of T2NNS $C_i (i = 1, 2)$, respectively. The relations between them can be defined as follows:

Table 4
The CO_2 emission values for each alternative.

Alternatives	CO_2 emissions (g)
A1	164,140.89
A2	6,348,337.35
A3	46,685.19
A4	61,799,523.51
A5	2,005,341.22

1. If $S(\widetilde{C}_1) > S(\widetilde{C}_2)$, then $\widetilde{C}_1 > \widetilde{C}_2$
2. If $S(\widetilde{C}_1) = S(\widetilde{C}_2)$, $A(\widetilde{C}_1) > A(\widetilde{C}_2)$ then $\widetilde{C}_1 > \widetilde{C}_2$
3. If $S(\widetilde{C}_1) = S(\widetilde{C}_2)$, $A(\widetilde{C}_1) = A(\widetilde{C}_2)$ then $\widetilde{C}_1 = \widetilde{C}_2$

Definition 6. (Ruipu & Wende, 2017). Let $\widetilde{C}_1 = ((T_1, T_2, T_3), (I_1, I_2, I_3), (F_1, F_2, F_3))$ and $\widetilde{C}_2 = ((K_1, K_2, K_3), (L_1, L_2, L_3), (M_1, M_2, M_3))$ be two type-2 neutrosophic numbers. The distance measure $d(\widetilde{C}_1, \widetilde{C}_2)$ between $\widetilde{C}_1$ and $\widetilde{C}_2$ can be stated as follows:

$$d\left(\widetilde{C}_1, \widetilde{C}_2\right) = 1 - \frac{\sum_{i=1}^{3} T_i K_i + \sum_{i=1}^{3} I_i L_i + \sum_{i=1}^{3} F_i M_i}{\left(\sum_{i=1}^{3}(T_i)^2 + \sum_{i=1}^{3}(I_i)^2 + \sum_{i=1}^{3}(F_i)^2\right) \times \left(\sum_{i=1}^{3}(K_i)^2 + \sum_{i=1}^{3}(L_i)^2 + \sum_{i=1}^{3}(M_i)^2\right)} \tag{8}$$

4.3. *Proposed hybrid model including WASPAS and TOPSIS*

The steps of hybrid model are as follows:

Let $a_i = \{a_1, a_2, \cdots, a_m\}$ be set of alternatives, $b_j = \{b_1, b_2, \cdots, b_n\}$ be set of criteria, and $d_z = \{d_1, d_2, \cdots, d_t\}$ be set of decision makers.

Step 1: The fuzzy decision matrix $\widetilde{P} = (p_{ij})_{m\times n}$ is constructed as in the following. p_{ij} is the evaluation value of the alternative a_i $(i = 1, 2, \ldots, m)$ according to the criteria $b_j (j = 1, 2, \ldots, n)$,

$$\widetilde{P} = (p_{ij})_{m\times n} = \begin{matrix} \\ B_1 \\ B_2 \\ \vdots \\ B_n \end{matrix} \begin{pmatrix} A_1 & A_2 & \cdots & A_m \\ p_{11} & p_{12} & \cdots & p_{1n} \\ p_{21} & p_{22} & \cdots & p_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ p_{1m} & p_{2m} & \cdots & p_{mn} \end{pmatrix} \tag{9}$$

where m denotes the number of alternatives and n denotes the number of criteria.

Step 2: Linear normalization of performance values are defined as follows Zavadskas et al. (2012):

$$\widetilde{r}_{ij} = \begin{cases} \dfrac{p_{ij}}{max_i p_{ij}} & \forall i \quad \text{if } j \in B \\ \dfrac{min_i p_{ij}}{p_{ij}} & \forall i \quad \text{if } j \in C \end{cases} \tag{10}$$

where B and C denote sets of benefit and cost criteria, respectively. Alternatives by $i = 1, 2, \ldots, m$ and criteria by $j = 1, 2, \ldots, n$ are denoted.

