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Evaluation of Cooperative Intelligent Transportation System scenarios for resilience in transportation using type-2 neutrosophic fuzzy VIKOR

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ABSTRACT

There is a critical need for research in proactive and predictive management of the resilience of transportation systems implementing new technologies. Cooperative Intelligent Transportation System (C-ITS) uses wireless technology to allow vehicles and infrastructure to talk to each other in real-time. This makes it easier for people to work together on the road and makes it possible to make safer and more efficient traffic flows. Significant progress may be made in the transportation industry as a result of the incorporation of self-powered sensors into C-ITS providing resilience in transportation operation. One advantageous feature is that these sensors, which generate their power, could be deployed in a variety of C-ITS implementation scenarios. To assist decision-makers in making the most informed choice possible concerning investments and implementations, a type-2 neutrosophic number (T2NN) based VIKOR (VlseKriterijumska Optimizacija I Kompromisno Resenje) method is used to perform advantage prioritization. To accomplish this goal, a case study is carried out to determine which of the three alternatives is the most suitable based on a set of twelve criteria that is divided into four aspects. According to the findings, the applicability and short-term benefits are the most crucial factors in determining which option is the most advantageous for the use of self-powered sensors in C-ITS. This is because both of these factors have an immediate impact on the system.

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1. Introduction

Resilience in transportation system is the ability to quickly recover from a disruption to an operational level similar to before the disruption. The longer and more profound the effect of a disruption on operations, the less resilient a transportation system becomes. A risk for transportation systems and supply chains is that planners and operators prioritize efficiency, assuming that disruptions will be rare and random. The inherent resilience of an efficient network or supply chain is assumed to be sufficient to handle the most anticipated disruptions, which are typically caused by traffic sensors. Sensors that generate their power draw their power from a variety of sources, including light, heat, chemical reactions, and mechanical motion. Because sensor systems must frequently be located in inaccessible areas, for example, for environmental monitoring or implanted sensors, to give another example, and so on powering these sensor systems can be a challenge to achieving long-term sustainability in their functional capabilities. Therefore, robustness in the sensors is necessary for transportation systems in order to maintain a continuous level of service for their customers. Because of this, the implementation of technology such as C-ITS will eventually be completely seamless.

Advancements in communication technologies have enabled the transmission of data in-between vehicles and between vehicles and infrastructure (Dey et al., 2016). Integrating this data transmission with intelligent transportation systems introduced the concept of cooperative intelligent transportation systems (C-ITS) (Choosakun et al., 2021). Cooperative Intelligent Transportation Systems (K-AUS), one of the technologies used in ITS applications, refers to a set of technologies and applications that enable effective data exchange between transportation system components and actors, or between vehicles and infrastructure, using wireless communication technologies. C-ITS provides robustness and resilience by providing a quick and efficient response to random and targeted disruptions in transportation networks. To transmit data, the initial step is to collect data through the sensors. In recent years, self-powered sensors, which do not rely on batteries or outside energy sources, have become a hot topic for researchers. The main contribution of these sensors is that they can produce their energy from various sources, such as nanogenerators, which convert mechanical load into electrical energy and collect traffic data by using self-generated energy (Askari et al., 2017, 2019). Data collected by these self-powered sensors can be transmitted to roadside units (RSU) and onboard units (OBU), which are components of C-ITS applications, using communication technologies such as DSRC and 5G (Xu et al., 2017).

The main objective of C-ITS applications is to inform drivers on different subjects, such as road works and slow or stationary vehicles. Road works and slow or stationary vehicle warnings have the motivation to sustain the safety of drivers by informing them of the location of road works or stationary vehicles ahead (Sjoberg et al., 2017). This C-ITS application can be conducted by sensors such as self-powered sensors detecting stationary vehicles and/or road works on the network and transmitting this information to the RSU. Then, the RSU transmits this information to the OBU, which is in the vehicle, to inform the driver. Once the driver is informed, they adjust their speed or their location concerning the warning, which increases the safety aspect of the driver and the traffic as a whole (Santamaria et al., 2014). According to a study, traffic incidents are simulated using SUMO simulation software, and incident information is transmitted to drivers upstream (Porfyri et al., 2019). Since incident information is similar to stationary vehicle information, the benefits acquired from this study are valid for the slow or stationary vehicle warning application. The results indicate that informing the drivers upstream of the stationary vehicles and increasing headway due to the warning have increased the safety aspect of the traffic. In addition to the C-ITS applications, which aim to increase the safety aspect of the drivers, other applications aim to inform the drivers of the current regulations and conditions of the road network, such as speed limits, weather conditions, and vehicle signage. These C-ITS applications are useful in terms of displaying the aspects, which are used to maintain the order of the network and regulate the traffic to increase efficiency. For these applications to work, self-powered sensors can be deployed to keep track of the network conditions such as weather status. In a different study, it is stated that in a track in Northern Finland, real-time road weather information is transmitted using ITS-5G and 5G technologies to inform the autonomous vehicle, which is made to test the autonomous vehicle technologies that are being developed (Perälä et al., 2022).

With the increase in urban population and traffic volumes, traffic management systems have gained more importance to increase the efficiency and safety of traffic (Djahel et al., 2014). To conduct traffic management implementations, the collected data is vital. Traffic data such as density, flow, and speed can be collected sustainably using a self-powered sensor (Liu et al., 2020). Using the collected data and the traffic management algorithm, vehicles can be instructed or guided through the onboard unit to adjust their position and/or speed. In the context of C-ITS, there are various traffic management applications such as Green Light Optimal Speed Advisory (GLOSA), which aims to reduce the average waiting time at traffic lights by advising the drivers with a calculated speed to increase overall traffic safety, mitigate congestion and enhance driving comfort (Sharara et al., 2019). In a different study, the GLOSA-based route planning algorithm is used in the context of C-ITS (Karoui et al., 2021). The results indicate that the implementation of the proposed C-ITS application provides a balance between travel time reduction and fuel savings to the driver.

C-ITS allows vehicles to interact with each other, the surrounding infrastructure, and other transportation users, providing drivers with the right information at the right time based on where they are and the situations they encounter, increasing traffic efficiency and comfort. However, there is a gap in the literature regarding the prioritization of the C-ITS implementations using self-powered sensors. Therefore, the objective of this study is to prioritize different groups of self-powered sensor-based C-ITS implementations based on different criteria, which are selected from a thorough literature view, according to the evaluations performed by the experts considering the resilience in transportation system. Before face-to-face expert evaluation, a survey is created in which every alternative is evaluated according to each criterion formed using a thorough literature review. For these experts to base their decisions on actual data, a case study is created. After gathering expert opinions, the data are added to the proposed MCDM model where the benefits of the alternatives are prioritized. Hence, a type-2 neutrosophic number (T2NN) based VIKOR (VlseKriterijumska

Optimizacija I Kompromisno Resenje) method is proposed to rank and evaluate to the alternatives. T2NN was improved in Abdel-Basset et al. (2019) as an efficient tool to address the uncertainty VIKOR allows different decision makers to evaluate all plans using various decision criteria systems. Since C-ITS applications are developing and novel technologies, there is a scarcity in the number of studies in the literature, which is a contribution of this study. Also, the usage of self-powered sensors in the context of C-ITS applications provides a sustainability measure for the study.

Based on the characteristics mentioned above of the proposed multi-criteria methodology, we can summarize the advantages and contributions of the T2NN VIKOR algorithm:

(1) The T2NN VIKOR model represents a new approach to handling uncertainty in the literature dealing with intelligent transportation systems. The presented methodology has a new algorithm for transforming inaccuracies in expert assessments using T2NN.

(2) In the T2NN VIKOR model, an original aggregation function has been implemented that enables flexible decision-making by simulating different scenarios during sensitivity analysis.

(3) The application of the presented multi-criteria framework enables an overview of different levels of risk through scenarios and an effective check of the robustness of the results.

(4) The proposed methodology has greater generality and objectivity when processing group information compared to traditional multi-criteria models.

