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Prioritizing transport planning strategies for freight companies towards zero carbon emission using ordinal priority approach

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A B S T R A C T

Freight transportation counts for remarkable negative effects like emissions, noise, and congestion. This urges for a modal shift toward structuring a more efficient systematic network, facilitating full use of potentials among the transportation modes. Decision-makers face uncertainty and restricted information processing skills when assessing the alternatives for sustainable freight transportation. In this study, a novel extension of the Ordinal Priority Approach under picture fuzzy sets (OPA-P) is proposed to rank the alternatives. In the OPA-P algorithm, experts' preferences are used to determine the weighting coefficients of criteria and rank the alternatives. A case study is employed to demonstrate the formulation and solution of the problem. The outcome of this study suggests the top-ranked and most important solution for the sustainable transport planning. In addition, to verify the stability of the proposed model, a validation analysis is carried out.

1. Introduction

Freight transportation contributes to a country's gross national product and grows nearly all economic sectors (Crainic and Laporte, 1997). This system strikes at the core of maintaining industrial operations and economic progress (Jansuwan et al., 2021) Freight transport operations have been planned to lower costs (Forkenbrock, 2001). With global concern for the environment expanding, supply chain managers and freight forwarders have gradually taken greater attention to the critical aspects of the activities (Demir et al., 2011). These involve - pollutants, crashes, congestion, resource usage, degradation of land usage, and the danger of global warming (Schreyer et al., 2008).

European Union governments have stated that the existing traffic patterns are unsustainable to the environment, corporate productivity, safety, and increasing road congestion. Highways account for passengers (79%) and freight transportation (44%) (Ülengin et al., 2007). The expansion of road freight transportation is indeed the main factor in environmental issues (Böge, 1995). The freight component of overall transport greenhouse gas emissions is expected to rise from 42% in 2010 to 60% by 2050 (ITF, 2015).

Some EU countries have created systems for projecting future freight transportation capacities and vehicle movements (De Jong et al., 2004). Unimodal transportation is one of these models. A unimodal road transport operation includes three components which are a collection tour, transportation from one place to another, and a distribution trip. There is no need for transshipment (Janic, 2007). It is a standard procedure to use transportation designs to analyze options (Friedrich et al., 2003). SPIN (Scanning the Potential for Intermodal Transport) is a multimodal system implementation for European freight transport. The SPIN system serves as the foundation for computing the best route, depending on time and budget constraints. In this way, authorities can find the most appropriate method based on time and cost. Then, those are used to evaluate the quality of the various modes (Bottani and Rizzi, 2007).

A freight transportation system comprises links, also terminal nodes with a specific capacity, and transmission delay time features (Friedrich et al., 2003). Logistic hub advancements are one of those that meet the needs of freight transportation (Huber et al., 2015). Some cities might

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consider themselves a desirable place for logistics operations. For instance, in Kaunas, promoting the city as a logistics center is a strategic target (Lindholm and Behrends, 2012).

The overuse of road networks in freight transportation has resulted in traffic jams and detrimental environmental repercussions (Yamada et al., 2009). An efficient network organization of multimodal transportation systems can reduce disadvantages while also establishing sustainability (Hesse, 2002). Multimodality is defined as the use of at least two distinct forms of transport (UNECE, 2010). Intermodal transport is one such expansion, with network connectivity and regulated cargo containers serving as the primary quality requirement (Steadie-Seifi et al., 2014). Integrated and co-modal transportation are two new concepts that have evolved (UNECE, 2001; European Commission, 2006). These phrases are nearly interchangeable, with the key distinction being that integrated transportation focuses on using the highway as little as possible at the beginning or final leg, whereas co-modal focuses on the effective utilization of resources (Ambra et al., 2018).

Synchromodal strategy is a type of multimodal planning where the optimum feasible arrangement of transportation modes for each transport demand is chosen (Mes and Iacob, 2016). Synchromodal transport strives to integrate and cooperate across transportation and modalities to give service operators with additional options for offering better transportation choices by employing various services from different modes (Zhang and Pel, 2016). The ability to re-route goods to alternate ways of travel at hubs depending on concrete data about the delivery in transit is characterized by synchronmodal transport systems (Yee et al., 2021). Synchromodal transport has sparked a lot of attention since it can profit from the benefits of intermodal transport without losing the rate (Zhang and Pel, 2016).

Considering the worldwide transition to a zero-carbon emission model, many countries have constituted and/or agreed on new policies regarding the decarbonization of freight transportation (Eidhammer and Andersen, 2010). Therefore, a need for a method, which effectively evaluates and prioritizes sustainable freight transportation alternatives according to their advantages based on various criteria, has risen. The utilization of such studies proposing these methods is important in the subject of transportation planning strategies toward zero carbon emission. Thus, this study introduces a contribution that freight transportation companies can benefit from while going through a transition to a more sustainable model.

1.1. The objective of the study

Road-based transportation for urban freight movement has led to a lot of urban traffic challenges, including heavy traffic congestion, increased energy use, and significant environmental consequences (Oguztimur and Canci, 2011). The freight transportation industry must adjust to quickly changing governmental, cultural, and economic situations and developments (Crainic and Laporte, 1997). Due to the obvious necessity to represent the change of operations over time, new models emerge in a wide range of transportation applications (Bektaş et al., 2019). It is a field that needs effective techniques and tools to aid in the planning and decision-making processes (Crainic and Laporte, 1997). There are several approaches to freight transportation planning (Gómez-Marín et al., 2020; He and Haasis, 2020). The objective of the study is to prioritize these strategies to assist policymakers during the planning process.

