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Evaluation of Metaverse integration of freight fluidity measurement alternatives using fuzzy Dombi EDAS model

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ABSTRACT

Developments in transportation systems, changes in consumerism trends, and conditions such as COVID-19 have increased both the demand and the load on freight transportation. Since various companies are transporting goods all over the world to evaluate the sustainability, speed, and resiliency of freight transportation systems, data and freight fluidity measurement systems are needed. In this study, an integrated decision-making model is proposed to advantage prioritize the freight fluidity measurement alternatives. The proposed model is composed of two main stages. In the first stage, the Dombi norms based Logarithmic Methodology of Additive Weights (LMAW) is used to find the weights of criteria. In the second phase, an extended Evaluation based on the Distance from Average Solution (EDAS) method with Dombi unction for aggregation is presented to determine the final ranking results of alternatives. Three freight fluidity measurement alternatives are proposed, namely doing nothing, integrating freight activities into Metaverse for measuring fluidity, and forming global governance of freight activities for measuring fluidity through available data. Thirteen criteria, which are grouped under four main aspects namely technology, governance, efficiency, and environmental sustainability, and a case study at which a ground framework is formed for the experts to evaluate the alternatives considering the criteria are used in the multi-criteria decision-making process. The results of the study indicate that integrating freight activities into Metaverse for measuring fluidity is the most advantageous alternative, whereas doing nothing is the least advantageous one.

1. Introduction

Recent changes in consumer behavior and current conditions have increased the pressure on freight transportation, increasing the number of commodities transported globally (European Environment Agency, 2021). Since demand has expanded, freight traffic via sea, rail, and road transportation has increased significantly, putting a tremendous burden on the environment, making it difficult to manage the high volume of transportation, and making the system prone to interruptions. As a result, the mobility of freight movement has become critical. Only a few of the many crucial components of freight fluidity include speed and schedule dependability, resistance to transportation system disruptions, sustainability, and cost-effectiveness (Rodrigue, 2008). The freight transportation system can be said to be fluid when these requirements are met. Freight fluidity measurement approaches such as big data operations and multi-modal routing applications must be used to boost the fluidity of freight transportation, optimize operations, and provide uninterrupted service.

Freight fluidity measurement applications have the potential to identify changes that can improve the reliability of freight transportation operations by boosting time reliability, sustainability, and cost-efficiency. Using the results of freight fluidity measurement applications, authorities and decision-makers can invest in open improvement sides of freight transportation networks, allowing them to create a more fluid system (Eisele et al., 2016). On the other hand, in recent years, extreme occurrences such as weather conditions caused by

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climate change and epidemics such as COVID-19 have been observed to have a significant impact on freight transportation, even bringing these operations to a halt (Gonzalez et al., 2022). Implementation of freight fluidity measuring systems appears potential as a means of mitigating the effects of such events while maintaining full operational efficiency.

Freight transportation authorities and decision-makers are looking for ways to improve the fluidity of their operations. The companies do their research into the present status of freight fluidity measurement applications. One of the most commonly utilized approaches is the collecting of data, such as GPS data, from each mode of operation (Cedillo-Campos et al., 2019). Shipping ports are another data source used to gauge system fluidity, and data obtained from this source is mostly used for long-term freight planning and travel demand forecasting (Asborno et al., 2020). Even if these measurement techniques appear to be effective, several new technologies are promising in terms of delivering more diverse fluidity measurement tools and assisting authorities in more efficiently improving their freight transportation systems. One example of such new technology is metaverse technology.

Blockchain technology and the Metaverse have quickly penetrated our lives in recent years. The production of digital twins, which mirror the real world in the digital verse, is one method that the Metaverse can be implemented in real life (Han et al., 2022). Creating digital twins of freight transportation agents and integrating these agents into Metaverse to track freight transportation operations and analyze freight fluidity has a lot of potential in terms of collecting diverse real-time data utilizing blockchain technology. Freight movement data gathered through the metaverse can be shared with clients in applications because data sharing can be handled using blockchain technology just as it is used for data gathering (Fan et al., 2018). For example, customers can track products being transported and purchase desired things while they are being transported, allowing enterprises to provide goods before they reach their destination, which is the warehouse. This type of solution is made possible by using freight fluidity metrics in Metaverse. Aside from Metaverse applications, another option for efficiently evaluating fright fluidity is the development of global governance of freight operations for measuring fluidity through available data.

Creating a global center for governing freight transportation concerns is a promising application in terms of collecting all data in one location and using the coupled data for overall freight fluidity measures. This type of application can greatly assist all authorities and decision-makers in optimizing their operations using accessible big data and increasing the flexibility of freight transportation. This has the potential to improve time reliability and sustainability by assigning freight transportation activities to various available and uncongested modes to reduce delays and use environmentally favorable modes of transportation.

The motivation of this research is to present novel freight fluidity measuring methods and utilize expert comments to rank them in order of their advantages. A multi-criteria decision-making tool is utilized during the procedure, and each alternative is evaluated according to the specified criteria, which are determined following a thorough literature review. The evaluation procedure is carried out by developing a questionnaire in which each possibility is asked to be evaluated on each criterion. The questionnaires are then distributed to specialists for review of the alternatives. Multi-criteria decision-making (MCDM) techniques have been successfully integrated into many real-life problems (Badi et al., 2022; Chattopadhyay et al., 2022; Bouraima et al., 2022).

This study aims to present an efficient fuzzy Dombi based MCDM model including Logarithmic Methodology of Additive Weights (LMAW) and Evaluation based on Distance from Average Solution (EDAS) (Keshavarz Ghorabaee et al., 2015) method for solving the freight fluidity measurement problem. The Dombi based LMAW (Pamucar et al., 2021) is applied for calculating the weight coefficients of the criteria. The Dombi based EDAS method is proposed for the evaluation of alternatives. The main contributions of this study are as follows:

(i) This study adds to the field by suggesting two new freight fluidity measurement applications: integrating freight operations into Metaverse for fluidity measurement and developing global governance of freight activities for fluidity measurement using existing data.
(ii) A case study is developed to serve as a foundation for the experts' evaluations, which may guide authorities and decision-makers in the transition to a more developed and advanced freight fluidity measuring system.
(iii) The proposed model enables decision-makers to better perceive the relationship between criteria, which contributes to rational reasoning and objective evaluation of alternatives.
(iv) EDAS method provides an optimistic and pessimistic evaluation of alternatives.
(v) The application of the triangular fuzzy numbers based Dombi function improved the flexibility of the traditional EDAS method
(vi) There is a scarcity of research on the integration of freight fluidity measurements with metaverse. This paper contributes significantly to the field by presenting various alternative integration approaches.
(vii) The findings of this study can be used as a guide for authorities and decision-makers who seek to carry out projects such as the alternatives in this study because they can select the most advantageous alternative over this study.

The rest of this study is built as follows: Section 2 contains a literature review on freight fluidity and freight fluidity measurement methods. The definition of the problem, alternatives, and criteria related to this study is provided in Section 3. Section 4 gives the proposed methodology of the study. The case study, results of the proposed methodology, and stability are explained in Section 5. The results and discussion is presented in Section 6. Section 7 discusses the managerial and policy implications. Finally, Section 8 provides the conclusion.

2. Literature review

There are various studies in the literature on the importance and utility of freight fluidity and freight fluidity assessment methods. As stated in different studies, efficiency, safety, and travel time reliability are important aspects of supply chains, and increasing freight fluidity means improving these aspects (Bueno-Solano et al., 2022; National Research Council Canada, 2022; Pisarski, 2016). According to a previous study, freight fluidity in sea transportation strives to boost journey time reliability and reduce supply chain end-to-end shipping expenses (Kruse et al., 2018). It is also claimed that the US Army Engineer Research and Development Center and Texas A&M Transportation Institute collaborated to implement a freight fluidity measurement system at ports to evaluate these ports' fluidity measurements in terms of oceangoing vessels. A different freight fluidity measurement application developed by the US Army Engineer Research and Development Center attempts to measure the fluidity of vessels traveling between the most heavily trafficked ports by using data such as travel information, weather conditions, directional flow currents, and so on (Mitchell et al., 2019). The goal is to identify the factors that influence trip time reliability. According to another study, efficient freight fluidity increases serviceability and predictability, which are two of the most essential quality indicators in supply chains (Swai et al., 2021). As a result, it is easy to argue that enhancing the flexibility of freight transportation is critical. To promote fluidity, freight fluidity measuring systems are required so that systems can be improved.

There are numerous real-world uses for freight fluidity measurement systems in their current state. Freight fluidity measurement is critical for authorities searching for ways to improve their freight transportation operations (Eisele et al., 2016). Because freight fluidity measurement is a performance-based evaluation, decision-makers may easily identify and rectify the system's flaws. According to a study on a freight fluidity measuring system, vessel Automatic Identification System (AIS) data held by public authorities is quite restricted (Asborno and Hernandez, 2021). The authors presented a multi-commodity assignment model and a stochastic approach to anticipate and collect commodity data to provide an effective freight fluidity assessment system. The presence of this application aims to collect data on origin–destination, timestamp, commodity carried, and vessel travel so that fluidity measurements can be performed. A mathematical model for estimating the fluidity of intermodal freight transportation is developed in another study (Cedillo-Campos et al., 2017). According to Cedillo-Campos et al. (2017), authorities and decision-makers must understand whether freight transportation activities are optimized sufficiently so that they can improve the weak operational components to increase economic growth. As a result, freight mobility is critical in terms of giving economic benefits to the organization. Another study on shipping company mode choice under carbon pricing studies freight fluidity elements such as time reliability, frequency, transit time, and so on when carbon pricing is imposed (Brooks et al., 2012). The study's findings are encouraging in terms of giving a framework if carbon pricing is implemented for other types of transportation such as vessels or rail transit. The results of this study show that freight transportation can be made more environmentally friendly while also looking for ways to make the system more fluid and efficient.

Even though there are beneficial implementation methods in place, fluidity measurement systems can be improved by utilizing novel technologies such as Metaverse. The metaverse creates a digital twin of the real world, and every action is tracked (Mozumder et al., 2022). As a result, gathering and storage of all types of freight transportation data will be possible. Fluidity measurement activities will be achieved by optimizing the relevant data. In addition to Metaverse applications, establishing a single worldwide center to handle freight fluidity assessment is attractive since data will be collected in one location, allowing for integrated optimization. In addition, the use of a metaverse in freight fluidity measurement systems is promising in the event of a disruption such as a pandemic or a political war zone. Because the use of metaverse provides various data such as the location of transported goods, available routes, and modes for transporting the goods to their destination point, even when there are disruptions, the use of metaverse eases freight mobility and possible solutions such as new routes and available transportation modes can be found in such situations.