Table 5
The T2NN linguistic variables for importance weight of each criterion.

Linguistic variables	$A = [(T_T, T_I, T_F), (I_T, I_I, I_F), (F_T, F_I, F_F)]$
Low (L)	((0.20,0.30,0.20), (0.60,0.70,0.80), (0.45,0.75,0.75))
Medium Low (ML)	((0.40,0.30,0.25), (0.45,0.55,0.40), (0.45,0.60,0.55))
Medium (M)	((0.50,0.55,0.55), (0.40,0.45,0.55), (0.35,0.40,0.35))
High (H)	((0.80,0.75,0.70), (0.20,0.15,0.30), (0.15,0.10,0.20))
Very High (VH)	((0.90,0.85,0.95), (0.10,0.15,0.10), (0.05,0.05,0.10))

Table 6
The T2NN linguistic variables for evaluating the alternatives.
Step 1. The aggregated fuzzy decision matrix for the criteria and alternatives are constructed. The fuzzy weights of criteria are obtained in Table 7 using Eqs. (4.2), (7) and (9).

Linguistic variables	$A = [(T_T, T_I, T_F), (I_T, I_I, I_F), (F_T, F_I, F_F)]$
Very Bad (VB)	((0.20,0.20,0.10), (0.65,0.80,0.85), (0.45,0.80,0.70))
Bad (B)	((0.35,0.35,0.10), (0.50,0.75,0.80), (0.50,0.75,0.65))
Medium Bad (MB)	((0.50,0.30,0.50), (0.50,0.35,0.45), (0.45,0.30,0.60))
Medium (M)	((0.40,0.45,0.50), (0.40,0.45,0.50), (0.35,0.40,0.45))
Medium Good (MG)	((0.60,0.45,0.50), (0.20,0.15,0.25), (0.10,0.25,0.15))
Good (G)	((0.70,0.75,0.80), (0.15,0.20,0.25), (0.10,0.15,0.20))
Very Good (VG)	((0.95,0.90,0.95), (0.10,0.10,0.05), (0.05,0.05,0.05))

Step 3: The measures of weighted sum (WS) ($\Pi_i^{(1)}$) and weighted product (WP) ($\Pi_i^{(2)}$) for each alternative are defined as follows Zavadskas et al. (2012):

$$\Pi_{ij}^{(1)} = \sum_{j=1}^{m} w_j \tilde{r}_{ij} \quad \forall i \tag{11}$$

and

$$\Pi_{ij}^{(2)} = \prod_{j=1}^{m} \left(\tilde{r}_{ij}\right)^{w_j} \quad \forall i \tag{12}$$

Step 4: The aggregated measure of the WASPAS method are obtained as follows Zavadskas et al. (2012):

$$\Pi_{ij} = \gamma_i \Pi_{ij}^{(1)} + (1 - \gamma_i)\Pi_{ij}^{(2)} \quad \forall i \tag{13}$$

where the parameter of the WASPAS method is defined as γ that is the set of numbers between 0 and 1. If γ is $= 1$, WASPAS method is transformed into WS, whereas $\gamma = 0$ leads to WP.

Step 5. The positive and negative ideal solutions (PIS and NIS) are obtained as follows:

$$\Upsilon^* = \{\Pi_1^*, \cdots, \Pi_n^*\} = \{(max(j)\Pi_{ij}|j \in B), (min(j)\Pi_{ij}|j \in C)\} \tag{14}$$

$$\Upsilon^- = \{\Pi_1^-, \cdots, \Pi_n^-\} = \{(min(j)\Pi_{ij}|j \in B), (max(j)\Pi_{ij}|j \in C)\} \tag{15}$$

Step 6. The Euclidean distances of each alternative from PIS and NIS are calculated as follows:

$$\delta_i^* = \sqrt{\sum_{j=1}^{n} \left(\Pi_{ij} - \Pi_i^*\right)^2}, \quad i = 1, \cdots, n \tag{16}$$

$$\delta_i^- = \sqrt{\sum_{j=1}^{n} \left(\Pi_{ij} - \Pi_i^-\right)^2}, \quad i = 1, \cdots, n \tag{17}$$