The rest of the paper is organized as follows: Section 2 provides a problem description, the definition of alternatives, and the criteria. In Sections 3 and 4, the proposed methodology and its application including experimental results, and comparative and sensitivity analysis are provided, respectively. Results and Discussion are given in Section 5. Policy implications and conclusions are presented in Sections 6 and 7.

2. Problem definition

Self-powered sensors can help implement C-ITS with the aim of providing resilience. In countries that invest in sensor technology, traffic could be optimized. Investing in C-ITS can improve traffic flow, safety, and sustainability due to self-powered systems that do not need recharging and can use renewable energy sources. Here, three infrastructure alternatives are being considered, namely self-powered sensors in C-ITS road work, slow or stationary vehicle warning, C-ITS in-vehicle signage, speed limit, and weather condition information using self-powered sensors, C-ITS traffic management using a self-powered sensor (e.g., green light optimum speed advice). Fig. 1 shows that C-ITS with self-powered sensors provide resilient transportation infrastructure operation.

2.1. Definition of alternatives

In this section, the definition of the alternatives are listed as:

A_1: *Self-powered sensor uses in C-ITS road works warning, slow or stationary vehicle warning:* C-ITS digitalizes and verifies warnings. Road closures or accidents can change a driver's behavior. Maintenance costs can be predicted fairly easily, but rehabilitation and rebuilding costs are harder to predict because they depend on funding as well as key principles (Huntington and Ksaibati, 2009). Hence, optimizing and integrating the self-powered sensor into daily traffic could be beneficial.

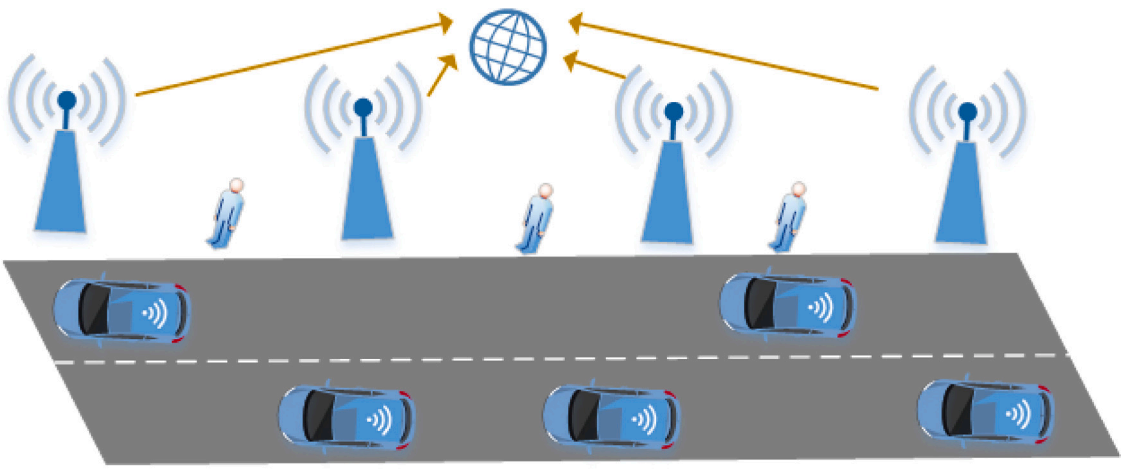

Fig. 1. C-ITS with self-powered sensor implementation for transportation operation resilience.

A_2: *Self-powered sensor uses in C-ITS vehicle signage, speed limit, weather condition information:* It is not possible to predict human behavior, which is especially problematic in traffic. Unfortunately, not every driver obeys the rules, which can lead to collisions. 11 people are killed for every 100 people who are injured in accidents (Lobanova and Evtiukov, 2020). C-ITS has the potential to increase road safety by providing information on things like vehicle signage, speed limits, and the current weather to help prevent accidents

A_3: *Self-powered sensor uses in C-ITS Traffic management information (e.g., green light optimum speed advises):* Mobility at a high speed is essential for modern civilizations (De Souza et al., 2017). Today, this objective is pursued by nearly every major metropolitan area. Traffic could be optimized with the help of sensors that generate their power, which would reduce congestion and unnecessary fuel consumption.

2.2. Definition of criteria

Three alternatives are evaluated using the following criteria grouped into four aspects.

(1) Operational Aspect

C_1: *Improved traffic flow (benefit):* Transportation is directly related to the connection between people and infrastructure. It is the driver's responsibility to maintain vehicle control in unforeseen situations, such as changing lanes or controlling speed (Miglani and Kumar, 2019). C-ITS traffic management information could help in improving traffic flow.

C_2: *Increased traffic safety (benefit):* Human casualties in traffic should be avoided. Fatal accidents are part of transportation. In the United States, the number of traffic fatalities increased from 26 in 1899 to 29,592 in 1929, as a result of the introduction of the automobile (Sadik-Khan and Solomonow, 2020). Hence, imposing the limitations of technology over which humans have no control will improve traffic safety.

C_3: *Increased fuel consumption and emission (cost) :* Increased use of C-ITS' self-powered sensor will increase traffic flow and car usage. In 2004, transportation accounted for 60 percent of global oil emissions (Quadrelli and Peterson, 2007). Since electric vehicles will not be as common as hoped in the future, fuel consumption and GHG emissions would also rise, worsening the global climate change crisis.

(2) Security and Data Infrastructure Aspect

C_4: *Advance hardware requirement (cost):* Self-powered sensors in C-ITS require development and advanced hardware. Discussing application needs, research objectives, and problems is difficult (Romer and Mattern, 2004). Since this area affects human life, improvements must meet demand.

C_5: *Need for cybersecurity for providing data (cost):* Sensors are vulnerable to external threats. Cybercrime is a critical topic not only in this case but also in other technology-related issues involving data. Private information must be protected from hackers (Capra et al., 2019). Cybersecurity must be prioritized as widespread use is sought.

C_6: *Providing timely transfer of information about safety conditions to drivers (benefit):* Automatization requires proper data transfer because the system processes data. Proper association requires synchronized sensor data and object state (Kaempchen and Dietmayer, 2003). Human drivers need accurate information transfer because their behavior depends on it. So, giving drivers safety updates is important.

(3) Competence Aspect

C_7: *The requirement for the competence of implementation activities planning (cost):* One of the most important things that any company must do is calculate how many of their goods and services they will need to produce in the coming years (Bogetoft, 2000). Planning the activities is the first step toward achieving success. Skill in implementation is essential because failure to complete the project could result in the loss of all resources invested in it, and the situation would deteriorate to the point where it could no longer be reversed. society.

C_8: *The requirement for the competence of control, inspection and maintenance (cost):* Because self-powered sensors are the type of devices that could be associated with C-ITS, they require control, inspection, and maintenance. Aside from the initial applications, the rate of success of projects is also determined by how the progress increases over the course of a product's service life. Because of the trend toward mechanization and automation, the importance of equipment in industrial operations has grown.

C_9: *The requirement for the competence of software hardware production (cost):* Self-powered sensors are C-ITS devices that need control, inspection, and maintenance. Other than initial applications, a project's success depends on its progress during its service life. Competence in manufacturing is key to expanding implantation areas and replacing broken devices. Building new factories and increasing the productivity of existing ones must meet production demands. Productivity equals a factory's output minus its production costs (Kumar Satyam et al., 2020).

(4) Legislation, Regulation and Standardization Aspect

C_{10}: *Providing better protocol used in communication with roadside infrastructure (benefit):* The protocol controls how computers exchange data. Improving the roadside infrastructure protocol is important by definition. Sensor networks are often hardwired for a specific purpose (Wan et al.). Today's data transfer requires Wi-Fi sensors. Excluding cable, maintenance could reduce costs.

C_{11}: *The need for implementation standardization (cost):* According to De Vries (2013), a standard is the temporally frozen result of a standardization process. With this definition, the significance of standardization can be seen with visual inspection. Because this implementation is novel, standardization should be carried out by experts from diverse fields such as transportation engineering and computer engineering.