The study's goal is to introduce a novel fuzzy multi-criteria decision making (MCDM) model to focus on choosing the best transport planning strategies for freight companies toward zero-carbon emission and thus it provides a tangible basis for policymaking.

1.2. The methodology of the study

In this study, the Ordinal Priority Approach (OPA) methodology (Ataei et al., 2020) is applied, which fits the group of subjective models for determining the weighting coefficients of the criteria/alternatives. The algorithm of the conventional OPA method is based on the determination of weight coefficients based on predefined ranks of alternatives under a defined set of criteria. Although it is a more recent methodology, the OPA method has in a short time stood out as a promising tool for the objective and rational definition of priority criteria and alternatives in decision-making models. We can point out the following advantages of the OPA methodology: (1) Most subjective models for determining criterion/alternative weighting coefficients, such as FUCOM (Pamucar et al., 2018), BWM (Rezaei, 2015), or LBWA (Zizovic and Pamucar, 2019), are based on comparisons in pairs of home matrix elements. This increases the number of comparisons in a case of more than eight criteria/alternatives, which impairs the quality of the solution. On the other hand, the OPA method is based on defining weighting criteria/alternatives based on predefined ranks, thus eliminating the problem of a limited range of predefined scales for comparing the criteria used in AHP methods and BWM models (Alosta et al., 2021; Durmic et al., 2020; Dwivedi et al., 2021; Jokic et al., 2021); and (2) OPA mathematical model can be used to define expert weights, attributes, and alternatives simultaneously.

In the past few years, the authors have confirmed the effectiveness and efficiency of the OPA method through several studies dealing with project selection (Mahmoudi, Deng, et al., 2021), performance evaluation of construction sub-contractors (Mahmoudi and Javed, 2021), and adopting of distributed ledger technology for the sustainable construction industry (Sadeghi et al., 2021). However, the increasingly dynamic environmental conditions and the need to process incomplete and uncertain information place new demands on mathematical models for multi-criteria optimization. Mahmoudi, Javed, et al. (2021) extended the OPA algorithm in a fuzzy environment to respond to these challenges. Apart from the fuzzy extension, no literature papers deal with the possibilities of applying the OPA algorithm by using other uncertainty theories.

In addition to the numerous advantages of conventional fuzzy theory (Zadeh, 1965), there are certain limitations that researchers have tried to overcome by applying intuitionistic fuzzy sets (IFS) (Atanassov, 1999). The IFS concept originated as a generalization of classic fuzzy sets (Zadeh, 1965) to incorporate the degree of non-membership (Karamaşa et al., 2021). However, IFSs do not adequately address the degree of neutrality, especially in situations where decision attributes are presented as yes, no, restraint, and rejection in group decision-making. Picture fuzzy sets (PFS) (Cuong & Kreinovich, 2013; Cuong, 2014) extend intuitionistic fuzzy sets. Accordingly, the PFS considers the degree of refusal and provides a more accurate and granular analysis with subjective and inaccurate information in conditions of uncertainty. This paper presents a novel extension of the OPA algorithm using PFS (OPA-P). In the OPA-P algorithm, expert preferences were used to define the weighting coefficients of criteria and alternatives. However, not all alternatives and/or criteria of interest to experts or, in some cases, opinions may be neutral in nature. Therefore, the application of PFS is a logical step for modeling uncertainty in expert estimates in the OPA-P algorithm.

The picture fuzzy OPA methodology presented in this study provides several advantages that also represent the contribution of this study:

(1) Picture fuzzy OPA is a novel methodology that allows objective and adequate addressing of expert neutralities and ambiguities.
(2) OPA-P is based on prioritizing alternatives and criteria in a picture fuzzy environment, which greatly facilitates the presentation of expert preferences. This eliminates the limited range of predefined scales for comparing criteria and alternatives, which exists in some multi-criteria techniques. As is well known, most subjective models for determining the weighting coefficients of criteria/alternatives are based on comparisons in pairs of home matrix elements. This increases the number of comparisons in the case of an increase in the number of criteria/alternatives, which

reduces the consistency of the comparison and impairs the quality of the resulting solution.

(3) The proposed mathematical model can be used for simultaneous prioritization and definition of expert weighting coefficients, attributes, and alternatives.

(4) The OPA-P method implements a picture fuzzy mathematical model for aggregating expert preferences, so it does not require additional models for averaging results.

(5) Picture fuzzy OPA method can be used in group and individual decision-making.

(6) Picture fuzzy OPA algorithm has flexibility and allows uncertain and imprecision information processing. The algorithm defines alternative priorities if the expert cannot rank individual alternatives under a specific attribute due to a lack of information. The application of the proposed methodology enables flexible decision-making and the consideration of mutual connections between information in the decision-making model.

Conclusively, many authorities from various sectors, such as freight transportation, are considering making their operations more environmentally friendly and achieving zero-carbon emissions. This goal is sustained with numerous policies and agreements, which incentivize the authorities to implement the decarbonization methods in a faster manner. This study aims to propose a model, which uses the OPA algorithm, for freight transportation companies to use in the process of making their freight transportation systems more sustainable. Also, going through the literature, the absence of a study, which evaluates the alternatives of this study and proposes a multi-criteria decision-making (MCDM) model, is observed. Thus, the utilization of the model put forward in this study is unique in means of providing a guide for the authorities of the freight transportation sector. Additionally, the proposed model is adjustable to different aspects of implementation since the criteria used in this study are revisable, which makes the proposed algorithm applicable in every region.