A collaborative study between the Transportation Research Board (TRB) and the Federal Highway Administration (FHWA) is described in a study about diverse parties working together to quantify freight fluidity (Turnbull, 2016). According to the study, the private and public sectors discussed how to adopt a freight fluidity measuring system to improve freight transportation. This study demonstrates that bringing together numerous parties to connect various components such as data is advantageous in terms of freight fluidity measurement.

In this study, three alternatives for measuring freight fluidity are advantage prioritized using the proposed MCDM tool. Hence, a guide for authorities and decision-makers is developed that may be used during the transition from traditional measurement techniques to more modern and technological measurement methods.

3. Problem Definition

Freight fluidity measurement systems are required to increase the fluidity of freight transportation systems, which involves boosting time reliability, service quality, resilience, sustainability, and so on. Various approaches, such as GPS and port data collection, can be used to make use of these systems. Using this information, freight transportation operations can be optimized, mode selections can be made more advantageously, and freight transit routes can be maximized. Transportation networks, on the other hand, are vulnerable to incidents. Problems such as diplomatic issues and communication conflicts between countries, for example, might harm freight transportation systems. Adapting freight transportation systems to technological advances and using freight fluidity can help to mitigate these negative features. In this study, three distinct freight fluidity measuring alternatives and thirteen criteria were identified, and the advantages were ranked for decision-makers.

3.1. Definition of alternatives

The three alternatives presented for this study are described below:

A_1: Do nothing— Individual fluidity measures are already in place: In supply chains, it's possible that things won't be delivered on time, or that the wrong products or missing products will be delivered. There are occasions when it is possible to disregard these issues and carry on without making any modifications to the existing system. These upgrades might be overlooked due to a lack of funding. This ignorance can result in susceptibility, increased costs, and the lack of a business network that is beneficial to the environment (Burges, 1998).

A_2: Integrating freight activities into Metaverse for measuring fluidity: Even though metaverse technology is still a relatively new field, it is one of the technologies that is becoming increasingly integrated into everyday life. The technology of the Metaverse allows for the performance of activities such as shopping, the management of personal relationships through the establishment of connections to other environments, the efficient operation of corporate networks, and the reduction of transportation costs (Pamucar et al., 2022).

A_3: Forming global governance of freight activities for measuring fluidity through available data: Planning and management are vitally crucial aspects to consider when developing a network for the movement of freight that is both sustainable and effective. To properly plan and manage this process, it is necessary to take into account the freight transport activities that occurred in the past. These operations are recorded in data collection, and freight activities are scheduled more carefully, which leads to a reduction in the amount of fuel used and the amount of time wasted (Srour and Newton, 2006).

3.2. Definition of criteria

In this study, twelve criteria are defined as the following:

(1) Technology Aspect.

C_1: Fuller image to better inform process participants: (the use of Big Data underlying freight movement analysis) (benefit): The widespread lack of trust that exists between buyers and sellers in the freight industry presents a significant obstacle for businesses in this sector. Additionally, there is the concern that customers will be unable to obtain the product for which they have made a financial commitment but have not yet received it. It is predicted that the gathering of data relating to freight transportation, as well as the construction of a medium that is more open and transparent in terms of informing the stakeholders, will lead to an increase in levels of trust. Using such big data related to freight transportation has the potential to enhance trade volume since buyers will have more trust in the sellers. In addition, this problem can be avoided by informing all of the pertinent parties from a reliable third-party auditing agency (Govindan et al., 2018).

C_2: Creating transparency by exchanging data with suppliers (benefit): One of the most vital components of successful commercial exchange is a clear and open line of communication. As a result, being in a position to establish this transparency using a collection of diverse, large, and precise data and then communicating this data with the supplier is a helpful activity. Therefore, situations that can cause trust problems can be avoided by exchanging data with suppliers (Lamming et al., 2001).

C_3: Increased use of innovative solutions (e.g., AI) for improving security and accuracy (benefit): Because of advancements in technology, there are now more approaches available that can be used to make systems more accurate and secure. Methods that make use of artificial intelligence (AI) and machine learning (ML) are only two examples of the many cutting-edge approaches that can be utilized to make accuracy and safety improvements. Innovative applications, such as artificial intelligence and

machine learning, can be used to take rapid action against harmful attacks (Haider et al., 2020). This enables faster resolution of security issues. Additionally, these cutting-edge applications can be used for optimization, which has a significant potential for increasing the level of precision achieved by the activities that are carried out.

(2) Governance Aspect.

C_4: Lowered economic activity due to disruptions (cost): Economic activity can be disrupted for a variety of different reasons, including pandemics, crises, and diplomatic confrontations. As a result, the authorities may run into some budgetary issues (Michie, 2020).

C_5: The need to manage risk more effectively (cost): Every industry, including retail, finance, and construction, is exposed to some degree of risk. The proper management of this risk can contribute to the consistent and long-term operation of the business process (Krysiak, 2009).

C_6: Challenges of resiliency and access to life-critical goods (cost): The absence of essential goods like food and medicine can result in adverse effects on both the economy and the health of the population. Users could concentrate on acquiring access to these things (Blyth and Mallet, 2020). During a worldwide emergency, such as the outbreak of a pandemic or a diplomatic dispute, if a freight transportation system is not resilient enough, it will be more likely to experience disruptions, which will have a detrimental impact on the availability of items that are essential to life.

C_7: The need for tracking performance (cost): While they are out shopping, users might wish to be kept informed at all times on the whereabouts of their purchases. Demand can be significantly increased if it is possible to monitor the activity of the organization from whom the goods are acquired (Shamsuzzoha, 2013).

(3) Efficiency Aspect.

C_8: Increased congestion in urban roads (cost): Because they stay in traffic for longer periods than other vehicles, heavy vehicles that are employed for road transport can contribute to an increase in traffic density. Since freight operations typically include the usage of heavy vehicles, there is a strong correlation between the density of traffic and the volume of freight activities (McKinnon et al., 2009).

C_9: Enhance freight mobility (more efficient routing) (benefit): When it comes to freight transportation and distribution, having a route that is better optimized can help reduce the amount of fuel used (Chandra et al., 2020). Additionally, operations that have their route optimized have the potential to reduce travel times while simultaneously increasing the reliability of travel times, which is a highly beneficial component of freight transportation.

C_{10}: Increasing the use of circular supply chains that are localized and dependable (benefit): This criterion refers to the utilization of the local supply chain as opposed to the global supply chain. This allows for the establishment of a local circular system and does away with the local system's reliance on external factors. It gives customers the ability to adapt to these networks sooner by putting in place and constructing reliable supply chain networks that have been utilized in a region previously. As a result, it is possible to establish circular supply chains that are more efficient and sustainable (Simatupang and Sridharan, 2002).

(4) environmental sustainability ASPECT

C_{11}: The need for integrating emission metrics in procurement standards (cost): Every single step in the transportation process for freight results in the release of emissions like CO2 and CO. When authorities place limits on the total amount of emissions, it may encourage suppliers to adopt more environmentally friendly practices. On the other hand, this can be reflected as an additional cost by the suppliers (Zanni and Bristow, 2010).

C_{12}: Yielding wider sustainability benefits (benefit): If technical endeavors are carried out on a broader scale, the current system is amenable to optimization to lower the amount of fuel used and the expenditures incurred per unit of distance (Aloui et al., 2021). Accurate data collection is required for optimization procedures to be carried out in the correct manner, which is necessary to achieve the goal of effectively and efficiently increasing the system's capacity for sustainability.

C_{13}: Minimal energy use (benefit): Each process in the freight sector consumes a specific amount of energy. Increasing energy efficiency by reducing the amount and enhancing the quality of these operations (Fan et al., 2019). As a result, optimizing the use of the gathered freight fluidity measurement data can give minimal energy use. Also, because a collection of big data is available in the metaverse, one might become conscious of their carbon footprint through the collected records. This can make people more concerned about environmental problems and encourage them to support the use of the study's alternatives.

4. Proposed methodology

In this section, some definitions and operations about Dombi norms, and the steps of the proposed model are provided as follows:

4.1. Dombi T-norm and T-conorm

In this study, triangular fuzzy numbers are applied to address the uncertainty in the information (Zadeh, 1965, 1975). The notions and operations of the Dombi *T*-norm and *T*-conorm were introduced by Dombi (1982), which present the advantage of good flexibility with the operational parameter. Some definitions of the Dombi *T*-norm and *T*-conorm under triangular fuzzy numbers (TFNs) are expressed by:

Definition 1. (Dombi, 1982, 2009). *Let γ_1 and γ_2 be any two real numbers. Then, the operations of Dombi T-norm and T-conorm between γ_1 and γ_2 are expressed by*:

$$\mathrm{T}_D(\gamma_1,\gamma_2) = \frac{1}{1+\left\{\left(\frac{1-\gamma_1}{\gamma_1}\right)^{\Phi}+\left(\frac{1-\gamma_2}{\gamma_2}\right)^{\Phi}\right\}^{1/\Phi}} \tag{1}$$

$$\mathrm{T}^c_D(\gamma_1,\gamma_2) = 1-\frac{1}{1+\left\{\left(\frac{\gamma_1}{1-\gamma_1}\right)^{\Phi}+\left(\frac{\gamma_2}{1-\gamma_2}\right)^{\Phi}\right\}^{1/\Phi}} \tag{2}$$

where $\Phi > 0$ and$(\gamma_1,\gamma_2) \in [0,1]$.