C_{12}: *The requirement for legislation (cost):* When putting government regulations into effect, legislation is necessary. The autonomous, sensor-integrated, connected intelligent transportation system (C-ITS) is at the center of transportation, which requires legislation.

3. Proposed methodology

3.1. Preliminaries

The type-2 neutrosophic numbers (T2NNs) was introduced by Abdel-Basset et al. (2019) and is extended the neutrosophic set improved by Smarandache (1998). Neutrosophic sets have been successfully applied to decision making problems (Kalantari et al., 2022; Broumi et al., 2022). Some basic expressions of T2NN are as follows:

A T2NN $\mathring{R}$ is characterized by a truth $\zeta_{\mathring{R}}$, indeterminacy $\sigma_{\mathring{R}}$, and falsity $\eta_{\mathring{R}}$ membership functions.

Definition 1 (*Abdel-Basset et al., 2019*)**.** A T2NN $\mathring{R}$ in $\wp$ is expressed by:

$$\mathring{R} = \left\{ \left\langle \mathring{\wp}, \zeta_{\mathring{R}}(\mathring{\wp}), \sigma_{\mathring{R}}(\mathring{\wp}), \eta_{\mathring{R}}(\mathring{\wp}) \right\rangle \middle| \mathring{\wp} \in \wp \right\}, \tag{1}$$

where $\zeta_{\mathring{R}}(\mathring{\wp}), \sigma_{\mathring{R}}(\mathring{\wp}), \eta_{\mathring{R}}(\mathring{\wp}) : \wp \to [0,1]^3$. The T2NN can be represented by:

$$\zeta_{\mathring{R}}(\mathring{\wp}) = \left(\zeta_{\zeta_{\mathring{R}}}(\mathring{\wp}), \zeta_{\sigma_{\mathring{R}}}(\mathring{\wp}), \zeta_{\eta_{\mathring{R}}}(\mathring{\wp}) \right)$$
$$\sigma_{\mathring{R}}(\mathring{\wp}) = \left(\sigma_{\zeta_{\mathring{R}}}(\mathring{\wp}), \sigma_{\sigma_{\mathring{R}}}(\mathring{\wp}), \sigma_{\eta_{\mathring{R}}}(\mathring{\wp}) \right)$$
$$\eta_{\mathring{R}}(\mathring{\wp}) = \left(\eta_{\zeta_{\mathring{R}}}(\mathring{\wp}), \eta_{\sigma_{\mathring{R}}}(\mathring{\wp}), \eta_{\eta_{\mathring{R}}}(\mathring{\wp}) \right)$$

or;

$$A = \left((\zeta_\zeta, \zeta_\sigma, \zeta_\eta), (\sigma_\zeta, \sigma_\sigma, \sigma_\eta), (\eta_\zeta, \eta_\sigma, \eta_\eta) | \mathring{\wp} \in \wp \right)$$
$$\zeta_{\mathring{R}}(\mathring{\wp}) = \left(\zeta^1_{\mathring{R}}(\mathring{\wp}), \zeta^2_{\mathring{R}}(\mathring{\wp}), \zeta^3_{\mathring{R}}(\mathring{\wp}) \right)$$
$$\sigma_{\mathring{R}}(\mathring{\wp}) = \left(\sigma^1_{\mathring{R}}(\mathring{\wp}), \sigma^2_{\mathring{R}}(\mathring{\wp}), \sigma^3_{\mathring{R}}(\mathring{\wp}) \right)$$
$$\eta_{\mathring{R}}(\mathring{\wp}) = \left(\eta^1_{\mathring{R}}(\mathring{\wp}), \eta^2_{\mathring{R}}(\mathring{\wp}), \eta^3_{\mathring{R}}(\mathring{\wp}) \right)$$

where $\zeta_{\mathring{R}}(\mathring{\wp}), \sigma_{\mathring{R}}(\mathring{\wp})$ and $\eta_{\mathring{R}}(\mathring{\wp})$ are $\wp \to [0,1]^3$. For every $\mathring{\wp} \in \wp : 0 \le \zeta^1_{\mathring{R}}(\mathring{\wp}) + \sigma^1_{\mathring{R}}(\mathring{\wp}) + \eta^1_{\mathring{R}}(\mathring{\wp}) \le 3$, $\quad 0 \le \zeta^2_{\mathring{R}}(\mathring{\wp}) + \sigma^2_{\mathring{R}}(\mathring{\wp}) + \eta^2_{\mathring{R}}(\mathring{\wp}) \le 3$, and $0 \le \zeta^3_{\mathring{R}}(\mathring{\wp}) + \sigma^3_{\mathring{R}}(\mathring{\wp}) + \eta^3_{\mathring{R}}(\mathring{\wp}) \le 3$ are stated.

Let two T2NNs $\mathring{R}_1$ and $\mathring{R}_2$ be expressed by: $\mathring{R}_1 = \Big\langle (\zeta_{\zeta_{\mathring{R}_1}}(\mathring{\wp}), \zeta_{\sigma_{\mathring{R}_1}}(\mathring{\wp}), \zeta_{\eta_{\mathring{R}_1}}(\mathring{\wp})), (\sigma_{\zeta_{\mathring{R}_1}}(\mathring{\wp}), \sigma_{\sigma_{\mathring{R}_1}}(\mathring{\wp}) \sigma_{\eta_{\mathring{R}_1}}(\mathring{\wp})),$ $\left(\eta_{\zeta_{\mathring{R}_1}}(\mathring{\wp}), \eta_{\sigma_{\mathring{R}_1}}(\mathring{\wp}), \eta_{\eta_{\mathring{R}_1}}(\mathring{\wp}) \right) \Big\rangle$, and $\mathring{R}_2 = \Big\langle \left(\zeta_{\zeta_{\mathring{R}_2}}(\mathring{\wp}), \zeta_{\sigma_{\mathring{R}_2}}(\mathring{\wp}), \zeta_{\eta_{\mathring{R}_2}}(\mathring{\wp}) \right), \left(\sigma_{\zeta_{\mathring{R}_2}}(\mathring{\wp}), \sigma_{\sigma_{\mathring{R}_2}}(\mathring{\wp}), \sigma_{\eta_{\mathring{R}_2}}(\mathring{\wp}) \right),$ $\left(\eta_{\zeta_{\mathring{R}_2}}(\mathring{\wp}), \eta_{\sigma_{\mathring{R}_2}}(\mathring{\wp}), \eta_{\eta_{\mathring{R}_2}}(\mathring{\wp}) \right) \Big\rangle$

Definition 2. The addition of two T2NNs can be expressed by (Abdel-Basset et al., 2019):

$$\begin{aligned}
\mathring{R}_1 \oplus \mathring{R}_2 = \Big\langle \Big(& \zeta_{\zeta_{\mathring{R}_1}}(\mathring{\wp}) + \zeta_{\zeta_{\mathring{R}_2}}(\mathring{\wp}) - \zeta_{\zeta_{\mathring{R}_1}}(\mathring{\wp}) \cdot \zeta_{\zeta_{\mathring{R}_2}}(\mathring{\wp}), \\
& \zeta_{\sigma_{\mathring{R}_1}}(\mathring{\wp}) + \zeta_{\sigma_{\mathring{R}_2}}(\mathring{\wp}) - \zeta_{\sigma_{\mathring{R}_1}}(\mathring{\wp}) \cdot \zeta_{\sigma_{\mathring{R}_2}}(\mathring{\wp}), \\
& \zeta_{\eta_{\mathring{R}_1}}(\mathring{\wp}) + \zeta_{\eta_{\mathring{R}_2}}(\mathring{\wp}) - \zeta_{\eta_{\mathring{R}_1}}(\mathring{\wp}) \cdot \zeta_{\eta_{\mathring{R}_2}}(\mathring{\wp}) \Big), \\
& \Big(\sigma_{\zeta_{\mathring{R}_1}}(\mathring{\wp}) \cdot \sigma_{\zeta_{\mathring{R}_2}}(\mathring{\wp}), \sigma_{\sigma_{\mathring{R}_1}}(\mathring{\wp}) \cdot \sigma_{\sigma_{\mathring{R}_2}}(\mathring{\wp}), \\
& \sigma_{\eta_{\mathring{R}_1}}(\mathring{\wp}) \cdot \sigma_{\eta_{\mathring{R}_2}}(\mathring{\wp}) \Big), \Big(\eta_{\zeta_{\mathring{R}_1}}(\mathring{\wp}) \cdot \eta_{\zeta_{\mathring{R}_2}}(\mathring{\wp}), \\
& \eta_{\sigma_{\mathring{R}_1}}(\mathring{\wp}) \cdot \eta_{\sigma_{\mathring{R}_2}}(\mathring{\wp}), \eta_{\eta_{\mathring{R}_1}}(\mathring{\wp}) \cdot \eta_{\eta_{\mathring{R}_2}}(\mathring{\wp}) \Big) \Big\rangle .
\end{aligned} \tag{2}$$