The rest of this paper is organized as follows: Section 2 presents a literature review. Section 3 describes the problem definition, alternatives, and criteria. The concepts of the developed model are introduced in Sections 4-6. The results are presented in Section 7. Policy implications and conclusions are provided in Section 8 and Section 9.

2. Literature review

The operations that define the term logistics are responsible for shipment, planning, and controlling processing and distribution activities from the cargo owner to a recipient across the whole distribution chain (Solvay et al., 2018). Interconnections between service and infrastructure are challenging, as is the absence of a verified forecasting model and high calculation durations in practical uses. Sustaining with shifting requirements is critical for the freight transportation business (Zhang et al., 2013).

Freight transportation is critical to industrial operations diğerlerine bakıyorum şimdi and economic advancement (Jansuwan et al., 2021). Freight transportation is an essential activity that takes place both between cities and inside cities (Yamada et al., 2009). Road-based freight transport has expanded dramatically, and as a result, the usage and misuse of road systems have resulted in a variety of downsides (Yamada et al., 2009). As worldwide protection of the environmental concern has grown, logistics managers and delivery companies have emphasized the crucial parts of their operations (Demir et al., 2011).

Expansion of road freight transportation is one of the main factors in environmental considerations. The rising freight transport volume, the transportation system's infrastructure overload, and its consequences on population and global warming are the main elements indicating that achieving a more sustainable and effective transport network is a priority (Solvay et al., 2018). The freight portion of general transportation pollutants is predicted to climb from 42% in 2010 to 60% in 2050, rendering freight transportation one of the most difficult sectors in reducing carbon emissions (Sachs et al., 2014).

EU member states have developed methods for forecasting future freight transportation capacity and vehicle movements (De Jong et al., 2004). One of these models is multimodal transportation. In unimodality, there is no requirement for transshipment (Janic, 2007). One of these models is unimodal transportation. A system's resilience is defined as its capacity to devote resources to respond to disruption and, as a result, reduce the volume and breadth of negative consequences (Jansuwan et al., 2021). In a unimodal transportation system, trucks are the single means of transportation available. Without the requirement for a transit stop, the whole travel from town to town is handled by a single-vehicle. Unimodal road transport entails gathering items at the starting point, transporting goods from the starting point to the designated destination, and distributing products at the chosen destination (Zgonc et al., 2019). Unimodal truck transport is ideal for short transit distances since there are no extra shipping charges or wait periods, leading to less operational effort than multimodal transport (Kogler and Rauch, 2018).

Freight transportation is incredibly challenging because of the enormous number of interactions that must be supported among the participants and the high command structure that must be maintained. The efficient operation of the freight transportation industry is critical to a region's economic success. The setup of a transportation network, along with the sequencing of interconnection, the potential offered, the supply chain and intermodal services, and the potential of collaboration and integration between participants in the supply chain, marks an essential explanatory variable of geographic performance that defines the procedure of lowering costs (Gattuso et al., 2020).

Logistics-related developments have taken into account the expanding importance of freight transportation services, influencing transportation operations in freight transport modeling. Logistic hubs are one of those that address freight transportation demands (Huber et al., 2015). On the network side, freight models must incorporate the management of the supply structure of transport networks. To provide a strong base for mode selection and deployment, a model that defines the positioning of hubs is necessary. Even with unimodality, cars are routed through hubs, rather than directly between the origin and the destination (Friedrich et al., 2003). The hub offers a decrease in average cost with the existence of these markets, as well as the potential for adding new links to the framework (Gattuso et al., 2020). A hub system is used to lower the number of paths. Capacity management maximizes the utilization of constrained resources, which is a typical management issue in freight transport systems (Xu et al., 2015).

According to Xu and friends' study (2015), a dynamic integer programming approach for the container capacity allocation issue. The goal is to optimize overall transportation income by distributing container capacity correctly across the planned period. The model proposes a real concern hybrid algorithm with a unique gene encoding mechanism to solve the large-scale dynamic integer programming paradigm. The study shows that the quantity of freight cannot exceed the available capacity and the personnel, vehicle, and railway at the container main station are presumed to be adequate. A hub is a site where goods move and are transferred around the world. The purpose is to save money by using a hub instead of distributing directly (Osorio-Mora et al., 2020). Transshipment can improve security, lower distribution costs, consolidate, and make a variety of modes of transportation available (Xu, et al., 2015).

Excessive usage of roads for freight transportation has led to traffic bottlenecks and negative effects on the environment (Yamada et al., 2009). Given the increased demand for multimodal transportation, it is crucial to know the issues and techniques for overcoming the most significant hurdles associated with multimodal transportation administration. Issues that occur in cross-border locations grow considerably (Kramarz et al., 2021). A well-organized system of multimodal transport networks may eliminate inefficiencies while also ensuring sustainability (Hesse, 2002). Road capacity is limited, and certain road segments are in