Step 7. The relative closeness of each alternative is determined as follow:

$$\phi_i = \frac{\delta_i^-}{\delta_i^+ + \delta_i^-}, \quad i = 1, \cdots, n \tag{18}$$

Step 8. The alternative are ranked according to ϕ_i in decreasing order. (See Tables 3 and 4)

5. Experimental results

Each criterion is evaluated by four decision makers (DMs) with the help of the linguistic terms as given in Table 5. The linguistic evaluations for DMs are given in Table (Appendix A.1). Alternatives are evaluated with respect to criteria based on the linguistic terms in Table 6. Table (Appendix A.2) presents the evaluation rating of alternatives. The analysis of the proposed hybrid model is detailed below.

The linguistic values of alternative are converted to the fuzzy numbers based on the scale given in Table 6. Further, the aggregated fuzzy evaluation matrix is constructed in Table 8.

Step 2. The fuzzy normalized decision matrix is constructed using Table 8 with the help of Eq. (10) as presented in Table 9.
Step 3. The measures of WS ($\Pi_i^{(1)}$) and WP ($\Pi_i^{(2)}$) for each alternative in terms of criteria are calculated by Eqs. (11) and (12) using Table 9. The results of weighted sum and product are given in Tables 10 and 11.
Step 4: Then, using Tables 10 and 11 with the help of Eq. (13), the aggregated measure of the WASPAS method are provided in Table 12 ($\gamma = 0.5$).
Step 5: The min and max values are determined in Table 12 with the help of Eqs. (14) and (15) to find the fuzzy positive and negative ideal solution (PIS and NIS).
Step 6: Subsequently, the Euclidean distance of each alternative are found by Eqs. (16) and (17) using Table 12. The distance values are given in Table 13.
Step 7: Finally, the values of each alternative for final ranking are calculated by Eq. (18) using Table 13. The results are presented in Table 14.
Step 7: The alternative are ranked according to the relative closeness.

Table 7
The criteria weights.

	T			I			F				
Criteria	T	I	F	T	I	F	T	I	F	Score value	Normalized value
C1	0.702	0.666	0.721	0.000	0.000	0.000	0.000	0.000	0.000	0.896	0.130
C2	0.463	0.475	0.465	0.007	0.013	0.017	0.005	0.010	0.006	0.817	0.119
C3	0.614	0.586	0.590	0.001	0.001	0.002	0.000	0.000	0.001	0.864	0.126
C4	0.614	0.586	0.590	0.001	0.001	0.002	0.000	0.000	0.001	0.864	0.126
C5	0.553	0.543	0.557	0.002	0.004	0.003	0.001	0.001	0.002	0.848	0.123
C6	0.530	0.520	0.499	0.004	0.004	0.009	0.002	0.002	0.003	0.837	0.122
C7	0.593	0.564	0.533	0.002	0.001	0.005	0.001	0.001	0.002	0.853	0.124
C8	0.698	0.671	0.640	0.000	0.000	0.002	0.000	0.000	0.000	0.890	0.130

Table 8
The aggregated matrix for alternatives.

	Criteria							
Alternatives	C1	C2	C3	C4	C5	C6	C7	C8
A1	0.720	0.814	0.878	0.875	0.848	0.684	0.684	0.846
A2	0.814	0.857	0.911	0.875	0.716	0.821	0.826	0.906
A3	0.670	0.857	0.911	0.875	0.860	0.670	0.670	0.837
A4	0.749	0.889	0.911	0.914	0.801	0.911	0.914	0.901
A5	0.670	0.801	0.878	0.670	0.768	0.911	0.816	0.878

Table 9
The normalized decision matrix.