Definition 2. *Let $\gamma_1 = (\gamma_1^{(a)},\gamma_1^{(b)},\gamma_1^{(c)})$ and $\gamma_2 = (\gamma_2^{(a)},\gamma_2^{(b)},\gamma_2^{(c)})$ be two TFNs, $\Phi > 0$ and let it be $f(\gamma_i) = \left(f\left(\gamma_i^{(a)}\right),f\left(\gamma_i^{(b)}\right),f\left(\gamma_i^{(c)}\right)\right) = \left(\gamma_i^{(a)}/\sum_{i=1}^n\gamma_i^{(a)},\gamma_i^{(b)}/\sum_{i=1}^n\gamma_i^{(b)},\gamma_i^{(c)}/\sum_{i=1}^n\gamma_i^{(c)},\right)$ a fuzzy function, then some operational laws of TFNs based on the Dombi T-norm and T-conorm are defined by*:

(1) Addition of two fuzzy numbers γ_1 and γ_2 can be defined as follows:

$$\gamma_1+\gamma_2 = \begin{pmatrix} \sum_{i=1}^2\gamma_i^{(a)} - \dfrac{\sum_{i=1}^2\gamma_i^{(a)}}{1+\left\{\left(\dfrac{f\left(\gamma_1^{(a)}\right)}{1-f\left(\gamma_1^{(a)}\right)}\right)^{\Phi}+\left(\dfrac{f\left(\gamma_2^{(a)}\right)}{1-f\left(\gamma_2^{(a)}\right)}\right)^{\Phi}\right\}^{1/\Phi}}, \\ \sum_{i=1}^2\gamma_i^{(b)} - \dfrac{\sum_{i=1}^2\wp_i^{(b)}}{1+\left\{\left(\dfrac{f\left(\gamma_1^{(b)}\right)}{1-f\left(\gamma_1^{(b)}\right)}\right)^{\Phi}+\left(\dfrac{f\left(\gamma_2^{(b)}\right)}{1-f\left(\gamma_2^{(b)}\right)}\right)^{\Phi}\right\}^{1/\Phi}}, \\ \sum_{i=1}^2\gamma_i^{(c)} - \dfrac{\sum_{i=1}^2\gamma_i^{(c)}}{1+\left\{\left(\dfrac{f\left(\gamma_1^{(c)}\right)}{1-f\left(\gamma_1^{(c)}\right)}\right)^{\Phi}+\left(\dfrac{f\left(\gamma_2^{(c)}\right)}{1-f\left(\gamma_2^{(c)}\right)}\right)^{\Phi}\right\}^{1/\Phi}} \end{pmatrix} \tag{3}$$

(2) Multiplication of γ_1 and γ_2 can be defined by:

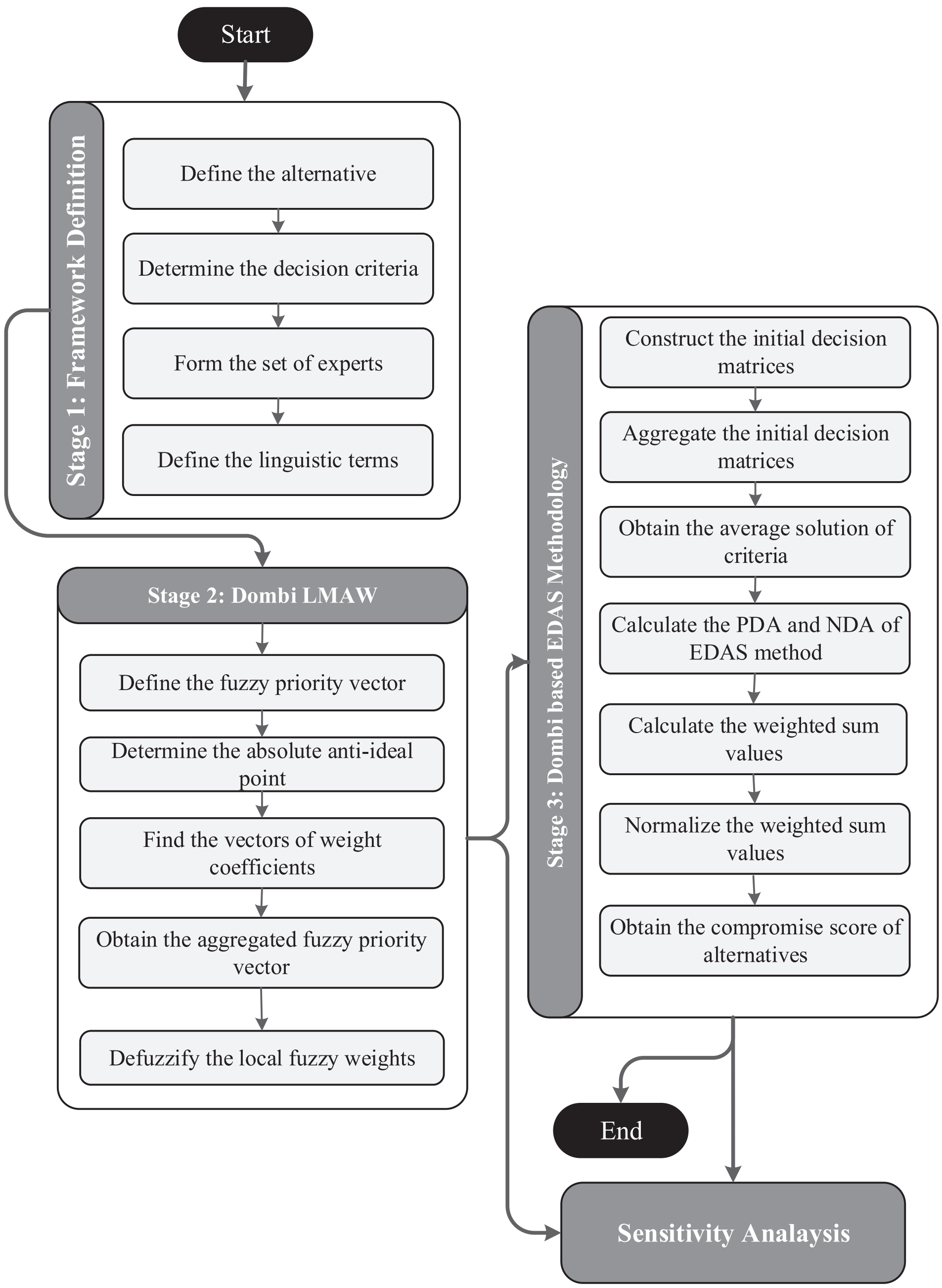

Fig. 1. The stages of the proposed methodology.

Table 1
Fuzzy linguistic terms and their triangular fuzzy numbers for evaluating criteria and alternatives.

Linguistic terms	Corresponding values
Absolutely low (AL)	(1, 1, 1)
Very low (VL)	(1, 2, 3)
Low (L)	(2, 3, 4)
Medium low (ML)	(3, 4, 5)
Equal (E)	(4, 5, 6)
Medium high (MH)	(5, 6, 7)
High (H)	(6, 7, 8)
Very high (VH)	(7, 8, 9)
Absolutely high (AH)	(8, 9, 9)

$$\gamma_1 \times \gamma_2 = \left(\begin{array}{c} \dfrac{\sum_{i=1}^{2} \gamma_i^{(a)}}{1 + \left\{ \left(\dfrac{1 - f\left(\gamma_1^{(a)}\right)}{f\left(\gamma_1^{(a)}\right)} \right)^{\Phi} + \left(\dfrac{1 - f\left(\gamma_2^{(a)}\right)}{f\left(\gamma_2^{(a)}\right)} \right)^{\Phi} \right\}^{1/\Phi}}, \\ \dfrac{\sum_{i=1}^{2} \gamma_i^{(b)}}{1 + \left\{ \left(\dfrac{1 - f\left(\gamma_1^{(b)}\right)}{f\left(\gamma_1^{(b)}\right)} \right)^{\Phi} + \left(\dfrac{1 - f\left(\gamma_2^{(b)}\right)}{f\left(\gamma_2^{(b)}\right)} \right)^{\Phi} \right\}^{1/\Phi}}, \\ \dfrac{\sum_{i=1}^{2} \gamma_i^{(u)}}{1 + \left\{ \left(\dfrac{1 - f\left(\gamma_1^{(c)}\right)}{f\left(\gamma_1^{(c)}\right)} \right)^{\Phi} + \left(\dfrac{1 - f\left(\gamma_2^{(c)}\right)}{f\left(\gamma_2^{(c)}\right)} \right)^{\rho} \right\}^{1/\Phi}} \end{array} \right) \tag{4}$$

(3) Scalar multiplication,

$$\zeta\gamma_1 = \left(\gamma_i^{(a)} - \frac{\gamma_i^{(a)}}{1 + \left\{ \zeta \left(\frac{f\left(\gamma_1^{(a)}\right)}{1 - f\left(\gamma_1^{(a)}\right)} \right)^{\Phi} \right\}^{1/\Phi}}, \gamma_i^{(b)} - \frac{\gamma_i^{(b)}}{1 + \left\{ \zeta \left(\frac{f\left(\gamma_1^{(b)}\right)}{1 - f\left(\gamma_1^{(b)}\right)} \right)^{\Phi} \right\}^{1/\Phi}}, \gamma_i^{(c)} - \frac{\gamma_i^{(c)}}{1 + \left\{ \zeta \left(\frac{f\left(\gamma_1^{(c)}\right)}{1 - f\left(\gamma_1^{(c)}\right)} \right)^{\Phi} \right\}^{1/\Phi}} \right) \tag{5}$$

$\zeta > 0$

(4) Power,

$$\gamma_1^{\zeta} = \left(\frac{\gamma_i^{(a)}}{1 + \left\{ \zeta \left(\frac{1 - f\left(\gamma_1^{(a)}\right)}{f\left(\gamma_1^{(a)}\right)} \right)^{\Phi} \right\}^{1/\Phi}}, \frac{\gamma_i^{(b)}}{1 + \left\{ \zeta \left(\frac{1 - f\left(\gamma_1^{(b)}\right)}{f\left(\gamma_1^{(b)}\right)} \right)^{\Phi} \right\}^{1/\Phi}}, \frac{\gamma_i^{(c)}}{1 + \left\{ \zeta \left(\frac{1 - f\left(\gamma_1^{(c)}\right)}{f\left(\gamma_1^{(c)}\right)} \right)^{\Phi} \right\}^{1/\Phi}} \right) \tag{6}$$

$\zeta > 0$

Definition 3. *Let* $\gamma_j = (\gamma_j^{(a)}, \gamma_j^{(b)}, \gamma_j^{(c)}); (j = 1, 2, ..., n)$, *a set of TFNs, and* $\psi_j \in [0, 1]$ *denotes the weight of coefficients of* γ_j, *which fulfills the requirement that it is* $\sum_{j=1}^{n} \psi_j = 1$. *Then, the fuzzy weighted averaging (FWA) operator and fuzzy weighted geometric averaging (FWGA) operator are expressed by*:

$$FWA(\gamma_1, \gamma_2, .., \gamma_n) = \sum_{j=1}^{n} \psi_j \cdot \gamma_j = \left(\sum_{j=1}^{n} \psi_j \cdot \gamma_j^{(a)}, \sum_{j=1}^{n} \psi_j \cdot \gamma_j^{(b)}, \sum_{j=1}^{n} \psi_j \cdot \gamma_j^{(c)} \right) \tag{7}$$

$$FWGA(\gamma_1, \gamma_2, .., \gamma_n) = \prod_{j=1}^{n} (\gamma_j)^{\psi_j} = \left(\prod_{j=1}^{n} \left(\gamma_j^{(a)}\right)^{\psi_j}, \prod_{j=1}^{n} \left(\gamma_j^{(b)}\right)^{\psi_j}, \prod_{j=1}^{n} \left(\gamma_j^{(c)}\right)^{\psi_j} \right) \tag{8}$$

4.2. Dombi based LMAW and EDAS methodology

The Dombi based LMAW and EDAS (Keshavarz Ghorabaee et al., 2015) methods are used to determine the weights of criteria and assess the freight fluidity measurement alternatives. The proposed Dombi based LMAW and EDAS method follow three consecutive stages as presented in Fig. 1.