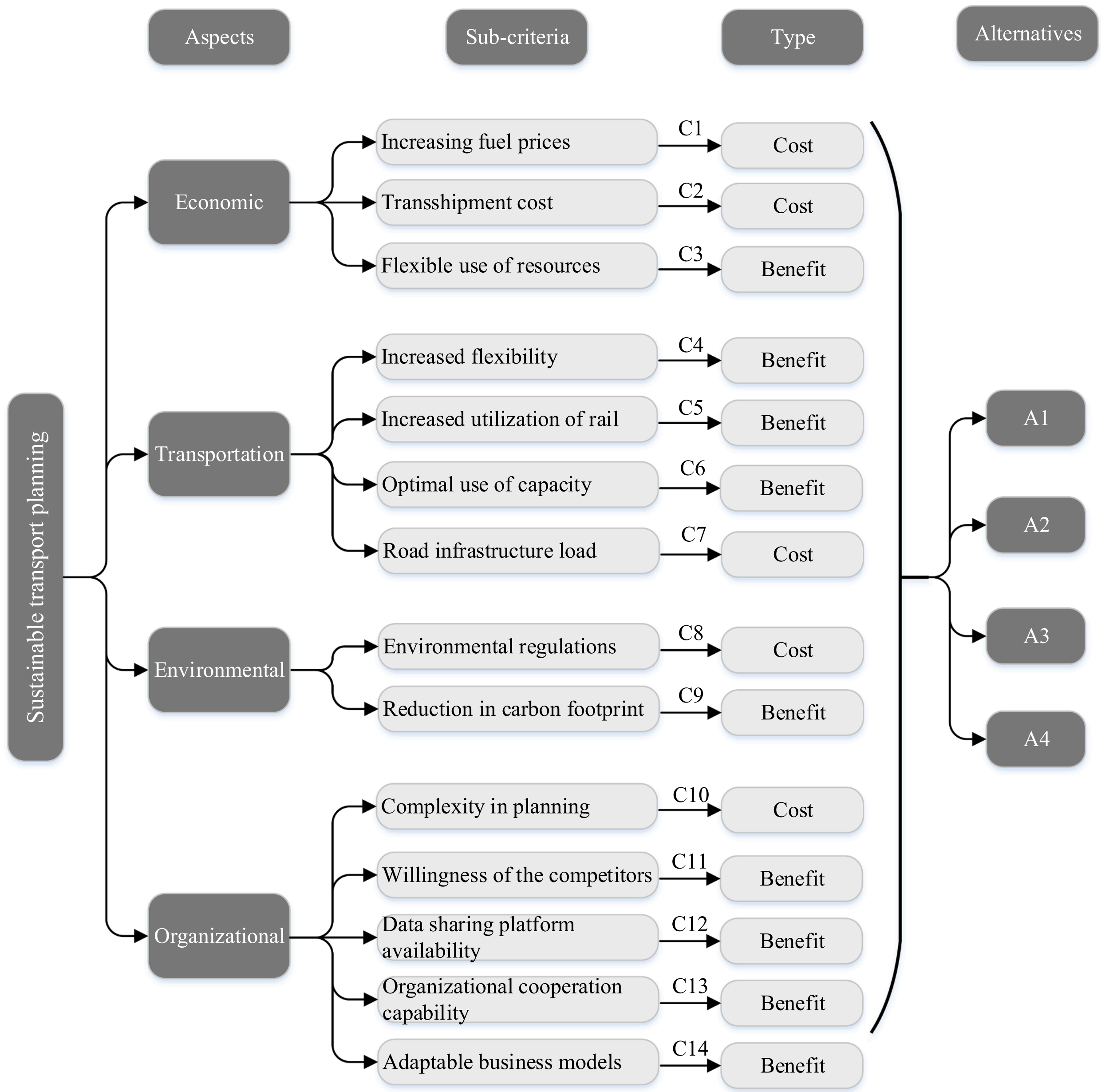

Fig. 1. The decision hierarchy of prioritizing the sustainable transport planning alternatives.

decay (Yamada et al., 2009). Global travel will necessitate the use of either marine transit or air transport. Various modes should be used in conjunction together (Nieuwenhuis, 2016). Policymakers can manage the financial and social benefits of multimodality by increasing mode choice at the supply chain level.

A synchromodal approach is a sort of multimodal planning in which the best possible combination of transportation modes is determined for each transport need (Mes and Iacob, 2016). The synchromodality has created this choice much more complicated (Dong et al., 2018). With new synchromodal concepts and constraints, new planning challenges must be handled (Kramarz et al., 2021). Policymakers and companies must cope with significant variability and dramatic advances in transportation demand and supply. They must constantly modify their operations and plans to meet the needs of their customers, processes, and goods. The relationship between designing service schedules, capacity, regulating capacity deployment, and freight allocation would be closer in a synchromodal system than today in multimodal transport.

Synchromodal transportation helps combine and collaborate across modes of transportation to provide service operators with extra possibilities for giving adequate transportation options by utilizing various services (Zhang and Pel, 2016). Synchromodal transportation relates to the total notion of integrating the use of numerous modes of transportation at the tactical, technical, or functional levels. Following the container transportation and cargo movements in real-time are critical in the synchromodal network (Kramarz et al., 2021). Alternative forms can be employed for different categories of goods, distance transfers, and requirements. The proportional reliance of a corporation on different modes can also change the density of transportation modes (Dong et al., 2018). Synchromodality's key purpose is to minimize expenses, emissions, and late delivery (Giusti et al., 2019). Synchromodality necessitates flexible and relatively close logistics decision-making technologies that address ideal solutions, such as operation planning or content distribution. The best approach is distinguished by low logistic costs, environmentally friendly nature, and increased network overall performance (Kramarz et al., 2021).