Definition 3. The multiplication of two T2NNs can be expressed by (Abdel-Basset et al., 2019):

$$\begin{aligned}
\mathring{R}_1 \otimes \mathring{R}_2 = & \Big\langle \Big(\Big(\zeta_{\zeta_{\mathring{R}_1}}(\mathring{\wp}) \cdot \zeta_{\zeta_{\mathring{R}_2}}(\mathring{\wp}), \zeta_{\sigma_{\mathring{R}_1}}(\mathring{\wp}) \cdot \zeta_{\sigma_{\mathring{R}_2}}(\mathring{\wp}), \\
& \zeta_{\eta_{\mathring{R}_1}}(\mathring{\wp}) \cdot \zeta_{\eta_{\mathring{R}_2}}(\mathring{\wp}) \Big), \Big(\sigma_{\zeta_{\mathring{R}_1}}(\mathring{\wp}) + \sigma_{\zeta_{\mathring{R}_2}}(\mathring{\wp}) - \sigma_{\zeta_{\mathring{R}_1}}(\mathring{\wp}) \cdot \\
& \sigma_{\zeta_{\mathring{R}_2}}(\mathring{\wp}) \Big), \big(\sigma_{\sigma_{\mathring{R}_1}}(\mathring{\wp}) + \sigma_{\sigma_{\mathring{R}_2}}(\mathring{\wp}) - \sigma_{\sigma_{\mathring{R}_1}}(\mathring{\wp}) \cdot \sigma_{\sigma_{\mathring{R}_2}}(\mathring{\wp})\big), \\
& \big(\sigma_{\eta_{\mathring{R}_1}}(\mathring{\wp}) + \sigma_{\eta_{\mathring{R}_2}}(\mathring{\wp}) - \sigma_{\eta_{\mathring{R}_1}}(\mathring{\wp}) \cdot \sigma_{\eta_{\mathring{R}_2}}(\mathring{\wp})\big) \Big), \\
& \Big(\big(\eta_{\zeta_{\mathring{R}_1}}(\mathring{\wp}) + \eta_{\zeta_{\mathring{R}_2}}(\mathring{\wp}) - \eta_{\zeta_{\mathring{R}_1}}(\mathring{\wp}) \cdot \eta_{\zeta_{\mathring{R}_2}}(\mathring{\wp})\big), \\
& \big(\eta_{\sigma_{\mathring{R}_1}}(\mathring{\wp}) + \eta_{\sigma_{\mathring{R}_2}}(\mathring{\wp}) - \eta_{\sigma_{\mathring{R}_1}}(\mathring{\wp}) \cdot \eta_{\sigma_{\mathring{R}_2}}(\mathring{\wp})\big), \\
& \big(\eta_{\eta_{\mathring{R}_1}}(\mathring{\wp}) + \eta_{\eta_{\mathring{R}_2}}(\mathring{\wp}) - \eta_{\eta_{\mathring{R}_1}}(\mathring{\wp}) \cdot \eta_{\eta_{\mathring{R}_2}}(\mathring{\wp})\big) \Big) \Big\rangle .
\end{aligned} \tag{3}$$

Definition 4. The arithmetic operation for a T2NN can be expressed by (Abdel-Basset et al., 2019):

$$\begin{aligned}
\mathring{R} = & \Big\langle \Big(1-(1-\zeta_{\zeta_{\mathring{R}}}(\mathring{\wp}))^{\vartheta}, \\
& 1-(1-\zeta_{\sigma_{\mathring{R}}}(\mathring{\wp}))^{\vartheta}, 1-(1-\zeta_{\eta_{\mathring{R}}}(\mathring{\wp}))^{\vartheta} \Big), \\
& \Big((\sigma_{\zeta_{\mathring{R}}}(\mathring{\wp}))^{\vartheta}, (\sigma_{\sigma_{\mathring{R}}}(\mathring{\wp}))^{\vartheta}, (\sigma_{\eta_{\mathring{R}}}(\mathring{\wp}))^{\vartheta} \Big), \\
& \Big((\eta_{\zeta_{\mathring{R}_1}}(\mathring{\wp}))^{\vartheta}, (\eta_{\sigma_{\mathring{R}}}(\mathring{\wp}))^{\vartheta}, (\eta_{\eta_{\mathring{R}}}(\mathring{\wp}))^{\vartheta} \Big) \Big\rangle,
\end{aligned} \tag{4}$$

where $\vartheta > 0$.

Definition 5. The exponent of a T2NN can be expressed by (Abdel-Basset et al., 2019):

$$\begin{aligned}
\mathring{R}^{\vartheta} = & \Big\langle \Big((\zeta_{\zeta_{\mathring{R}}}(\mathring{\wp}))^{\vartheta}, (\zeta_{\sigma_{\mathring{R}}}(\mathring{\wp}))^{\vartheta}, (\zeta_{\eta_{\mathring{R}}}(\mathring{\wp}))^{\vartheta} \Big), \\
& \Big(1-(1-\sigma_{\zeta_{\mathring{R}}}(\mathring{\wp}))^{\vartheta}, 1-(1-\sigma_{\sigma_{\mathring{R}}}(\mathring{\wp}))^{\vartheta}, \\
& 1-(1-\sigma_{\eta_{\mathring{R}}}(\mathring{\wp}))^{\vartheta} \Big), \\
& \Big(1-(1-\eta_{\zeta_{\mathring{R}}}(\mathring{\wp}))^{\vartheta}, 1-(1-\eta_{\sigma_{\mathring{R}}}(\mathring{\wp}))^{\vartheta}, \\
& 1-(1-\eta_{\eta_{\mathring{R}}}(\mathring{\wp}))^{\vartheta} \Big) \Big\rangle
\end{aligned} \tag{5}$$

where, $\vartheta > 0$.

Definition 6. The score function $S(\mathring{R}_1)$ of T2NN $\mathring{R}_1$ can be expressed by (Abdel-Basset et al., 2019):

$$S(\mathring{R}_1) = \frac{1}{12}\Big\langle 8 + (\zeta_{\zeta_{\mathring{R}_1}}(\mathring{\wp}) + 2\,\zeta_{\sigma_{\mathring{R}_1}}(\mathring{\wp}) + \zeta_{\eta_{\mathring{R}_1}}(\mathring{\wp})) - (\sigma_{\zeta_{\mathring{R}_1}}(\mathring{\wp}) + 2\,\sigma_{\sigma_{\mathring{R}_1}}(\mathring{\wp}) + \sigma_{\eta_{\mathring{R}_1}}(\mathring{\wp})) - (\eta_{\zeta_{\mathring{R}_1}}(\mathring{\wp}) + 2\,\eta_{\sigma_{\mathring{R}_1}}(\mathring{\wp}) + \eta_{\eta_{\mathring{R}_1}}(\mathring{\wp}))\Big\rangle \tag{6}$$

The accuracy function $A(\mathring{R}_1)$ of T2NN $\mathring{R}_1$ can be expressed by (Abdel-Basset et al., 2019):

$$A(\mathring{R}_1) = \frac{1}{4}\Big\langle (\zeta_{\zeta_{\mathring{R}_1}}(\mathring{\wp}) + 2(\zeta_{\sigma_{\mathring{R}_1}}(\mathring{\wp})) + \zeta_{\eta_{\mathring{R}_1}}(\mathring{\wp})) - (\eta_{\zeta_{\mathring{R}_1}}(\mathring{\wp}) + 2(\eta_{\sigma_{\mathring{R}_1}}(\mathring{\wp})) + \eta_{\eta_{\mathring{R}_1}}(\mathring{\wp}))\Big\rangle \tag{7}$$

3.2. Type-2 neutrosophic Fuzzy VIKOR

The VIKOR method by is proposed to solve uncertain decision-making problems introduced by Opricovic (1998). The steps of implementing the T2NN VIKOR approach are as follows:

Step 1: Structure the fuzzy decision matrix $\mathring{P} = (\mathring{\wp}_{ij})_{m\times n}$. $\mathring{\wp}_{ij}$ is the assessment of the alternatives $\mathbb{A}_i$ $(i = 1, 2, \ldots, n)$ under $\mathbb{C}_j$ $(j = 1, 2, \ldots, m)$ in terms of the experts $\mathbb{E}_e$ $(e = 1, 2, \ldots, \ell)$.