(1) Framwork definition.

Step 1. The objectives for the decision-making problem are described, including the determination of alternatives, the selection of criteria, and the creation of a set of experts to build the proposed model. The alternatives $\wp_i = (\wp_1, \wp_2, \ldots, \wp_n)(i = 1, 2, \ldots, n)$ and $\varsigma_i = (\varsigma_1, \varsigma_2, \ldots, \varsigma_n)(j = 1, 2, \ldots, m)$ are evaluated by a set of experts $E_l = (E_1, E_2, \ldots, E_e)(l = 1, 2, \ldots, e)$.

Step 2. The linguistic terms and their corresponding values are determined.

(2) Determining criteria weights – Fuzzy Dombi based Logarithmic Methodology of Additive Weights (LMAW) (Deveci et al., 2021).

Step 3. The steps of this model are summarized as follows:

Step 3.1. The fuzzy priority vector is described. The criteria are evaluated by the expert team with the help of fuzzy linguistic terms and their corresponding values (see Table 1). Afterward, the fuzzy priority vector $\chi^{\ell} = (\chi_1^{\ell}, \chi_2^{\ell}, .., \chi_m^{\ell})$ is obtained, where $(1 \le \ell \le e)$.

Step 3.2. The absolute anti-ideal point (θ_{AIP}) is determined.

$$\theta_{AIP} < \min\left(\chi_j^{\ell}, \chi_j^{\ell}, .., \chi_j^{\ell}\right) \tag{9}$$

The relationship between the fuzzy priority vector elements and the θ_{AIP} is found by:

Table 2
The decision criteria.

Main-criteria	Sub-criteria	Types
Technology Aspect (MC_1)		
C_1	More complete picture to better inform all stakeholders in the process	Benefit
C_2	Creating transparency by exchanging data with suppliers	Benefit
C_3	Increased use of innovative solutions	Benefit
Governance Aspect (MC_2)		
C_4	Lowered economic activity due to disruptions	Cost
C_5	The need to manage risk more effectively	Cost
C_6	Challenges of resiliency and access to life-critical goods	Cost
C_7	The need for tracking performance	Cost
Efficiency Aspect (MC_3)		
C_8	Increased congestion on urban roads	Cost
C_9	Enhance freight mobility (more efficient routing)	Benefit
C_{10}	Increasing the use of circular supply chains	Benefit
Environmental Sustainability Aspect (MC_4)		
C_{11}	The need for integrating emission metrics in procurement standards	Cost
C_{12}	Yielding wider sustainability benefits	Benefit
C_{13}	Minimal energy use	Benefit

Table 3
The linguistic decision matrix of thirteen criteria in terms of six experts.

Criteria	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6
C_1	MH	MH	MH	VH	VL	H
C_2	E	MH	VH	AH	H	MH
C_3	VH	H	H	H	VH	AH
C_4	VH	MH	VH	AH	VH	AH
C_5	MH	H	H	H	VL	L
C_6	H	VH	VH	VH	E	E
C_7	VH	E	MH	MH	VL	H
C_8	VH	VH	H	E	VL	H
C_9	H	H	VH	VH	AH	MH
C_{10}	E	H	VH	AH	E	L
C_{11}	MH	H	MH	E	E	MH
C_{12}	VH	H	H	AH	E	H
C_{13}	AH	VH	VH	VH	VH	AH

$$\eta_j = \frac{\chi_j}{\theta_{AIP}} = \left(\frac{\chi_j^{(a)}}{\theta_{AIP}^{(c)}}, \frac{\chi_j^{(b)}}{\theta_{AIP}^{(b)}}, \frac{\chi_j^{(c)}}{\theta_{AIP}^{(a)}}\right) \tag{10}$$

where $\left(\chi_j^{(a)}, \chi_j^{(b)}, \chi_j^{(c)}\right)$ represents the elements of the priority vectorη.

Step 3.3. The vectors of weight coefficients $\aleph_j$ are foundf by Eq. (11):

$$\hbar_j = \frac{\ln(\eta_j)}{\ln(\tau)} = \left(\frac{\ln\left(\eta_j^{(a)}\right)}{\ln(\tau^{(c)})}, \frac{\ln\left(\eta_j^{(b)}\right)}{\ln(\tau^{(b)})}, \frac{\ln\left(\eta_j^{(c)}\right)}{\ln(\tau^{(a)})}\right) \tag{11}$$

where$\tau = \prod_{j=1}^{m} \eta_j = \left(\prod_{j=1}^{m} \eta_j^{(a)}, \prod_{j=1}^{m} \eta_j^{(b)}, \prod_{j=1}^{m} \eta_j^{(c)}\right)$, and$\sum_{j=1}^{m} \hbar_j = 1$.

Step 3.4. The aggregated fuzzy priority vector $\hbar = (\hbar_1, \hbar_2, .., \hbar_m)$ is calculated by the fuzzy Dombi function as given in Eq. (12).

$$\rho_j^{\xi} = \left(\rho_j^{\xi(a)}, \rho_j^{\xi(b)}, \rho_j^{\xi(c)}\right)$$

$$= \left(\frac{\sum_{j=1}^{m}\left(\hbar_{ij}^{(a)}\right)}{1+\left\{\sum_{j=1}^{m}\omega_j\left(\frac{1-f\left(\hbar_{ij}^{(a)}\right)}{f\left(\hbar_{ij}^{(a)}\right)}\right)^{\xi}\right\}^{1/\xi}}, \frac{\sum_{j=1}^{m}\left(\hbar_{ij}^{(b)}\right)}{1+\left\{\sum_{j=1}^{m}\omega_j\left(\frac{1-f\left(\hbar_{ij}^{(b)}\right)}{f\left(\hbar_{ij}^{(b)}\right)}\right)^{\xi}\right\}^{1/\xi}}, \frac{\sum_{j=1}^{m}\left(\hbar_{ij}^{(c)}\right)}{1+\left\{\sum_{j=1}^{m}\omega_j\left(\frac{1-f\left(\hbar_{ij}^{(c)}\right)}{f\left(\hbar_{ij}^{(c)}\right)}\right)^{\xi}\right\}^{1/\xi}}\right) \tag{12}$$

Where$\xi > 0$, and$\sum_{\ell=1}^{e} \omega_\ell = 1$, and.

Step 3.5. The triangular fuzzy value of $\rho_j = \left(\rho_j^{(p)}, \rho_j^{(r)}, \rho_j^{(s)}\right)$ is defuzzified by:

$$def(\rho_j) = \frac{\rho_j^{(a)} + 4 \cdot \rho_j^{(b)} + \rho_j^{(c)}}{6} \tag{13}$$

(3) Application of Dombi based EDAS method for ranking the alternatives.

Step 4. The initial decision matrices regarding experts' opinions using the linguistic terms given in Table 1.

Step 5. The initial decision matrix using the fuzzy Dombi weighted geometric averaging (FDWGA) operator as given in Eq. (14) is aggregated.

$$\mathbb{Q}_j^{\xi} = \left(\mathbb{Q}_i^{\xi(a)}, \mathbb{Q}_i^{\xi(b)}, \mathbb{Q}_i^{\xi(c)}\right)$$

$$= \left(\frac{\sum_{j=1}^{m}\left(x_{ij}^{(a)}\right)}{1+\left\{\sum_{j=1}^{m}\omega_j\left(\frac{1-f\left(x_{ij}^{(a)}\right)}{f\left(x_{ij}^{(a)}\right)}\right)^{\xi}\right\}^{1/\xi}}, \frac{\sum_{j=1}^{m}\left(x_{ij}^{(b)}\right)}{1+\left\{\sum_{j=1}^{m}\omega_j\left(\frac{1-f\left(x_{ij}^{(b)}\right)}{f\left(x_{ij}^{(b)}\right)}\right)^{\xi}\right\}^{1/\xi}}, \frac{\sum_{j=1}^{m}\left(x_{ij}^{(c)}\right)}{1+\left\{\sum_{j=1}^{m}\omega_j\left(\frac{1-f\left(x_{ij}^{(c)}\right)}{f\left(x_{ij}^{(c)}\right)}\right)^{\xi}\right\}^{1/\xi}}\right) \tag{14}$$

Table 4
The converted fuzzy numbers of criteria in terms of each expert.

Criteria	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5	Expert 6
C_1	(5,6,7)	(5,6,7)	(5,6,7)	(7,8,9)	(1,2,3)	(6,7,8)
C_2	(4,5,6)	(5,6,7)	(7,8,9)	(8,9,9)	(6,7,8)	(5,6,7)
C_3	(7,8,9)	(6,7,8)	(6,7,8)	(6,7,8)	(7,8,9)	(8,9,9)
C_4	(7,8,9)	(5,6,7)	(7,8,9)	(8,9,9)	(7,8,9)	(8,9,9)
C_5	(5,6,7)	(6,7,8)	(6,7,8)	(6,7,8)	(1,2,3)	(2,3,4)
C_6	(6,7,8)	(7,8,9)	(7,8,9)	(7,8,9)	(4,5,6)	(4,5,6)
C_7	(7,8,9)	(4,5,6)	(5,6,7)	(5,6,7)	(1,2,3)	(6,7,8)
C_8	(7,8,9)	(7,8,9)	(6,7,8)	(4,5,6)	(1,2,3)	(6,7,8)
C_9	(6,7,8)	(6,7,8)	(7,8,9)	(7,8,9)	(8,9,9)	(5,6,7)
C_{10}	(4,5,6)	(6,7,8)	(7,8,9)	(8,9,9)	(4,5,6)	(2,3,4)
C_{11}	(5,6,7)	(6,7,8)	(5,6,7)	(4,5,6)	(4,5,6)	(5,6,7)
C_{12}	(7,8,9)	(6,7,8)	(6,7,8)	(8,9,9)	(4,5,6)	(6,7,8)
C_{13}	(8,9,9)	(7,8,9)	(7,8,9)	(7,8,9)	(7,8,9)	(8,9,9)

Table 5
The local fuzzy weights and score values of criteria.