Conducted thorough literature review shows that there are various sustainable freight transportation methods, which freight transportation authorities can utilize. However, it is also seen that there is a gap in the literature considering the studies involving these methods together as alternatives, using expert views and various criteria to prioritize these alternatives according to their advantages based on the application area and location. Thus, there is a need for a study, which aids the freight transportation authorities in selecting the most effective and efficient method to achieve the goal of reaching zero-carbon emission operations. This study aims to fill this gap by providing a guide for authorities to use in the transition of decarbonizing their freight transportation operations.

3. Problem definition

Freight transport accounts for significant consequences like pollution, noise, and traffic congestion, although the industry is critical to globalized trade and foundations of worldwide and interregional business. Sustainable logistics aims to reduce emissions. Particular emphasis is placed on lowering CO_2 levels through improved operational planning. Measuring and lowering emissions need accurate projections (Demir et al., 2011). Policy-makers need to prioritize the alternatives in terms of sustainable transportation policy. They can consider the alternatives which are multimodal transport, logistic hubs, synchromobility, and unimodality. During considering process, reduction in carbon footprint and optimal use of network criteria can direct to better planning.

Four alternatives are considered for this problem. These alternatives are evaluated according to the fourteen criteria under four aspects. The decision hierarchy of sustainable transport planning actions is shown in Fig. 1.

3.1. Definition of alternatives

A_1: Multimodal transport: Current multimodal infrastructures, such as roadways and railways, are still underdeveloped. Road capacity, particularly out beyond metropolitan regions, is insufficient, and some road portions are in disrepair (Yamada et al., 2009). The purpose of a multimodal system design is to develop a network model that optimizes network costs and meets transportation needs. Typically, total network usage is believed to remain constant. Transport expenses often consist of out-of-pocket transportation charges, excluding inventory costs and exterbirnal expenditures. Other factors influencing station network layout include transportation regulations relating to local growth limits or the use of fiscal tools, such as capital subsidy or transportation pricing (Zhang et al., 2013).

A_2: Logistic hubs: Capacity planning uses the scarce resources best, which is a common management challenge in freight transportation networks (Xu, et al., 2015). A hub is a location where resources flow and are transported worldwide. The goal is to provide a financial benefit by using a hub rather than delivering directly (Osorio-Mora et al., 2020). Shipping can boost protection, reduce distribution costs, standardize, and provide the availability of many means of transportation. It is becoming increasingly significant in the freight transportation network. While a container hub is a huge container processing station built to current logistics hub specifications, it is also a terminal station for loading or unloading container-based freight for sea, land, or air transit (Xu, et al., 2015). The sources and locations might be tailored for different items, suggesting that they can only address specific markets (Osorio-Mora et al., 2020).

A_3: Synchromodality: The primary goal of synchromodality is to reduce costs, pollutants, and late deliveries while preserving supply chain servqual via intelligent resource use and synchronization of transport flows (Giusti et al., 2019). Synchromodality creates a basis for transporters who want to operate their distribution networks, providing the potential for mode switching (Dong et al., 2018). A distribution network is a flow of transporting goods from the client's request through raw materials, supply, assembly, and delivery of goods to the consumers. Also, logistics management controls the sequence of events in this activity. Synchromodality frequently appears to be connected primarily to the synchronization of transportation, and hence encompasses just the accompanying supply chain management operations (Giusti et al., 2019).

A_4: Unimodality: Trucks are the only mode of transportation used in unimodal road transport. It is expected that vehicles are loaded at a given gathering point. Then, the goods will be delivered to a particular distribution point. The entire transit from town to town is handled by a certain vehicle, with no transit point. Unimodal road transport involves goods gathering in the starting location, transportation from the starting location to the particular destination, and goods distributing in the chosen destination (Zgonc et al., 2019). Intermodal transport struggles to engage with unimodal transport across shorter distances (Zhang and Pel, 2016).

3.2. Definition of criteria

(1) Economic Aspect

C_1: Increasing Fuel Prices: The policymakers may use the financial and social benefits of multimodal rail transportation with improving modal choice at the supply chain level. Instead, the trade-off increased transportation costs for lower emissions. External forces, such as a carbon tax, a growing consumer desire to pay for lower emissions products, or sharp rises in fossil fuel costs, will have to promote such a trade-off (Dong et al., 2018).

C_2: Transshipment Cost: Distribution network stakeholders are linked to one another (Giusti et al., 2019). The interdependence is based on their activity and transferring of information. Modern enterprises rely on a logistics company (Giusti et al., 2019). A demand-driven supply chain involves consumers, providers, and workers that perceive and respond to market indications through a system of synchronized technology and procedures (Budd et al., 2012). Four drivers have been developed to make it much more adaptable to demands (Budd et al., 2012). They are data awareness across the supply chain, facilities that are reliable enough to adjust rapidly to short-term market changes, stakeholder cooperation to manage efficiently and cost-effectively, and improvement of the total management of the supply chain to give the best solutions to customers while maintaining financial advantages (Giusti et al., 2019).

C_3: Flexible Use of Resources: When situations risk destabilizing any component, network, or other methods of analysis, resourcefulness means the ability to detect issues, set targets, and mobilize resources. The simplicity with which a disruption might cause a system to vary from its typical behavior is referred to as vulnerability. The adaptability of a system is its ability to commit resources to respond to a disturbance and, as a result, lessen the volume and scope of undesirable repercussions. As a strategic priority, the resources and money might be properly directed to the relevant areas and modes of transportation (Jansuwan et al., 2021).