Step 2: Calculate the score values $\mathring{S} = (\mathring{p}_{ij})_{m\times n}$ of each alternatives with the help of Eq. (6) and fuzzy decision matrix.

Step 3: Calculate the weights for each criterion Ω_j using Eq. (6).

Step 4: Find the normalization values $\mathring{X} = (\mathring{s}_{ij})_{m\times n}$ using score values and Eq. (8):

$$\mathring{x}_{ij} = \begin{cases} \dfrac{\mathring{s}_{ij}}{\max_i \mathring{s}_{ij}} & \forall i \quad \text{if } j \in Benefit \\ \dfrac{\min_i \mathring{s}_{ij}}{\mathring{s}_{ij}} & \forall i \quad \text{if } j \in Cost, \end{cases} \tag{8}$$

Step 5: Obtain the weighted normalized matrix.

$$\psi_i = \sum_{j=1}^{m} \Omega_j \mathring{x}_{ij} \quad \forall i, \tag{9}$$

Step 6: Calculate the index values as follows:

$$\alpha_i = \sum_{j=1}^{m} s_{ij} \quad \forall i, \tag{10}$$

$$\beta_i = \max\left(s_{ij}\right) \quad \forall i, \tag{11}$$

$$\alpha^+ = \min\left(\alpha_i\right), \quad and \quad \alpha^- = \max\left(\alpha_i\right), \tag{12}$$

$$\beta^+ = \min\left(\beta_i\right), \quad and \quad \beta^- = \max\left(\beta_i\right), \tag{13}$$

Step 7: Find the θ_i index value for each alternative.

$$\theta_i = \lambda \frac{\left(\alpha_i - \alpha^+\right)}{\left(\alpha^- - \alpha^+\right)} + (1-\lambda) \frac{\left(\beta_i - \beta^+\right)}{\left(\beta^- - \beta^+\right)} \tag{14}$$

The λ value emphasizes the importance of the strategy that provides the majority of the criteria or the maximum group benefit $\lambda = 0.5$, while the $1 - \lambda$ corresponds to the individual regret value.
Step 8: The alternatives are ranked according to θ_i value. The minimum value of this index indicates, while the maximum value indicate the worst alternative.

4. Application of proposed model

Self-powered sensors are one of the most important advances in technology in the past few years. Local officials on a small scale and national governments on a large scale should spend money to improve how they effectively manage traffic. Taking into account the results of these studies, decision-makers need to advantage prioritized the three alternatives by using twelve criteria and four aspects including operational, security and data infrastructure, competence and legislation, regulation, and standardization.

4.1. Experimental results

Each criterion is assessed by the six experts to find the criteria weights. The linguistic assessments of the criteria are provided in Table 1. Later, each alternative in terms of criteria is assessed by a set of experts using linguistic terms, and reported in Table 2. In this study, the linguistic terms and their corresponding values in the Abdel-Basset et al. (2019)'s study are used to evaluate the criteria and alternatives. Then, the linguistic evaluations of experts are converted to the T2NNs.
Steps 1–2. The T2NNs based decision matrix is structured, and then the score values are computed by Eq. (6). The score values of each alternative are given in Table 3.
Step 3. The weights of criteria are obtained by Eq. (6) with the help of Table 1.
Step 4. The normalized decision matrix is constructed by Eq. (8) using Table 3. The normalized values are provided in Table 5.
Step 5. Later, the weighted normalized decision matrix is created by Eq. (9) with teh help of Tables 4 and 5.
Step 6. Afterwards, the index values of VIKOR approach are calculated by Eqs. (10)–(13) with the help of weighted normalized values. These index values are given in Table 6.
Steps 7–8. The θ_i values of alternatives are calculated by Eq. (14) using Table 6. The θ_i values of each alternative are reported in Table 7.

The minimum θ_i value among three alternatives is selected as a best alternative. Therefore, A_2 alternative is the best alternative; on the other hand, A_3 is the worst alternative.

Table 1
Linguistic assessments of criteria for each expert.

Criteria	E1	E2	E3	E4	E5	E6
C1	VSI	SI	VSI	VSI	VSI	AI
C2	AI	VSI	AI	SI	VSI	AI
C3	VSI	EI	AI	WI	VSI	VSI
C4	SI	AI	SI	EI	SI	EI
C5	VSI	VSI	SI	SI	SI	SI
C6	VSI	VSI	SI	VSI	AI	AI
C7	SI	VSI	EI	SI	Sı	EI
C8	SI	EI	EI	VSI	VSI	EI
C9	EI	EI	EI	EI	SI	WI
C10	VSI	VSI	SI	SI	VSI	AI
C11	SI	VSI	EI	VSI	SI	SI
C12	AI	SI	SI	AI	VSI	VSI

Table 2
Linguistic assessments of alternatives under criteria for each expert.

Alt.	E	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
A1	E1	B	VG	G	MB	MB	VG	M	B	M	G	MG	B
	E2	MB	MG	G	VG	M	G	M	M	M	B	MB	M
	E3	MG	MG	MB	MB	M	MG	MB	MB	B	G	G	B
	E4	MG	MG	M	MB	MB	MG	MB	MB	M	MG	G	MB
	E5	MB	MG	MG	M	B	G	MB	MB	M	G	G	MB
	E6	MG	VG	MB	M	VB	VG	B	B	MB	MB	MB	M
A2	E1	G	MG	MG	B	VG	B	MB	MG	MB	MB	M	MB
	E2	VG	G	MB	MG	G	M	MG	M	M	G	VG	B
	E3	M	MG	B	M	M	MG	MG	M	B	M	G	MB
	E4	VG	G	MG	B	B	G	B	B	MB	G	G	MB
	E5	MG	MG	MB	M	B	G	MG	M	M	G	M	MG
	E6	MG	G	B	MG	M	MB	G	G	G	MG	M	MB
A3	E1	VG	MG	VB	B	VB	G	VB	VB	B	G	G	MB
	E2	M	MG	VG	G	VB	G	M	M	M	MB	G	MB
	E3	G	G	VB	B	B	G	B	B	MB	MG	MG	MB
	E4	G	VG	G	B	VB	VG	B	VB	B	VG	VG	M
	E5	VG	G	VB	B	B	VG	B	MB	M	VG	MG	B
	E6	G	M	B	MB	VB	VG	B	B	B	MG	MG	B

Table 3
The score values.

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
A1	0.839	0.886	0.851	0.844	0.797	0.890	0.813	0.810	0.802	0.858	0.864	0.805
A2	0.885	0.871	0.826	0.815	0.839	0.844	0.848	0.823	0.823	0.860	0.859	0.828
A3	0.890	0.875	0.811	0.810	0.750	0.893	0.778	0.778	0.797	0.887	0.880	0.810

Table 4
The weights of criteria of each criterion.