Criteria	Local fuzzy weights	Score	Rank
C_1	(0.04,0.07,0.09)	0.0680	11
C_2	(0.06,0.08,0.1)	0.0781	7
C_3	(0.06,0.08,0.1)	0.0823	3
C_4	(0.06,0.08,0.1)	0.0833	2
C_5	(0.04,0.07,0.09)	0.0644	13
C_6	(0.06,0.08,0.1)	0.0783	6
C_7	(0.04,0.07,0.09)	0.0672	12
C_8	(0.04,0.07,0.09)	0.0688	10
C_9	(0.06,0.08,0.1)	0.0814	4
C_{10}	(0.05,0.07,0.09)	0.0723	9
C_{11}	(0.05,0.07,0.09)	0.0742	8
C_{12}	(0.06,0.08,0.1)	0.0800	5
C_{13}	(0.07,0.08,0.1)	0.0849	1

Where$\xi > 0$,$\sum_{\ell=1}^{e}\omega_\ell = 1$ $(1 \le \ell \le e)$, and$f(x_j) = \left(x_j^{(a)}/\sum_{j=1}^{m}x_j^{(a)}, x_j^{(b)}/\sum_{j=1}^{m}x_j^{(b)}, x_j^{(c)}/\sum_{j=1}^{m}x_j^{(c)}\right)$.

Step 6. The score of criteria $(\mathbb{Q}_{ij})$ with respect to each alternative using the initial matrix and Eq. (15).

$$\pi_{ij} = \left(\frac{\mathbb{Q}_{ij}^{(a)} + 4\mathbb{Q}_{ij}^{(b)} + \mathbb{Q}_{ij}^{(c)}}{6}\right) \tag{15}$$

Step 7. The average solution (π_{ij}) of criteria is found with the help of Eq. (16).

$$\pi_{ij} = \frac{\sum_{j=1}^{m}\mathbb{Q}_{ij}}{n}, \quad i = 1,2,\ldots,n. \tag{16}$$

Step 8. The PDA (positive distance from average value) and NDA (negative distance from average value) of the EDAS method are computed by Eqs. (17)-(20).

$$PDA_{ij} = \frac{\max\left(0, \mathbb{Q}_{ij} - \pi_j\right)}{\pi_j}, \ if \quad Benefit \tag{17}$$

$$NDA_{ij} = \frac{\max\left(0, \pi_j - \mathbb{Q}_{ij}\right)}{\pi_j}, \ if \quad Benefit \tag{18}$$

$$PDA_{ij} = \frac{\max\left(0, \pi_j - \mathbb{Q}_{ij}\right)}{\pi_j}, \ if \quad \mathrm{Cost} \tag{19}$$

$$NDA_{ij} = \frac{\max\left(0, \mathbb{Q}_{ij} - \pi_j\right)}{\pi_j}, \ if \quad Benefit \tag{20}$$

Step 9. The weighted sum (α_i) and (β_i) of PDA and NDA values are obtained by Eqs. (21)- (22) using the weight coefficient of each criterion.

$$\alpha_i = \sum_{j=1}^{m}\rho_j \cdot PDA_{ij}, \quad i = 1,2,\ldots,n. \tag{21}$$

$$\beta_i = \sum_{j=1}^{m}\rho_j \cdot NDA_{ij}, \quad i = 1,2,\ldots,n. \tag{22}$$

where ρ_j represents the weights of the criteria.

Step 10. The α_i and β_i of PDA and NDA are normalized with the help of Eqs. (23)- (24).

$$\delta_i = \frac{\alpha_i}{\max(\alpha_i)}, \quad i = 1,2,\ldots,n. \tag{23}$$

$$\lambda_i = 1 - \frac{\beta_i}{\max(\beta_i)}, \quad i = 1,2,\ldots,n. \tag{24}$$

where δ_i and λ_i denotes the normalized values of α_i andβ_i.

Step 11. The final ranking (compromise score) of alternatives is obtained by Eq. (25).

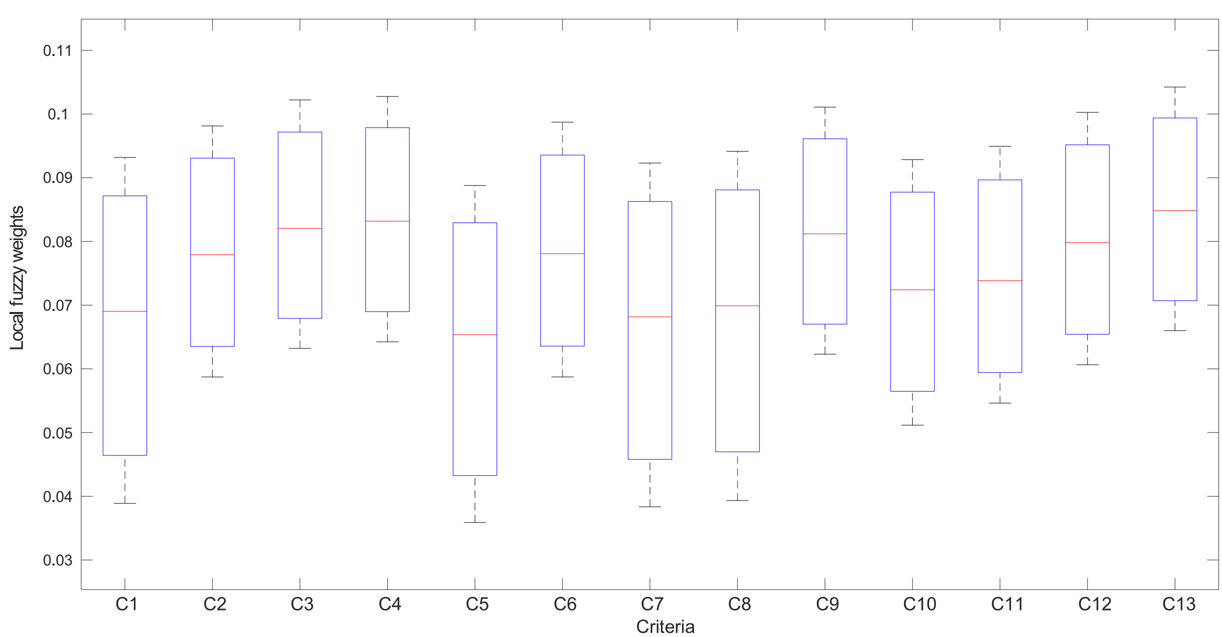

Fig. 2. Local fuzzy weights of criteria.

Table 6
The linguistic assessments of three alternatives in terms of each criterion.

Expert 1	A_1	A_2	A_3	Expert 2	A_1	A_2	A_3	Expert 3	A_1	A_2	A_3
C_1	L	AH	H	C_1	H	VH	E	C_1	MH	VH	L
C_2	ML	AH	MH	C_2	H	VH	H	C_2	VH	VH	AL
C_3	E	AH	MH	C_3	VH	AH	MH	C_3	E	H	MH
C_4	H	L	H	C_4	E	L	ML	C_4	E	H	E
C_5	H	L	MH	C_5	E	VL	L	C_5	VH	VH	H
C_6	VH	VL	ML	C_6	E	VL	ML	C_6	L	E	AH
C_7	E	AL	L	C_7	ML	L	ML	C_7	AH	E	MH
C_8	VH	ML	ML	C_8	VL	ML	VL	C_8	VH	MH	AH
C_9	L	VH	H	C_9	E	AH	MH	C_9	VH	VH	H
C_{10}	L	H	MH	C_{10}	E	VH	H	C_{10}	H	ML	E
C_{11}	AH	VL	MH	C_{11}	ML	VL	L	C_{11}	MH	AH	H
C_{12}	L	H	MH	C_{12}	MH	H	E	C_{12}	VH	VH	E
C_{13}	L	H	H	C_{13}	H	VH	MH	C_{13}	H	AH	E
Expert 4	A_1	A_2	A_3	Expert 5	A_1	A_2	A_3	Expert 6	A_1	A_2	A_3
C_1	E	AH	AL	C_1	VL	VH	VH	C_1	L	AH	MH
C_2	VH	AH	L	C_2	L	AH	E	C_2	VL	AH	H
C_3	E	VH	H	C_3	VL	AH	E	C_3	L	AH	E
C_4	E	MH	ML	C_4	VL	VH	ML	C_4	H	VL	E
C_5	H	H	AH	C_5	E	VH	MH	C_5	MH	L	MH
C_6	VL	E	VH	C_6	E	E	MH	C_6	MH	ML	E
C_7	AH	E	E	C_7	AH	VL	ML	C_7	H	AL	ML
C_8	AH	H	VH	C_8	L	VL	VL	C_8	VH	L	ML
C_9	VH	AH	H	C_9	VL	VH	E	C_9	E	VH	MH
C_{10}	MH	E	ML	C_{10}	AL	AH	AH	C_{10}	VL	H	H
C_{11}	H	VH	VH	C_{11}	VH	E	E	C_{11}	VH	VL	E
C_{12}	H	AH	E	C_{11}	VL	VH	MH	C_{11}	VL	VH	MH
C_{13}	MH	AH	E	C_{12}	E	AH	AH	C_{12}	L	H	H

Table 7
The initial decision matrix for the alternatives.

Alternatives	C_1	C_2	C_3	C_4	C_5
A_1	(2.29,3.58,4.73)	(2.63,4.06,5.31)	(2.51,3.85,5.02)	(2.88,4.33,5.54)	(5.1,6.14,7.17)
A_2	(7.47,8.47,9)	(7.64,8.64,9)	(7.41,8.42,8.82)	(2.39,3.75,4.95)	(2.45,3.85,5.08)
A_3	(2.66,3.05,3.34)	(2.63,3.02,3.32)	(4.74,5.75,6.77)	(3.6,4.64,5.67)	(4.31,5.52,6.56)
Alternatives	C_6	C_7	C_8	C_9	C_{10}
A_1	(2.56,3.93,5.13)	(5.33,6.48,7.27)	(2.92,4.55,5.84)	(2.63,4.04,5.27)	(1.93,2.56,2.97)
A_2	(1.95,3.24,4.39)	(1.5,1.86,2.06)	(2.37,3.65,4.8)	(7.3,8.31,9)	(5.07,6.17,7.15)
A_3	(4.33,5.44,6.44)	(3.08,4.14,5.17)	(2.04,3.46,4.66)	(5.22,6.24,7.25)	(4.83,5.92,6.89)
Alternatives	C_{11}	C_{12}	C_{13}		
A_1	(5.4,6.52,7.49)	(1.99,3.39,4.63)	(3.36,4.55,5.66)		
A_2	(1.71,3.1,4.32)	(6.77,7.77,8.64)	(7.05,8.06,8.64)		
A_3	(3.97,5.14,6.24)	(4.44,5.45,6.46)	(5.18,6.23,7.17)		

Table 8
The score values for the three alternatives regarding each criterion.