(2) Transportation Aspect

C_4: Increased Flexibility in Transport Choices: The benefit of the synchromodal network is giving greater flexibility in utilizing overall delivery in any mode. This is mostly due to the synchromodal system allowing greater flexibility in departing hours and more transshipment options in the region (Zhang and Pel, 2016). A study (Mirkouei et al., 2017) focuses on innovative design and control in the biomass supply chain and gives a wide knowledge base demonstrating how simulators increase supply chain comprehension and modeling flexibility.

C_5. Increased Utilization of Rail and Inland Waterway: The goal of synchromodal transport is to integrate and cooperate across transportation services and modalities to give services providers additional

options for giving adequate transport choices to shippers by utilizing various services of multiple modes. In the Dutch logistics sector, the advantages of synchromodal freight transport have been speculated as to the ability to cut shipping times, give greater employment of each mode's capacity, and permit for balancing mechanisms between alternative modes, resulting in a more resilient transportation network (Zhang and Pel, 2016).

C_6: Optimal Use of Capacity on The Network: In multimodal transportation, service operators cannot improve transport options in response to dynamic data on their service network's current available capacities. And the transporter does not have access to the data. Synchromodal transport strives for more transportation choices to be taken by operators, allowing transportation decisions to be made more quickly (Zhang and Pel, 2016). Lautala et al. (2015) examine modes of transportation and find that vehicle transport performs in network access, availability, efficiency, and adaptability.

C_7: Road Infrastructure Load: Because all the hubs are the same size, the efficacy of network operation can be deteriorated based on the handling levels, even though the preceding problem defined their position. If the goods arriving surpass the hub's limit, management expenses are applied, such as the fees connected with the postponement and storage (Hwang et al., 2018) Recognizing these shortcomings resulted in an extra action plan (FTLAP, 2005), in which greater utilization of infrastructure, better integration of modes, lower costs, and quality requirements are set out as new targets to increase intermodal transport's efficiency (Zhang and Pel, 2016).

(3) Environmental Aspect

C_8: Environmental Regulations: Synchromodal transportation is an impending new option that will replace intermodal transportation by providing more adaptable and collaborative freight transportation at the administrative level to cope with risks (Tavasszy et al., 2010). The strategic programs are applied on a regional scale. The transport system is sensitive to risks and changes during this procedure. This needs submission to regulate operational concerns (Qu et al., 2019).

C_9: Reduction in Carbon Footprint: The environmental consequences are calculated based on CO2 emissions estimated in kilograms, taking into consideration the type of vehicle, usual vehicle speed, and capacity factor of railways and ships. Railway and inland waterway CO2 emissions are computed using a non-linear regime. It can be seen that the synchromodal method eliminates CO2 emissions by 28 percent. This is related to the shift from road transportation to the railway, as well as, to a smaller extent, increasing capability residences of railway and ship services (Zhang and Pel, 2016).

(4) Organizational Aspect

C_{10}: Complexity in Planning: The ability to move between modes of transportation instantaneously is a fundamental feature that separates synchromodality from earlier transport models. Actual shifting relates to the actual adaptation of transportation planning, depending on the current system parameters (Behdani et al., 2014). Complex planning is required to facilitate synchromodal decision-making (Pfoser et al., 2021).

C_{11}: The willingness of The Competitors to Cooperate: A new collaboration will emerge to provide detailed information if the facilities are managed by various groups. Business plans should include gain- and loss-sharing processes to assign benefits and drawbacks equitably among the collaborators. It should also give incentives for people to join the synchromodal system, as well as clear collaboration agreements (Pfoser et al., 2021).

C_{12}: Data Sharing Platform Availability: The discovered pattern indicates a preference for container structure and activity, with a concentration on data sharing connection structures and visibility enhancements (Ambra et al., 2019) Many articles layout an Information infrastructure for the network operator that enables effective data sharing across parties (Pfoser et al., 2021).

C_{13}: Organizational Cooperation Capability: Advantages of cooperative collaborations are the strategic assets, lower operating costs, increased efficiency, and greater performance (Mungra and Yadav, 2019). Firms depend on trades with one another to get critical resources (Kim et al., 2018). Companies may only adapt to market needs with the participation and assistance of collaborators. Inter-firm cooperative transfer connections include fairness, accompanied by trust and loyalty (Berne-Manero and Marzo-Navarro, 2020).

C_{14}: Adaptable Business Models: Effective business models must be provided to organize complicated relationships in a synchromodal system and assist freight movement packing and simplification (Caris et al., 2014). Business practices need to contain gain- and loss-sharing systems o transfer advantages and expenses evenly between participants (Pfoser et al., 2021).

The synchromodality decreases logistics operations while also improving security, reducing harm, and allowing freight. With the aid of digitization in this field, a genuine connection might be established. The notion of synchromodality was developed further than the ideas of unimodality, multi-modality, and inter-modality in an attempt to implement the most use of transportation capacity (Haller et al., 2015).

4. Preliminaries on picture fuzzy sets

In the following section, the definitions of picture fuzzy sets are presented.

Definition 1. ((*Cuong & Kreinovich, 2013; Cuong, 2014*).) *Let picture fuzzy set B on a universe U be an object in the form of.*

$$B = \{\langle u, \mu_B(u), \eta_B(u), v_B(u)\rangle, u \in U\} \tag{1}$$

where$\mu_B(u)$, $\eta_B(u)$ and $v_B(u)$ represent the degrees of positive, neutral, and negative membership of u in B, respectively.