	Aggreagted T2NNs of the criteria	Score values	Normalized values
C1	$\langle(0.74, 0.71, 0.7), (0, 0, 0), (0, 0, 0)\rangle$	0.904	0.087
C2	$\langle(0.76, 0.74, 0.76), (0, 0, 0), (0, 0, 0)\rangle$	0.916	0.088
C3	$\langle(0.64, 0.61, 0.58), (0, 0, 0), (0, 0, 0)\rangle$	0.871	0.084
C4	$\langle(0.53, 0.51, 0.52), (0, 0, 0), (0, 0, 0)\rangle$	0.839	0.081
C5	$\langle(0.59, 0.61, 0.59), (0, 0, 0), (0, 0, 0)\rangle$	0.867	0.083
C6	$\langle(0.75, 0.72, 0.73), (0, 0, 0), (0, 0, 0)\rangle$	0.910	0.088
C7	$\langle(0.51, 0.5, 0.47), (0, 0, 0), (0, 0, 0)\rangle$	0.832	0.080
C8	$\langle(0.55, 0.49, 0.45), (0, 0, 0), (0, 0, 0)\rangle$	0.831	0.080
C9	$\langle(0.38, 0.34, 0.29), (0, 0, 0), (0, 0.01, 0)\rangle$	0.777	0.075
C10	$\langle(0.7, 0.68, 0.68), (0, 0, 0), (0, 0, 0)\rangle$	0.895	0.086
C11	$\langle(0.58, 0.57, 0.55), (0, 0, 0), (0, 0, 0)\rangle$	0.855	0.082
C12	$\langle(0.71, 0.7, 0.71), (0, 0, 0), (0, 0, 0)\rangle$	0.901	0.087

Table 5
The normalized decision matrix.

Alternatives	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
A1	0.942	1.000	0.953	0.960	0.941	0.997	0.957	0.960	0.993	0.968	0.981	1.000
A2	0.994	0.983	0.982	0.994	0.893	0.945	0.917	0.944	0.968	0.970	0.976	0.971
A3	1.000	0.987	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	0.993

Table 6
The index values.

Alternatives	α_i	β_i	α_+	α_-	β_+	β_-
A1	0.971	0.088	0.962	0.998	0.087	0.088
A2	0.962	0.087				
A3	0.998	0.088				

4.2. Comparative analysis

Since type-2 neutrosophic fuzzy (T2NF) sets belong to new concepts for treating uncertainty, we can find only a limited number of papers in the literature with their application in the MCDM field. So far, the T2NF approach has been used in only a few works

Table 7
The ranking of the alternatives.

Alternatives	$\lambda_i(0.0)$	$\lambda_i(0.5)$	$\lambda_i(1.0)$	Rank
A1	1.000	0.630	0.259	2
A2	0.000	0.000	0.000	1
A3	0.627	0.813	1.000	3

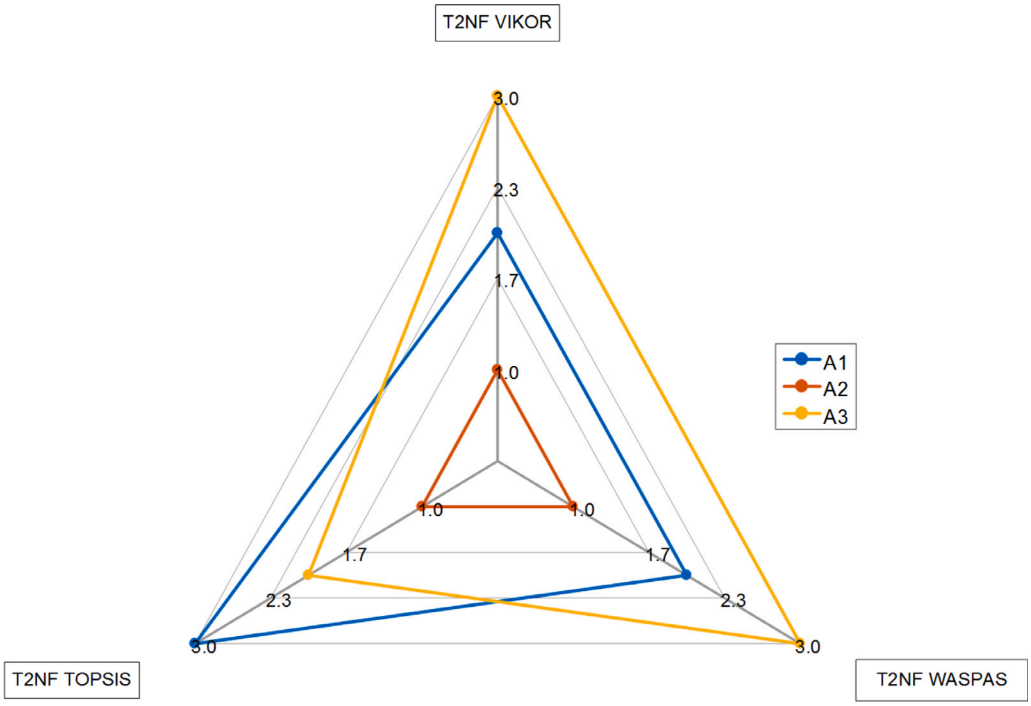

Fig. 2. The comparisons of MCDM techniques.

in which the extension of the TOPSIS method in the T2NF environment (Karaaslan and Hunu, 2020; Özlü and Karaaslan, 2022) and the extension of the TOPSIS-WASPAS model (Görçün, 2022) have been performed. In the next part, to compare and confirm the results of the T2NF VIKOR model, the results were compared with the T2NF TOPSIS and WASPAS models (see Fig. 2).

The results from Fig. 2 show that a high correlation of results was obtained between the applied MCDM models. By using all multi-criteria techniques, the dominance of alternative A_2 was confirmed. Smaller deviations occurred with the T2NF TOPSIS model, where the rank $A_2 > A_3 > A_1$ was obtained, while the initial rank was established with the T2NF WASPAS method. Despite the similar results with the applied MCDM techniques, we can single out one of the significant advantages of the T2NF VIKOR model compared to other T2NF methodologies. The T2NF VIKOR model allows consideration of scenarios in which different levels of risk are simulated. By simulating different values of the pessimistic and optimistic index, the T2NF VIKOR model enables prediction in a dynamic environment with consideration of risk when making decisions.

4.3. Sensitivity analysis

Since in the multi-criteria model, there are subjectively defined parameters and parameters that are defined by consensus based on a predefined interval, it is necessary to check how other parameter values affect the change in results. In the following part, as part of the sensitivity analysis, the robustness of the results was checked. Changes in specific input parameters in the home matrix were analyzed during the robustness analysis. Here, input parameters mean parameters that are subjectively defined from a corresponding predefined interval. Therefore, in the first section, the influence of other generated values of the weighting coefficients of the criteria on the ranking results was analyzed. The second section analyzed the influence of the stabilization parameter (λ) of the T2NN VIKOR model was analyzed.