	Criteria							
Alternatives	C1	C2	C3	C4	C5	C6	C7	C8
A1	0.884	0.983	0.964	0.766	0.986	0.981	0.748	0.990
A2	1.000	0.935	1.000	0.766	0.833	0.817	0.904	0.924
A3	0.823	0.935	1.000	0.766	1.000	1.000	0.734	1.000
A4	0.919	0.901	1.000	0.734	0.931	0.736	1.000	0.929
A5	0.823	1.000	0.964	1.000	0.893	0.736	0.893	0.953

Table 10
The values of WS measure ($\Pi_i^{(1)}$) for each alternative in terms of criteria.

	Criteria							
Alternatives	C1	C2	C3	C4	C5	C6	C7	C8
A1	0.115	0.117	0.121	0.096	0.122	0.119	0.093	0.128
A2	0.130	0.111	0.126	0.096	0.103	0.099	0.112	0.120
A3	0.107	0.111	0.126	0.096	0.123	0.122	0.091	0.130
A4	0.120	0.107	0.126	0.092	0.115	0.090	0.124	0.120
A5	0.107	0.119	0.121	0.126	0.110	0.090	0.111	0.123

Table 11
The values of WP measure ($\Pi_i^{(2)}$) for each alternative in terms of criteria.

	Criteria							
Alternatives	C1	C2	C3	C4	C5	C6	C7	C8
A1	0.984	0.998	0.995	0.967	0.998	0.998	0.965	0.999
A2	1.000	0.992	1.000	0.967	0.978	0.976	0.988	0.990
A3	0.975	0.992	1.000	0.967	1.000	1.000	0.962	1.000
A4	0.989	0.988	1.000	0.962	0.991	0.963	1.000	0.990
A5	0.975	1.000	0.995	1.000	0.986	0.963	0.986	0.994

By comparing the φ_i values of the four alternatives, we find that $A4 > A2 > A5 > A1 > A3$. $A4$ is the best among the four alternatives while $A3$ is the worst alternative.

5.1. Sensitivity analysis

The sensitivity analysis was carried out by varying the λ value on decision-making process. The impact of parameter (λ) is analyzed, and decision results are observed. The scale unit of the parameter settings is 0.1, and 11 scenarios are considered. The graphical displays of the sensitivity analysis are shown in Fig. 4. The results show that the same ranking of alternative is found. This finding shows that the proposed decision-making model is robust for the case in this paper.

6. Discussion

The prioritization process for the five bridges in the Marmara Region of Turkey is performed. The result is found as $A4 > A2 > A5 > A1 > A3$. In this section, this result is tested, and its validity is discussed in detail.

First, these five bridges show unique characteristics among themselves for each different criterion. Therefore, the decision of the prioritization of these bridges is not an effortless task without an appropriate multi-criteria decision-making system. Because, once each criterion is taken into account individually, the resultant rankings of the bridges become different from each other.

Once the first criterion, Cost Effectiveness, is considered individually, A2 is the most cost-effective bridge regarding its rehabilitation cost, while the A5 and A3 are the worst options in this criterion perspective. As it is observed, this individual criterion provides different rankings from the multi-criteria approach used in the paper. Again, the Additional Fuel Consumption criterion suggests that A5 is the best option for choosing first as in the maintenance program among the others. However, A5 is at the 3rd ranking in the overall multi-criteria decision-making model of this paper.

The same comparisons for each criterion can be performed, and differences can be observed for the other criteria in the decision-making model. This is the primary reason for choosing a multi-criteria prioritization model. This model allows amalgamating different prioritization results of each criterion into a general one. However, the last criterion, CO_2 Emission, provides the same order of bridge rankings with the multi-criteria decision-making model. The most calculated CO_2 emission amount among these gives bridge case in case of closure is of A4 alternative. A2, A5, A1, A3 are the following bridges in CO_2 emission amounts in this criterion, respectively. The decision-makers decide that

Table 12
The WASPAS measure Π_{ij} and score values.