For PFS defined by Eq. (1), the condition that$0 \leqslant \mu_B(u) + \eta_B(u) + v_B(u) \leqslant 1, \forall u \in U$. Since PFS represent the generalization of fuzzy sets and intuitionistic fuzzy sets (IFSs), then if the condition that $\eta_B(u) = 0$ is met, PFS is transformed into IFS. Also, if the condition that $v_B(u) = \eta_B(u) = 0$ is met then PFS is transformed into a traditional fuzzy set. The integration of the degree of neutral membership $\eta_B(u)$ in PFS enables more accurate measurement of information that directly affects the quality and rationality of the final results.

If U is one element, then $B = \{\langle u, \mu_B(u), \eta_B(u), v_B(u)\rangle, u \in U\}$ we call a picture fuzzy number where the condition that$\mu_B(u)$, $\eta_B(u)$ $v_B(u) \in [0, 1]$ is met. Then, the picture fuzzy number can be displayed as $B = \langle \mu_B(u), \eta_B(u), v_B(u)\rangle$ (Simić et al., 2021).

Definition 2. ((*Liang et al., 2018*).) *Complement picture fuzzy set $B = \{\langle u, \mu_B(u), \eta_B(u), v_B(u)\rangle, u \in U\}$ on a universe U can be represented as follows:*Liang et al., 2018.

$$B^c = \{\langle u, v_B(u), \eta_B(u), \mu_B(u)\rangle, u \in U\} \tag{2}$$

Definition 3. ((*Liu et al., 2019*).) *Let $B = \langle \mu_B(u), \eta_B(u), v_B(u)\rangle$ and $B_1 = \langle \mu_{B_1}(u), \eta_{B_1}(u), v_{B_1}(u)\rangle$ be two picture fuzzy numbers, and let$\theta > 0$, then operations with picture fuzzy numbers can be defined as follows:*Liu et al., 2019.

(1) Addition "$\oplus$".

$$B \oplus B_1 = \langle 1 - (\mu_B(u))(\mu_{B_1}(u)), \eta_B(u)\eta_{B_1}(u), (\eta_B(u) + v_B(u))(\eta_{B_1}(u) + v_{B_1}(u)) - \eta_B(u)\eta_{B_1}(u)\rangle \tag{3}$$

(2) Multiplication "$\otimes$".

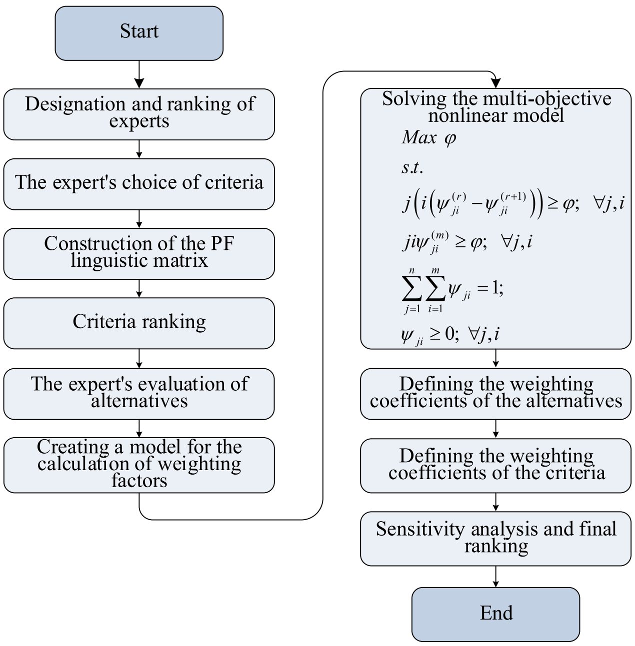

Fig. 2. The flowchart of the proposed OPA algorithm.

$$B\otimes B_1=\left\langle(\mu_B(u)+\eta_B(u))(\mu_{B_1}(u)+\eta_{B_1}(u))-\eta_B(u)\eta_{B_1}(u),\eta_B(u)\eta_{B_1}(u),1-(v_B(u))(v_{B_1}(u))\right\rangle \tag{4}$$

(3) Scalar multiplication, where$\theta>0$.

$$\theta\cdot B=\left\langle 1-(\mu_B(u))^{\theta},(\eta_B(u))^{\theta},(\eta_B(u)+v_B(u))^{\theta}-(\eta_B(u))^{\theta}\right\rangle \tag{5}$$

(4) Power, where$\theta>0$.

$$B^{\theta}=\left\langle(\mu_B(u)+\eta_B(u))^{\theta}-(\eta_B(u))^{\theta},(\eta_B(u))^{\theta},1-(v_B(u))^{\theta}\right\rangle \tag{5}$$

Definition 4. ((Wang et al., 2017).) *Let$B_i=\langle\mu_{B_i}(u),\eta_{B_i}(u),v_{B_i}(u)\rangle$, $(i=1,2,...,h)$ represent the collection picture of fuzzy numbers, and let $\alpha_i=(\alpha_1,\alpha_2,....,\alpha_h)^T$ be the vector of weight coefficients. Then the picture fuzzy weighted geometric average (PFWGA) operator can be defined as follows:* Wang et al., 2017.

$$PFWGA=\prod_{i=1}^{h}(B_i)^{\alpha_i}=\left\langle\prod_{i=1}^{h}(\mu_{B_i}+\eta_{B_i})^{\alpha_i}-\prod_{i=1}^{h}(\eta_{B_i})^{\alpha_i},\prod_{i=1}^{h}(\eta_{B_i})^{\alpha_i},1-\prod_{i=1}^{h}(1-v_{B_i})^{\alpha_i}\right\rangle \tag{6}$$

where $\alpha_i\in[0,1]$ and$\sum_{i=1}^{h}\alpha_i=1$.