Alternatives	C_1	C_2	C_3	C_4	C_5
A_1	3.557	4.032	3.822	4.290	6.137
A_2	8.392	8.533	8.320	3.722	3.820
A_3	3.032	3.005	5.753	4.639	5.491
Alternatives	C_6	C_7	C_8	C_9	C_{10}
A_1	3.904	6.420	4.492	4.012	2.524
A_2	3.218	1.830	3.629	8.256	6.152
A_3	5.423	4.134	3.421	6.237	5.901
Alternatives	C_{11}	C_{12}	C_{13}		
A_1	6.493	3.367	4.537		
A_2	3.070	7.750	7.991		
A_3	5.127	5.454	6.209		

$$\mathfrak{I}_i = \frac{1}{2}(\delta_i + \lambda_i) \tag{25}$$

5. Case study

Due to the world's adverse conditions over the past decade, such as a pandemic, climate change-related disasters, and diplomatic conflicts, freight fluidity is susceptible to interruptions. A fluidity measuring system is critical for increasing the robustness of freight transportation systems. Fluidity measurement implementations can disclose the causes of the disturbance and viable solutions. Optimization of freight operations has several implications, ranging from environmental sustainability due to reduced fuel usage to time travel reliability due to faster and more predictable travel times. The case study is about a freight transportation system that is severely impacted and disrupted by unfavorable weather conditions caused by climate change. Freight transportation decision-makers strive to solve this problem to improve travel

Table 9
The average solution for the thirteen criteria.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}
π_{ij}	4.994	5.190	5.965	4.217	5.149	4.182	4.128	3.847	6.168	4.859	4.897	5.524	6.246

Table 10
The PDA and NDA values.

PDA	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}
A_1	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A_2	0.68	0.64	0.39	0.12	0.26	0.23	0.56	0.06	0.34	0.27	0.37	0.40	0.28
A_3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.11	0.01	0.21	0.00	0.00	0.00
NDA	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}
A_1	0.29	0.22	0.36	0.02	0.19	0.00	0.56	0.17	0.35	0.48	0.33	0.39	0.27
A_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A_3	0.39	0.42	0.04	0.10	0.07	0.30	0.00	0.00	0.00	0.00	0.05	0.01	0.01

time reliability and resilience against disturbances. As a result, they require freight fluidity measurement alternatives to follow the system more precisely and identify potential areas for optimization. Several alternative measurement approaches are presented to successfully execute a freight fluidity measurement. Using the proposed MCDM technique, three alternatives are ranked based on 13 criteria organized into four aspects. The experts' opinions from academia and business are collected.

5.1. The proposed methodology results

A questionnaire is used to acquire the opinions of specialists from academic institutions and private industry, including government officials working in transportation and logistics departments and executives from technological businesses.

Stage 1. In this stage, the framework of the decision-making problem is defined.

Step 1. The three alternatives, thirteen decision criteria, and six experts are defined in this study. Additionally, the linguistic terms and their corresponding values are defined and determined.

Step 2. The linguistic scales are given in Table 1 to handle the experts' opinions.

Stage 2. In the second stage, the steps of fuzzy Dombi based LMAW are presented to calculate the weights of the criteria.

Steps 3.1–3.3. The criteria are grouped into four main criteria as provided in Table 2. These criteria are assessed by six experts. The linguistic assessments of the criteria are presented in Table 3.

Afterward, the linguistic evaluations of experts are converted to the triangular fuzzy numbers as given in Table 1 and provided in Table 4. Then, the absolute anti-ideal point is found using Eq. (9). The relationship between the fuzzy priority vector elements is calculated by Eq. (10). Next, the vectors of weight coefficients are computed using Eq. (11).

Steps 3.4–3.5. In these steps, the local fuzzy weights of the criteria are obtained using the relation vector and Eq. (12). Later, these fuzzy weights are defuzzified with the help of Eq. (13). The weights of the criteria are provided in Table 5. The local fuzzy weights of the criteria are shown in Fig. 2.

Stage 3. In this stage, the application of Dombi based EDAS method for ranking the alternatives is presented.

Step 4. A set of six experts is formed to assess the three alternatives against the selected thirteen decision criteria using linguistic ratings, as given in Table 1. The ratings obtained are reported in Table 6. Next, the linguistic evaluations of experts are converted to the corresponding fuzzy numbers in Table 1.

Step 5. To construct the initial decision matrix, the expert opinions are aggregated using Table 6 and Eq. (14). The aggregated decision matrix is presented in Table 7.

Step 6. The overall values $(\mathbb{Q}_{ij})$ of each alternative concerning thirteen criteria are obtained using Table 7 through Eq. (15) and presented in Table 8.

Step 7. The average solution (π_{ij}) of criteria is calculated using Eq. (16) and Table 8. These π_{ij} values are given in Table 9.

Step 8. The PDA and NDA of the EDAS method are calculated by Eqs. (17)-(20) with the help of Tables 8 and 9. The PDA and NDA values of alternatives in terms of criteria are provided in Table 10.

Step 9. The weighted PDA (α_i) and NDA (β_i) values are found by Eqs. (21)-(22) using the weights of criteria as given in Table 5, and reported in Table 11.

Steps 10–11. The α_i and β_i are normalized using Table 11 through Eqs. (23)-(24). Next, the final ranking of alternatives is calculated by Eq. (25). The normalized values and compromise score of each alternative are presented in Table 12.

The alternatives are ranked according to their $\mathfrak{I}_i$ values as follows: $\wp_2 \succ \wp_3 \succ \wp_1$.

5.2. Checking the stability of the results

In this section, the analysis of the parameters based on the subjective evaluations of the decision maker in the decision-making problem was made. In the first scenario, 100 experiments were carried out for ξ in

Table 11
The weighted PDA and NDA values.

α_i	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}
A_1	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A_2	0.05	0.05	0.03	0.01	0.02	0.02	0.04	0.00	0.03	0.02	0.03	0.03	0.02
A_3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.02	0.00	0.00	0.00
β_i	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9	C_{10}	C_{11}	C_{12}	C_{13}
A_1	0.02	0.02	0.03	0.00	0.01	0.00	0.04	0.01	0.03	0.03	0.02	0.03	0.02
A_2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A_3	0.03	0.03	0.00	0.01	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00

Table 12
The ranking results of the proposed methodology.

Alternatives	α_i	β_i	δ_i	λ_i	$\Im_i$	Rank
A_1	0.005	0.271	0.015	0.000	0.008	3
A_2	0.345	0.000	1.000	1.000	1.000	1
A_3	0.024	0.103	0.070	0.618	0.344	2

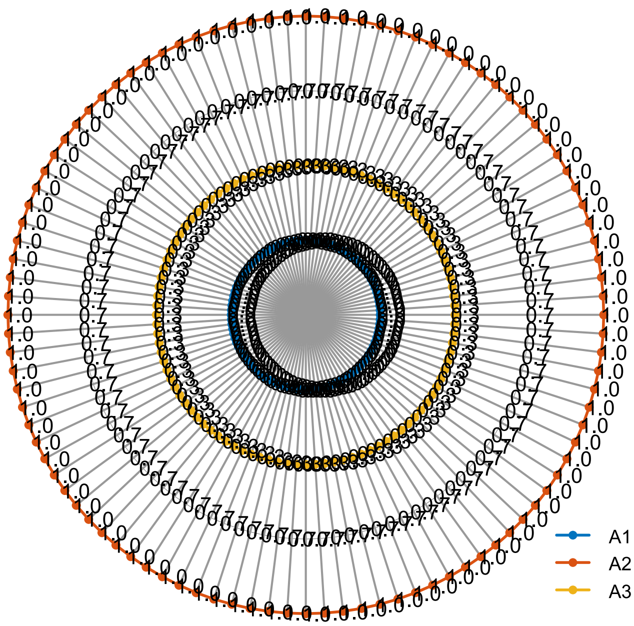

Fig. 3. Influence of ξ on change of alternatives.

fuzzy Dombi parameter to calculate the criteria weights. Fig. 3 illustrates the changes in the value of ξ that is from the interval $1 \leq \xi \leq 100$. It can be seen that there was no change in the order of alternatives.

In the second scenario, the impact of expert weights on the alternative was investigated. Therefore, we analyzed the influence of changing the parameter ω in the interval $[1, 100]$. Fig. 4 indicates that the ranking of alternatives $(\wp_2 \succ \wp_3 \succ \wp_1)$ is stable.

In the third scenario, 100 experiments were carried for ξ in the fuzzy Dombi parameter to calculate the values of lower, medium, and upper of alternatives in the initial matrix $\mathbb{Q}_j^{\xi} = \left(\mathbb{Q}_i^{\xi(a)}, \mathbb{Q}_i^{\xi(b)}, \mathbb{Q}_i^{\xi(c)}\right)$. Fig. 5 shows the changes in the value of ξ from interval $1 \leq \xi \leq 100$, and there was no change in the ranking of alternatives.

6. Results and discussion

This study provides three potential alternatives for freight fluidity measurement. These alternatives are evaluated in terms of technology, governance, efficiency, and environmental sustainability aspects. Experts are consulted to help efficiently and effectively prioritize the alternatives. Experts have determined that the metaverse application is the most advantageous of the three alternatives. The primary rationale for this choice is the simplicity with which correct data may be collected in Metaverse. Because fluidity measures are typically performed using freight transportation data, gathering large amounts of reliable data using blockchain technology is very promising as a means of optimizing freight transportation and increasing travel time reliability. In addition, by including freight activities in the metaverse for evaluating fluidity, the system's resilience to disruptions such as diplomatic disputes, pandemics, and climate change can be increased by employing AI and ML models in the metaverse environment using the acquired data.

The second most advantageous alternative is to form global governance of freight activities for measuring fluidity using available data. With this alternative, freight transportation authorities and decision-makers from around the world share data with a centralized freight fluidity measuring governance unit. This option is helpful in terms of being able to optimize the world's freight transportation system in one location. However, in the event of adversity, such as a diplomatic crisis, countries may cease exchanging data with the central governance body, thereby altering their functioning. Furthermore, this alternative is less helpful than the metaverse alternative because the diversity of the acquired data does not vary, but the volume of data and data location does, which metaverse applications do not.