Alternatives	Criteria							
	C1	C2	C3	C4	C5	C6	C7	C8
A1	0.550	0.557	0.558	0.532	0.560	0.559	0.529	0.563
A2	0.565	0.552	0.563	0.532	0.540	0.538	0.550	0.555
A3	0.541	0.552	0.563	0.532	0.562	0.561	0.527	0.565
A4	0.555	0.547	0.563	0.527	0.553	0.526	0.562	0.555
A5	0.541	0.559	0.558	0.563	0.548	0.526	0.548	0.559

Table 13
The positive and negative ideal solutions (PIS and FIS).

PIS	Criteria							
	C1	C2	C3	C4	C5	C6	C7	C8
A1	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.000
A2	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A3	0.001	0.000	0.000	0.000	0.000	0.001	0.001	0.000
A4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
A5	0.001	0.000	0.000	0.001	0.000	0.000	0.000	0.000
NIS	Criteria							
	C1	C2	C3	C4	C5	C6	C7	C8
A1	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000
A2	0.001	0.000	0.000	0.001	0.000	0.001	0.001	0.000
A3	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000
A4	0.000	0.000	0.000	0.001	0.000	0.001	0.001	0.000
A5	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000

Table 14
Overall score for alternatives using proposed model.

Alternatives	δ_i^+	δ_i^-	ϕ_i	Ranking
A1	0.417	0.152	0.428	4
A2	0.662	0.241	0.657	2
A3	0.415	0.151	0.410	5
A4	0.598	0.218	0.827	1
A5	0.651	0.237	0.460	3

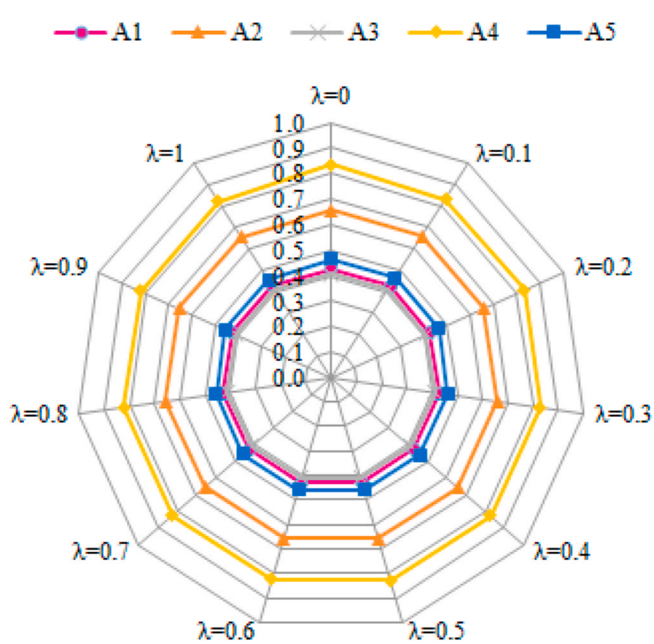

Fig. 4. Sensitivity analysis for different λ value.

the bridge that has the most CO_2 emission potential should go under maintenance first. This can be explained as the bridge with the highest CO_2 emission potential should be maintained as soon as possible. Therefore, it should be prevented from being closed due to adverse physical conditions. Hence, the higher CO_2 emission possibilities would be avoided among these bridge alternatives.

The exact match of the bridge rankings in both the multi-criteria decision-making process and the individual CO_2 emission criterion draws an important conclusion that the decision-makers' approach to the environmental impacts dominates the impact of the other criteria in the model for the case in this paper. This leads us that the CO_2 emission and other bridge management-related environment criteria should be much more involved in decision-making systems in bridge maintenance prioritization problems.

7. Conclusion

In the case study, the developed model has been used to test and rank five bridge maintenance projects. Also, a sensitivity analysis with a range of *lambda* value considered performed to investigate the impact of weightings on the ranking order of the alternatives.