(a) The impact of changing the weighting coefficients on the ranking results:

The weight coefficients of the criteria have a significant role in defining the final preferences in the MCDM model. Since subjective methodology was used to determine the weighting coefficients of the criteria, it is necessary to analyze: (1) the sensitivity of the model to changes in the weighting coefficients of the criteria and (2) whether the variation of the value of the most influential

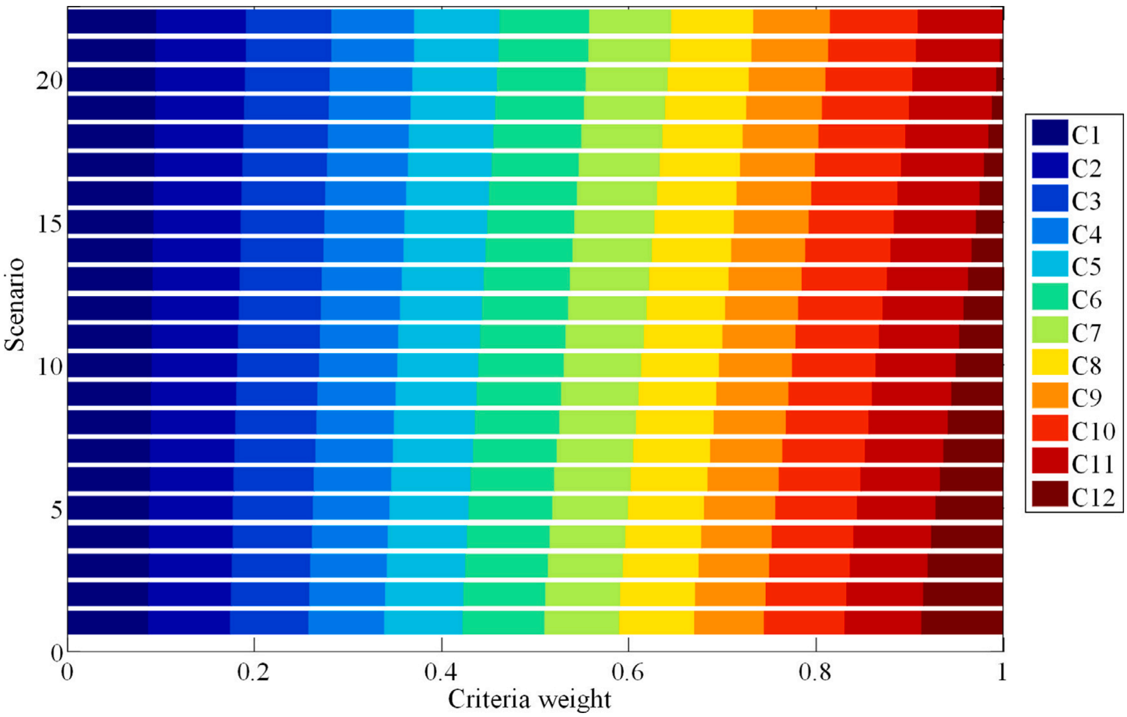

Fig. 3. New vectors of weight coefficients.

criterion leads to significant changes in the final preferences of the model. The following part presents the analysis of the impact of the newly generated vectors of weighting coefficients on the model results.

The weight coefficients of the criteria should meet the condition that $\Omega_j \in [0,1] (j = 1,2,\ldots,12)$ and $\sum_{j=1}^{m} \Omega_j = 1$. Also, the newly generated vectors of weighting coefficients should satisfy the relation that $\Omega_j : (1-\Omega_B) = \Omega_j^* : (1-\Omega_B^*); j = 1,2,\ldots,12; j \neq B$, where j represents the indexes of criteria, while B represents the index of the best criteria. In the first scenario, the best criterion (Ω_{12}) was reduced by 2%, while the weight values of the remaining criteria $(\Omega_{1j}, j = 1,2,\ldots,11)$ were defined by applying expression $\Omega_j : (1-\Omega_B) = \Omega_j^* : (1-\Omega_B^*)$. Thus, twenty-two new vectors of weighting coefficients were formed in which the value of the best criterion was modified in the interval $0.0009 \leq \Omega_{12} \leq 0.0867$. Also, the values of the remaining criteria were modified proportionally to fulfill the condition that $\Omega_j \in [0,1]$ and $\sum_{j=1}^{m} \Omega_j = 1$. The new vectors of weight coefficients of the criteria are shown in Fig. 3.

New vectors of weighting coefficients represented inputs to the home matrix, so for each vector of weighting coefficients, a new criterion function was generated for each alternative. Thus, twenty-two new criterion functions of alternatives were formed (see Fig. 4); that is, a new criterion function was generated for each vector of weighting coefficients.

The results from Fig. 4 show that the proposed multi-criteria framework is sensitive to the change of weighting coefficients of the criteria. Changes in the weighting coefficients of the criteria lead to changes in the values of the criteria function alternatives; however, these changes are not drastic and do not disturb the stability of the initial solution. During twenty-two scenarios, it was confirmed that alternative A_2 represents the best solution from the set, while alternative A_3 represents the worst solution. In order to ensure these results, an analysis of the statistical significance of the changes was performed using the Spriman correlation coefficient. Theoretically, the values of Spriman's correlation coefficient (Φ) range in the interval $\Phi \in [-1,1]$, where the value $\Phi = -1$ represents a negligible correlation while the value $\Phi = 1$ represents an extremely high degree of correlation. Fig. 5 shows the statistical significance of the correlation between the initial results and the criterion functions obtained during twenty-two scenarios (see Fig. 4).

The results from Fig. 5 show a high degree of correlation since Φ has values in interval $0.9984 \leq \Phi \leq 1.0$. Based on the presented results, we can conclude that the proposed methodology is sensitive to the change of input parameters and that the initial solution is credible.

(b) The influence of the stabilization parameter λ on the ranking results:

The parameter λ represents the stabilization parameter of the aggregation function of the T2NN VIKOR model. The values of the parameter λ are from the interval $0 \leq \lambda \leq 1$, where for values of $0.0 \leq \lambda < 0.5$ the preference is given to the optimistic scenario, while for $0.5 < \lambda \leq 1.0$ the pessimistic scenario is favored. The value $\lambda = 0.5$ gives equal importance to the pessimistic and optimistic

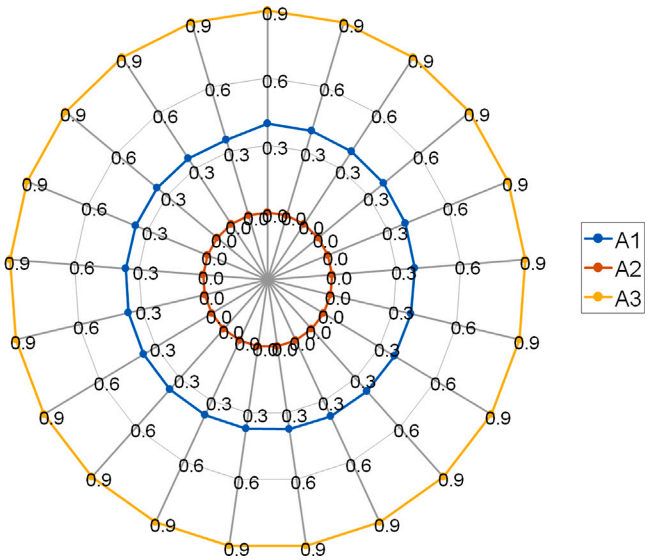

Fig. 4. Changes in criterion functions of alternatives.

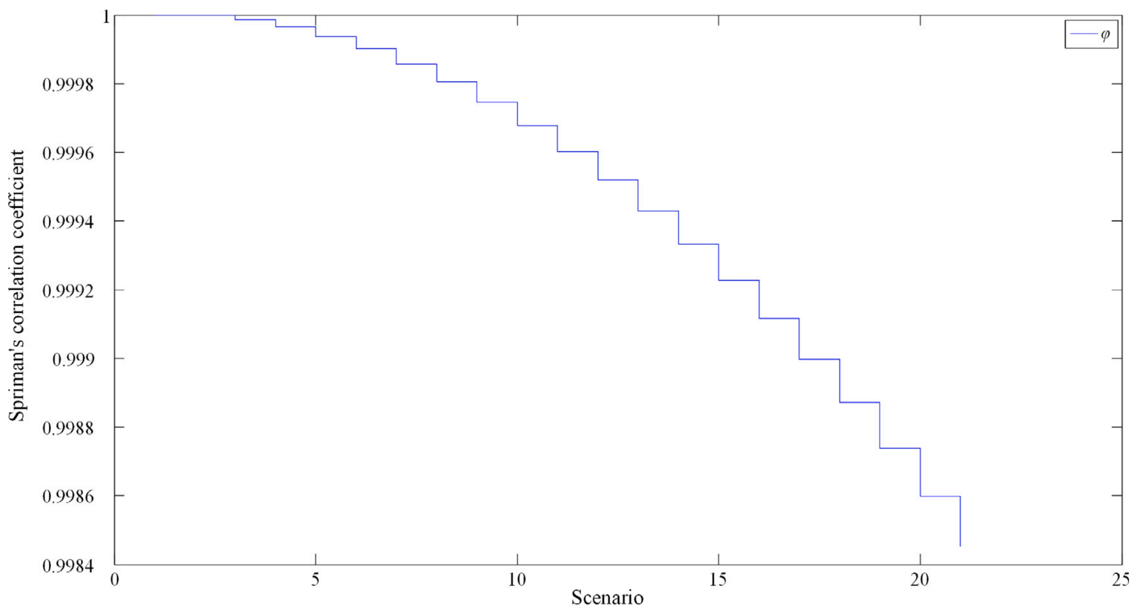

Fig. 5. Correlation of results over twenty-two scenarios.

scenarios. Based on what is shown, we can conclude that the parameter λ affects the final criterion functions. In the following part, the influence of other values of the parameter λ on the change of criterion functions of alternatives was analyzed.