Doing nothing is selected as the least favorable alternative. The present condition of freight fluidity measurement is maintained in this alternative, and fluidity measures are performed on an individual basis by authorities and companies. This alternative was chosen as the least advantageous since the existing state of fluidity measurement systems is

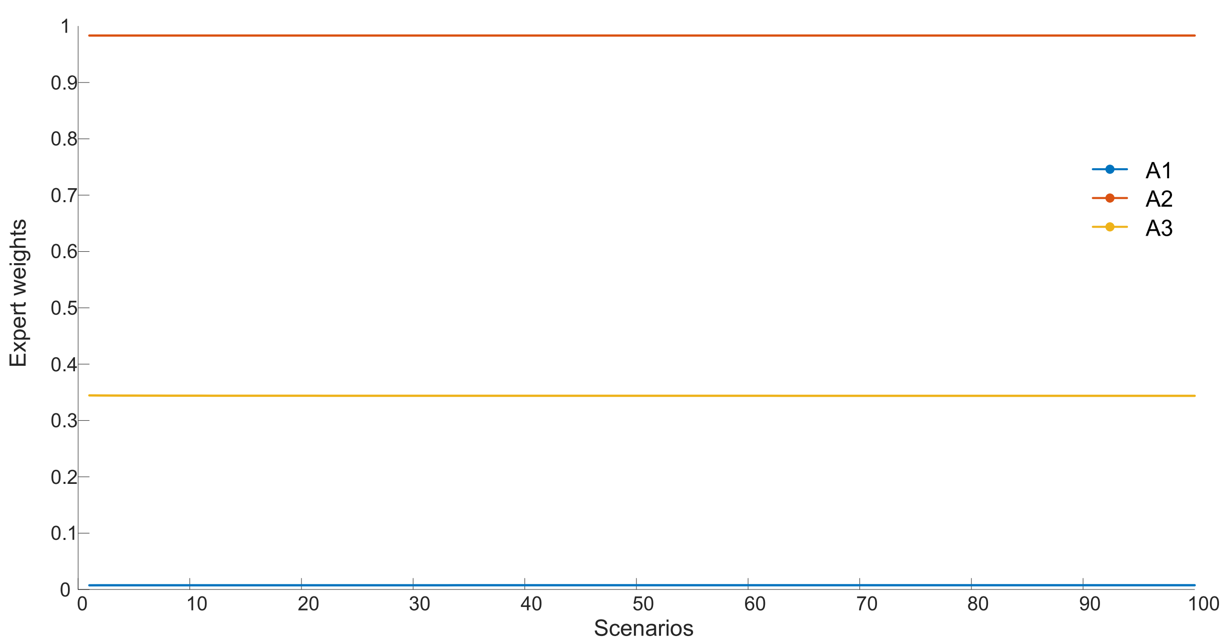

Fig. 4. Influence of ω on change of alternatives.

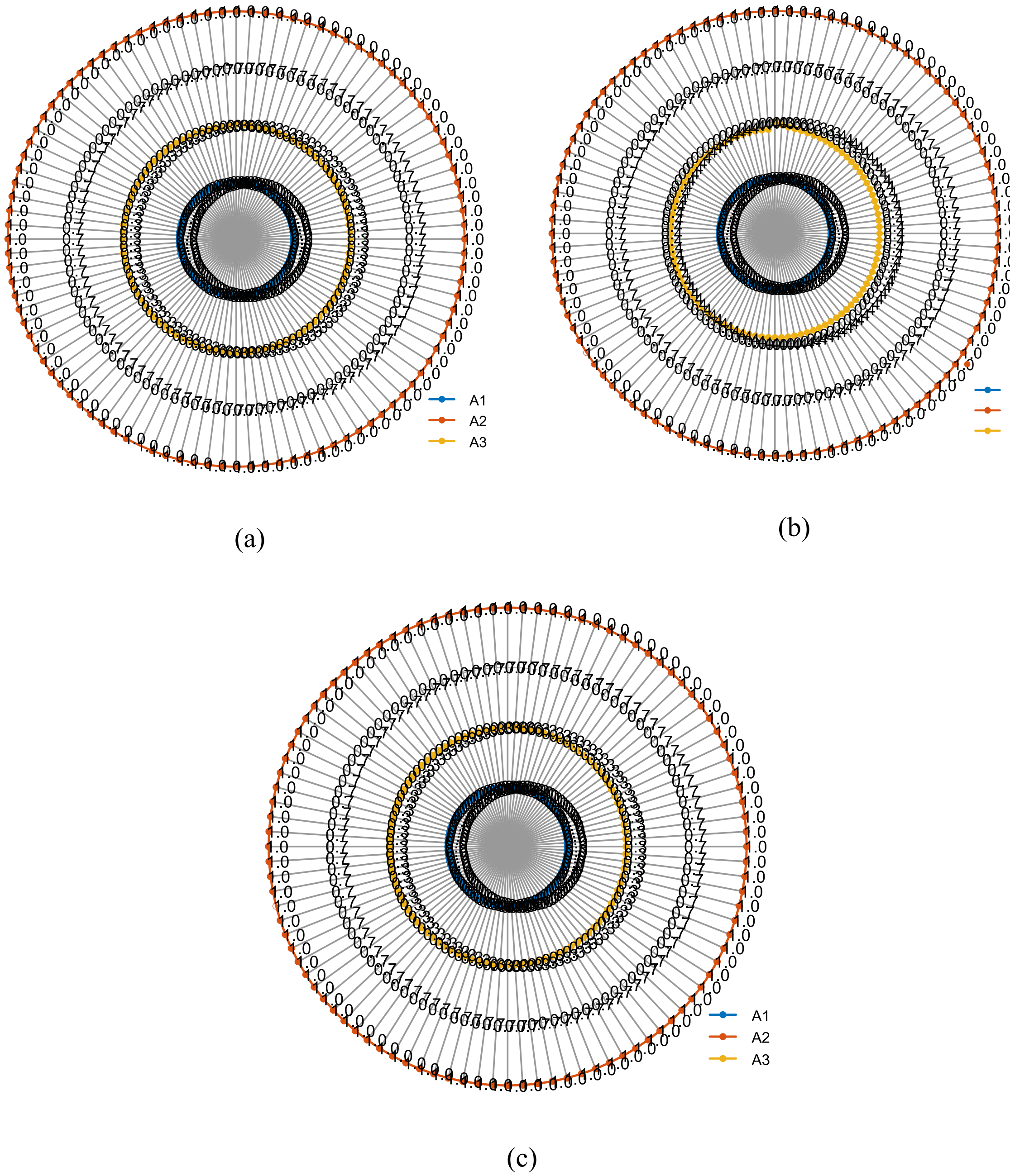

Fig. 5. Influence of ξ on change of the values of lower (a), medium (b), and upper (c) of alternatives in the initial matrix.

believed to be ineffective under severe conditions like pandemics. Therefore, the current measurement systems do not provide sufficient resilience for freight transportation networks.

7. Managerial and policy implications

Freight fluidity measurements are primarily based on data collection. Using the acquired data, decision-makers can determine which portions of the freight transportation system require optimization, thereby increasing the entire system's fluidity. The most advantageous solution is to integrate freight activity into Metaverse for assessing fluidity. Using blockchain technology, this alternative allows for easier and more reliable data collection. When accurate big data is available, decision-makers can develop policies to improve travel time reliability and sustainability through routing decisions, mode selection, multimodal transportation, and so on.

On the other hand, resilience to disruptions induced by events such as a pandemic or climate change is a key part of freight fluidity. For example, in recent history, the globe has encountered a pandemic, which has almost completely interrupted the freight transportation infrastructure (Fu et al., 2022). The Metaverse alternative can reduce the impact of such events on freight flow. Because data gathering in the Metaverse is easier and more precise, authorities will have a large amount of data to employ in artificial intelligence (AI) and machine learning (ML) models to foresee and solve disruptive conditions. As a result, system authorities and decision-makers can develop new policies on how to effectively and efficiently use the acquired data to overcome such interruptions and strengthen the system's resilience.

One problem with Metaverse is that information about users is also stored in blockchain technology. Cybersecurity of the system is very important because user information is stored in the system and data theft is a big risk (Mystakidis, 2022). Hence, Metaverse application administrators should develop policies to improve cybersecurity and safeguard the system from malicious attacks.

8. Conclusion

According to the study's findings, integrating freight activities into Metaverse for measuring freight fluidity is the most advantageous alternative, while doing nothing and leaving the system as it is is the least advantageous. This study contributes to the literature by introducing new technologically advanced ways of freight fluidity measurement alternatives and by employing a novel MCDM model to advantage prioritization. The results can also serve as a guide for authorities and decision-makers seeking to improve freight fluidity.

The limitation of the study is the computational complexity of the Dombi operator. A software tool can be developed for this in future studies. In future studies, various operators such as the fuzzy Aczel-Alsina function, Einstein function, and fuzzy Hamacher for aggregation can be integrated to handle the uncertainty in the information. Also, various decision-making models such as the Ordinal Priority Approach can be used to calculate criterion weights in the proposed model. Another limitation of the study is that the metaverse is a relatively new technology with few uses, such as those proposed in the alternative. As a result, the developed metaverse fluidity measurement system's problem-free continuity may not be possible in the short run. Furthermore, there is a lack of solid data privacy policies governing data acquired and used in the metaverse. Because the metaverse's main value is the simplicity of data collecting, a lack of a policy in this area may cause problems in the short term. In addition, the number of experts in this field is another limitation.

In future investigations, the choices and criteria of the study might be varied and extended in quantity to increase the study's adaptability. In addition, a pilot region can be chosen and the alternative implemented in the area to assess the real-life applicability and real-life advantages of the most favorable alternative, which is integrating freight activities into Metaverse for measuring fluidity. The results of the pilot project may provide a greater understanding of the alternative's potential if it is implemented on a bigger scale.

CRediT authorship contribution statement

Muhammet Deveci: Methodology, Software, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Ilgin Gokasar:** Conceptualization, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Oscar Castillo:** Validation, Writing – original draft, Writing – review & editing. **Tugrul Daim:** Validation, Writing – original draft, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

References

Aloui, A., Hamani, N., & Delahoche, L. (2021). An integrated optimization approach using a collaborative strategy for sustainable cities freight transportation: A Case study. *Sustainable Cities and Society, 75*, Article 103331. https://doi.org/10.1016/j.scs.2021.103331

Asborno, M. I., & Hernandez, S. (2021). Assigning a commodity dimension to AIS data: Disaggregated freight flow on an inland waterway network. *Research in Transportation Business & Management, 100683*. https://doi.org/10.1016/j.rtbm.2021.100683

Asborno, M. I., Hernandez, S., & Akter, T. (2020). Multicommodity port throughput from truck GPS and lock performance data fusion. *Maritime Economics & Logistics, 22*(2), 196–217. https://doi.org/10.1057/s41278-020-00154-7

Badi, I., Muhammad, L. J., Abubakar, M., & Bakır, M. (2022). Measuring Sustainability Performance Indicators Using FUCOM-MARCOS Methods. *Operational Research in Engineering Sciences: Theory and Applications, 5*(2), 99–116.

Blyth, M., & Mallett, S. (2020). Epidemics and pandemics: Effects on societal and organizational resilience. *Journal of Business Continuity & Emergency Planning, 14*(1), 17–36. Ανακτήθηκε από https://www.ingentaconnect.com/content/hsp/jbcep/2020/00000014/00000001/art00003.