Additionally, one of this paper's main contributions is that the importance of CO_2 emission in evaluating the bridge maintenance prioritization problems is analyzed. The results show that the highest importance weight is assigned to the CO_2 emission criterion that supports the claim mentioned above. In addition to this, the overall criteria's ranking of the bridge alternatives draws an exact match with the CO_2 emission criterion's ranking. This result leads us to an important conclusion that the environmental impact of a bridge maintenance project dominates the ranking of the alternatives according to the decision-makers.

The proposed approach combines the advantages of neutrosophic numbers sets and WASPAS. As such, neutrosphoic numbers can further express uncertain and incomplete information that is inherently existing in the decision-making process, while WASPAS provides formulation flexibility and simple calculation.

Although the proposed hybrid MCDM model has provided considerable insights into some advantages when trying to choose the bridge maintenance projects considering eight criteria, there are still some limitations that can be further studied. First, there were a limited amount of bridges in the existing dataset (Masoumi, 2014), having just one-year information about existing bridges, not having precise information for other possible environmental criteria. Therefore, we should consider more evaluation criteria to rank bridge maintenance, such as noise impact, and so on. Second, the proposed model can be hybridized with other MCDM approaches such as CODAS or ARAS.

In the future studies, other fuzzy sets can be used for proposed hybrid method such as pythagorean fuzzy sets, rough fuzzy sets, hesitant, and intuitionistic fuzzy sets to capture uncertainty of experts' subjective judgments. The proposed decision-making model can also be applied to address various fields such as transportation management, business and marketing management, supplier chain and logistics, military applications, health and safety management, and construction management.

CRediT authorship contribution statement

Ilgin Gokasar: Conceptualization, Writing - original draft, Writing - review & editing. **Muhammet Deveci:** Conceptualization, Methodology, Software, Writing - original draft, Writing - review & editing. **Onur Kalan:** Conceptualization, Writing - original draft, Writing - review & editing.

Appendix A

Table A.1Rating of criteria by decision makers.

	Criteria							
Decision Makers	C1	C2	C3	C4	C5	C6	C7	C8
DM1	VH	M	M	H	M	M	H	H
DM2	VH	M	ML	M	VH	M	M	H
DM3	VH	M	H	ML	ML	ML	ML	H
DM4	ML	ML	VH	VH	M	H	H	H

Table A.2
Rating of alternatives by decision makers.

		Criteria							
Alternatives	Decision makers	C1	C2	C3	C4	C5	C6	C7	C8
A1: Bayramdere	DM1	B	M	G	G	M	VB	VB	MG
	DM2	B	M	G	G	M	VB	VB	MG
	DM3	B	M	G	G	M	B	VB	MG
	DM4	B	MG	MG	M	VG	VB	B	G
A2: Kınalı	DM1	M	G	VG	G	VB	M	MB	VG
	DM2	M	G	VG	G	VB	M	G	VG
	DM3	M	MG	VG	G	VB	G	MB	VG
	DM4	MG	MB	G	M	MB	B	M	M
A3: Serefli Ciftligi	DM1	VB	G	VG	G	G	VB	VB	M
	DM2	VB	G	VG	G	M	VB	VB	M
	DM3	VB	MG	VG	G	G	VB	VB	B
	DM4	VB	MB	G	M	MG	VB	VB	VG
A4: Mudurnu	DM1	B	VG	VG	VG	M	VG	VG	VG
	DM2	B	VG	VG	VG	B	VG	VG	VG
	DM3	MB	G	VG	VG	M	VG	VG	VG
	DM4	B	VB	G	VG	MG	G	VG	VB
A5: Karahisar	DM1	VB	B	G	VB	B	VG	MG	G
	DM2	VB	B	G	VB	B	VG	M	G
	DM3	VB	VB	G	VB	B	VG	MG	G
	DM4	VB	VG	MG	VB	MG	G	MB	MG

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