Twenty scenarios were created in which the change of the parameter λ was simulated. For each scenario, new values of criteria functions of alternatives were generated, Fig. 6.

The results from Fig. 6 show that the parameter λ leads to a change in the initial results for the first two alternatives by rank (A_2 and A_1). Alternative A_1 represents the dominant solution for the parameter values $0.0 \le \lambda \le 0.35$, while alternative A_2 occupies the second position. While for the values of the parameter $0.35 < \lambda \le 1.0$, alternative A_2 is the dominant solution, while alternative A_1 is ranked second. Such changes in ranks are the result of favoring pessimistic and optimistic strategies. Given that alternative A_2 represents the dominant solution for the pessimistic scenario and most of the optimistic scenario, we can conclude that A_2 represents the dominant solution from the considered set of alternatives.

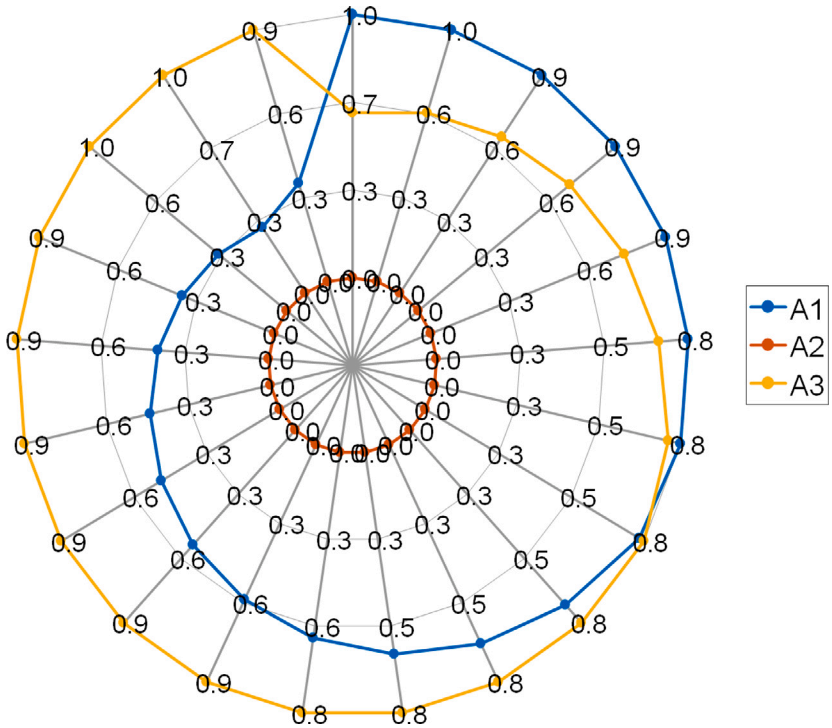

Fig. 6. Changes in criterion functions of alternatives depending on the parameter λ.

5. Results and discussion

The use of the self-powered sensor in C-ITS vehicle signage, speed limit, and weather condition information was determined to be the best alternative. Obtaining assistance from technology makes the most sense in the most realistic scenario. Self-powered sensor integration with vehicles is not difficult because vehicles are already equipped with similar technologies. Furthermore, because traffic safety is a priority, this alternative goes a step further than other alternatives. The use of a self-powered sensor in C-ITS road works warning, slow or stationary vehicle warning is the second most advantageous option. Although this alternative provides information about current traffic flow, its applicability is limited due to the nature of these events. As a result, it is not necessary to pursue this alternative right away. The use of a self-powered sensor in C-ITS traffic management information is the least advantageous option (e.g., green light optimum speed advice). Although this is the most effective option, it requires state-of-the-art equipment and a perfectly organized system to function properly. As a result, it can be considered the final stage of sensor integration. After the other technological developments are completed, this alternative could be very beneficial.

6. Policy implications

There is a demand for intelligent control measures that have the potential to enhance the resilience of a variety of transportation systems in the face of disruptions that cannot be predicted in advance. When engaging in activities that are concerned with human welfare, such as driving, the two most essential aspects to take into consideration are the potential for immediate gain and the viability of making use of the resources that are at one's disposal. Applications related to urban transportation are of direct concern to policymakers because urban transportation is an issue that falls under the purview of the government. In the interim, not only will it be necessary to install the infrastructure components required to put these alternatives into action, but there will also be a need to address issues of regulation, legislation, and standardization. In addition, these steps ought to be carried out with an eye toward the future to forestall the occurrence of additional issues as a consequence of the improvements that have been made.

7. Conclusion

The findings of the study indicate that selecting the most beneficial course of action involves taking into account both the applicability of an option and the benefit it provides in the short term. According to this result, even though there is an option among the alternatives that is more effective, barriers are preventing its implementation due to technological advancements, legislation, regulations, and standardization. In addition, it is important to keep in mind that, even though sensors are a type of advanced technology, they are still machines that depend on programming to operate, which means that there is always the possibility that they could be hacked. Consequently, it is necessary to conduct a comprehensive analysis of the cybersecurity features of the various options. Because of the methodical progression of the project, the level of expertise possessed by those in charge of making decisions is another essential component that will play a significant role in determining the outcome of the decision. Researchers should investigate alternative solutions even if the necessary infrastructure and regulations already exist or are in the process of being installed. Vehicles will be able to communicate with the road infrastructure, with other drivers, and with each other to improve overall road safety if they are equipped with sensors that are capable of generating their power. Vehicles, traffic signs, and other infrastructure will all be able to send standardized messages to drivers in the surrounding area by making use of a self-powered sensor technology that is both efficient and affordable. Using this method, which requires the least amount of energy, it is possible to make roads more sustainable and efficient in a greater variety of traffic conditions. Because of this, the applicability of these alternative solutions ought to be a topic of research in other fields, such as logistics.

The results show that the rough T2NN VIKOR algorithm is a powerful tool for rational and objective decision-making. However, in addition to the apparent advantages, there are also certain limitations. One of the limitations is the impossibility of eliminating the influence of extreme and unreasonable arguments in the initial decision matrix. To eradicate the limitation mentioned above, it is necessary to direct further research toward implementing Power averaging (PA) functions in the T2NN VIKOR methodology. By applying PA functions, it would be possible to present the interrelationships between the criteria, and the flexibility of the T2NN VIKOR model would be further improved. In addition, further research should be focused on enhancing the adaptability of the T2NN VIKOR methodology through the implementation of Einstein and Hamacher functions for processing uncertain information. Also, an exciting direction for further research is the implementation of rough sets for the processing of indeterminacy in the presented multi-criteria framework.

CRediT authorship contribution statement

Muhammet Deveci: Methodology, Validation, Software, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Ilgin Gokasar:** Conceptualization, Data curation, Investigation, Visualization, Validation, Writing – original draft, Writing – review & editing. **Dragan Pamucar:** Methodology, Validation, Software, Writing – original draft, Writing – review & editing, Visualization. **Aws Alaa Zaidan:** Validation, Writing – original draft, Writing – review & editing. **Xin Wen:** Writing – original draft, Writing – review & editing. **Brij B. Gupta:** Supervision, Writing – review & editing.

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