Bouraima, M. B., Kiptum, C. K., Ndiema, K. M., Qiu, Y., & Tanackov, I. (2022). Prioritization Road Safety Strategies Towards Zero Road Traffic Injury Using Ordinal Priority Approach. *Operational Research in Engineering Sciences: Theory and Applications, 5*(2), 206–221.

Brooks, M. R., Puckett, S. M., Hensher, D. A., & Sammons, A. (2012). Understanding mode choice decisions: A study of Australian freight shippers. *Maritime Economics & Logistics, 14*(3), 274–299. https://doi.org/10.1057/mel.2012.8

Bueno-Solano, A., Lagarda-Leyva, E. A., Miranda-Ackerman, M. A., Velarde-Cantú, J. M., & Pérez, K. G. (2022). Conceptual fluidity model for resilient agroindustry supply chains. *Production & Manufacturing Research, 10*(1), 281–293. https://doi.org/10.1080/21693277.2022.2075947

Burges, R., "Avoiding Supply Chain Management Failure: Lessons from Business Process Re-engineering", The International Journal of Logistics Management, Vol. 9, No. 1, 19984.

Cedillo-Campos, M. G., Lizarraga-Lizarraga, G., & Martner-Peyrelongue, C. D. (2017). MiF3 method: Modeling intermodal fluidity freight flows. *Research in Transportation Economics, 61*, 15–24. https://doi.org/10.1016/j.retrec.2017.01.001

Cedillo-Campos, M. G., Pérez-González, C. M., Piña-Barcena, J., & Moreno-Quintero, E. (2019). Measurement of travel time reliability of road transportation using GPS data: A freight fluidity approach. *Transportation Research Part A: Policy and Practice, 130*, 240–288. https://doi.org/10.1016/j.tra.2019.09.018

Chandra, S., Naik, R. T., & Jimenez, J. (2020). A Framework for Smart Freight Mobility with Crowdsourcing. *Transportation Research Procedia, 48*, 494–502. https://doi.org/10.1016/j.trpro.2020.08.055

Chattopadhyay, R., Das, P. P., & Chakraborty, S. (2022). Development of a rough-MABAC-DoE-based metamodel for supplier selection in an iron and steel industry. *Operational Research in Engineering Sciences: Theory and Applications, 5*(1), 20–40.

Deveci, M., Cali, U., & Pamucar, D. (2021). Evaluation of criteria for site selection of solar photovoltaic (PV) projects using fuzzy logarithmic additive estimation of weight coefficients. *Energy Reports, 7*, 8805–8824.

Dombi J. (2009) The Generalized Dombi Operator Family and the Multiplicative Utility Function. In: Balas V.E., Fodor J., Várkonyi-Kóczy A.R. (eds) Soft Computing Based Modeling in Intelligent Systems. Studies in Computational Intelligence, vol 196. Springer, Berlin, Heidelberg.

Dombi, J. (1982). A general class of fuzzy operators, the DeMorgan class of fuzzy operators and fuzziness measures induced by fuzzy operators. *Fuzzy sets and systems, 8*(2), 149–163.

Eisele, W. L., Juster, R. M., Sadabadi, K. F., Jacobs, T., & Mahapatra, S. (2016). Implementing Freight Fluidity in the State of Maryland. *Transportation Research Record: Journal of the Transportation Research Board, 2548*(1), 62–70. https://doi.org/10.3141/2548-08

European Environment Agency. (2021). Freight Transportation Demand. https://www.eea.europa.eu/data-and-maps/indicators/freight-transport-demand-version-2/assessment.

Fan, K., Wang, S., Ren, Y., Li, H., & Yang, Y. (2018). MedBlock: Efficient and Secure Medical Data Sharing Via Blockchain. *Journal of Medical Systems, 42*(8). https://doi.org/10.1007/s10916-018-0993-7

Fan, Y. V., Klemeš, J. J., Walmsley, T. G., & Perry, S. (2019). Minimizing energy consumption and environmental burden of freight transport using a novel graphical decision-making tool. *Renewable and Sustainable Energy Reviews, 114*, Article 109335. https://doi.org/10.1016/j.rser.2019.109335

Fu, X., Qiang, Y., Liu, X., Jiang, Y., Cui, Z., Zhang, D., & Wang, J. (2022). Will multi-industry supply chains' resilience under the impact of COVID-19 pandemic be different? A perspective from China's highway freight transport. *Transport Policy, 118*, 165–178. https://doi.org/10.1016/j.tranpol.2022.01.016

Gonzalez, J. N., Camarero-Orive, A., González-Cancelas, N., & Guzman, A. F. (2022). Impact of the COVID-19 pandemic on road freight transportation–A Colombian case study. *Research in Transportation Business & Management, 43*, Article 100802. https://doi.org/10.1016/j.rtbm.2022.100802

Govindan, K., Cheng, T., Mishra, N., & Shukla, N. (2018). Big data analytics and application for logistics and supply chain management. *Transportation Research Part E: Logistics and Transportation Review, 114*, 343–349. https://doi.org/10.1016/j.tre.2018.03.011

Haider, N., Baig, M. Z., & Imran, M. (2020). Artificial Intelligence and Machine Learning in 5G Network Security: Opportunities, advantages, and future research trends. *CoRR, abs/2007.04490*. Ανακτήθηκε από https://arxiv.org/abs/2007.04490.

Han, Y., Niyato, D., Leung, C., Miao, C., & Kim, D. I. (2022). A Dynamic Resource Allocation Framework for Synchronizing Metaverse with IoT Service and Data. *ICC 2022 - IEEE International Conference on Communications*. 10.1109/icc45855.2022.9838422.

Keshavarz Ghorabaee, M., Zavadskas, E. K., Olfat, L., & Turskis, Z. (2015). Multi-criteria inventory classification using a new method of evaluation based on distance from average solution (EDAS). *Informatica, 26*(3), 435–451.

Kruse, C. J., Mitchell, K. N., DiJoseph, P. K., Kang, D. H., Schrank, D. L., & Eisele, W. L. (2018). Developing and Implementing a Port Fluidity Performance Measurement Methodology using Automatic Identification System Data. *Transportation Research Record: Journal of the Transportation Research Board, 2672*(11), 30–40. https://doi.org/10.1177/0361198118796353

Krysiak, F. C. (2009). Risk Management as a Tool for Sustainability. *Journal of Business Ethics, 85*(S3), 483–492. https://doi.org/10.1007/s10551-009-0217-7

Lamming, R. C., Caldwell, N. D., Harrison, D. A., & Phillips, W. (2001). Transparency in Supply Relationships: Concept and Practice. *Journal of Supply Chain Management, 37*(3), 4–10. https://doi.org/10.1111/j.1745-493x.2001.tb00107.x

McKinnon, A., Edwards, J., Piecyk, M., & Palmer, A. (2009). Traffic congestion, reliability and logistical performance: A multi-sectoral assessment. *International Journal of Logistics Research and Applications, 12*(5), 331–345. https://doi.org/10.1080/13675560903181519

Michie, J. (2020). The covid-19 crisis – and the future of the economy and economics. *International Review of Applied Economics, 34*(3), 301–303. https://doi.org/10.1080/02692171.2020.1756040

Mitchell, K. N., DiJoseph, P. K., Chambers, M., & Kress, M. M. (2019). Inland Marine Transportation System Fluidity (ERDC/CHL TR-19-21). Engineer Research and Development Center. https://apps.dtic.mil/sti/pdfs/AD1085137.pdf.

Mozumder, M. A. I., Sheeraz, M. M., Athar, A., Aich, S., & Kim, H. C. (2022). Overview: Technology Roadmap of the Future Trend of Metaverse based on IoT, Blockchain, AI Technique, and Medical Domain Metaverse Activity. *2022 24th International Conference on Advanced Communication Technology (ICACT)*. 10.23919/icact53585.2022.9728808.

Mystakidis, S. (2022). *Metaverse. Encyclopedia, 2*(1), 486–497. https://doi.org/10.3390/encyclopedia2010031

National Research Council Canada. (2022). Applying artificial intelligence to improve the resilience, fluidity and safety of road freight transport in the Canadian Prairie and Northern Region - National Research Council Canada. Government of Canada. https://nrc.canada.ca/en/research-development/research-collaboration/programs/applying-artificial-intelligence-improve-resilience-fluidity-safety-road-freight-transport-canadian.

Pamucar, D., Žižović, M., Biswas, S., & Božanić, D. (2021). A new logarithm methodology of additive weights (LMAW) for multi-criteria decision-making: Application in logistics. Facta Universitatis, Series: Mechanical Engineering.

Pamucar, D., Deveci, M., Gokasar, I., Tavana, M., & Köppen, M. (2022). A metaverse assessment model for sustainable transportation using ordinal priority approach and Aczel-Alsina norms. *Technological Forecasting and Social Change, 182*, Article 121778. https://doi.org/10.1016/j.techfore.2022.121778

Pisarski, A. E. (2016). Applications of Freight Fluidity. Transportation Research Circular - Advancing Freight Fluidity Performance Measures Workshop, 38–50. https://trid.trb.org/view/1416570.

Rodrigue, J. P. (2008). The Thruport concept and transmodal rail freight distribution in North America. *Journal of Transport Geography, 16*(4), 233–246. https://doi.org/10.1016/j.jtrangeo.2007.08.003

Shamsuzzoha, A. H. M., Ehrs, M., Addo-Tenkorang, R., Nguyen, D., & Helo, P. T. (2013). Performance evaluation of tracking and tracing for logistics operations. *Int. J. Shipping and Transport Logistics, 5*(1), 31–54.

Simatupang, T. M., & Sridharan, R. (2002). The Collaborative Supply Chain. *The International Journal of Logistics Management, 13*(1), 15–30. https://doi.org/10.1108/09574090210806333

Srour, F. J., & Newton, D. (2006). Freight-Specific Data Derived from Intelligent Transportation Systems. *Transportation Research Record: Journal of the Transportation Research Board, 1957*(1), 66–74. https://doi.org/10.1177/0361198106195700110

Swai, S. A., Chimba, D., Jonga, T., & Kosanovic, A. (2021). Traffic operational fluidity Evaluation of Freight Intermodal Connectors. *Transportation Research Board 100th Annual Meeting*, 1–15.

Turnbull, K. F. (2016). Advancing Freight Fluidity Performance Measures: Summary of a Workshop. *Transportation Research Circular*, 1–98.

Zadeh, L. A. (1975). The concept of a linguistic variable and its application to approximate reasoning-III. *Information sciences, 9*(1), 43–80.

Zadeh, L. A. (1965). Fuzzy sets. *Inf. Control, 8*(1965), 338–353.

Zanni, A. M., & Bristow, A. L. (2010). Emissions of CO2 from road freight transport in London: Trends and policies for long run reductions. *Energy Policy, 38*(4), 1774–1786. https://doi.org/10.1016/j.enpol.2009.11.053