5. Picture fuzzy OPA Multi-Criteria framework

In this section, the definitions of the developed picture fuzzy OPA method are presented. The flowchart of the proposed method is presented in Fig. 2.

The picture fuzzy OPA algorithm is implemented through the following steps:

Step 1: Designation and ranking of experts. This step is performed only if the OPA-P method is applied in group decision-making. First, the final set of experts participating in the research is determined. For example, suppose that p experts marked with the set E_e $(e=1,2,...,p)$ participate in the study. After defining the final number of experts in the study, their qualifications are defined and ranked based on experience in the field covered and level of education.

Step 2: Defining and ranking criteria. In this step, the final set of n criteria C_j $(j=1,2,...,n)$ is defined. If individual criteria are divided into sub-criteria, the weighting coefficients of these criteria are defined based on the weighting coefficients of the sub-criteria. After defining the final list of criteria, the linguistic matrix $\Im^t=\left[\wp_j^t\right]_{n\times 1}$ $(1\leqslant t\leqslant p)$ is constructed in which experts represent the relative significance of the criteria:

$$\Im^t=\begin{matrix}C_1\\C_2\\C_3\\...\\C_n\end{matrix}\begin{bmatrix}\wp_1^t\\\wp_2^t\\\wp_3^t\\...\\\wp_n^t\end{bmatrix} \tag{7}$$

where $\wp_j^t=\left\langle\mu_j^e,\eta_j^e,v_j^e\right\rangle$ represents the relative importance of criterion j defined by the expert t $(1\leqslant t\leqslant p)$. Relative importance is determined using a predefined linguistic scale. Expert assessments in the linguistic matrix $\Im^t=\left[\wp_j^t\right]_{n\times 1}$ are averaged using Eq. (6). By averaging expert assessments, we obtain an aggregated linguistic matrix$\Im=\left[\wp_j\right]_{n\times 1}$. The actual scores of the elements $\wp_j=\left\langle\mu_j,\eta_j,v_j\right\rangle$ are defined by applying the Eqs. (8)-(11) as follows:

(1) Identification of the positive ideal solution (PIS)

$$\wp^+=\langle\mu^+,\eta^+,v^+\rangle=\left\langle\max_{1\leqslant j\leqslant n}(\mu_j),\min_{1\leqslant j\leqslant n}(\eta_j),\min_{1\leqslant j\leqslant n}(v_j)\right\rangle \tag{8}$$

(2) Defining positive and negative goal differences for each $\wp_j=\left\langle\mu_j,\eta_j,v_j\right\rangle$

$$\mu_j^+=\mu^+-\mu_j \tag{9}$$

$$v_j^-=v_j-v^+ \tag{10}$$

where μ_j^+ and v_j^- represent positive goal difference (PGD) and negative goal difference (NGD), respectively.

(3) Derive the actual score (AS) for each $\wp_j=\left\langle\mu_j,\eta_j,v_j\right\rangle$

$$\partial_j=\frac{\widehat{\Psi}_j}{1-(\overline{\eta}-\eta_j)} \tag{11}$$

where $\widehat{\Psi}_j=\left(1-\mu_j^+\right)-v_j^-$ represents the absolute score, while $\overline{\eta}$ represents the average neutral degree and is defined as the arithmetic mean of the elements$\overline{\eta}=\sum_{j=1}^{n}\eta_j/n$.

Based on the defined values of AS, the criteria are ranked, and the criterion should have the highest possible value∂_j. The ranking of the criteria is done by applying the following rules:

a) If $\partial_j>\partial_{j+1}$ then$C_j>C_{j+1}$, therefore, the criterion C_j has a better rank than the criterionC_{j+1};
b) If $\partial_j=\partial_{j+1}$ then if$\mu_j>\mu_{j+1}$, and $\eta_j>\eta_{j+1}$ then$C_j>C_{j+1}$;
c) If $\partial_j=\partial_{j+1}$ then if$\mu_j\geqslant\mu_{j+1}$, $\eta_j<\eta_{j+1}$ and $v_j\leqslant v_{j+1}$ then then$C_j>C_{j+1}$, otherwise$C_j<C_{j+1}$.

Step 3: Ranking of alternatives within a defined set of criteria. In this step, the ranking of alternatives A_i $(i = 1, 2, ..., m)$ is defined within the defined criteriaC_j $(j = 1, 2, ..., n)$. Experts E_e $(e = 1, 2, ..., p)$ evaluate alternatives within the home matrix $\Re^t = \left[\Omega_{ij}^t\right]_{m\times n}$ $(1\leqslant t\leqslant p)$, where $\Omega_{ij}^t = \left\langle \mu_{ij}^t, \eta_{ij}^t, v_{ij}^t \right\rangle$ represents the relative importance of ith alternative in relation to jth criterion defined by expert t $(1\leqslant t\leqslant p)$. The relative importance of alternatives is determined based on a predefined linguistic scale. Then, applying geometric weight averaging (6), we determine an aggregated home matrix$\Re = \left[\Omega_{ij}\right]_{m\times n}$.

The actual scores of the home matrix elements $\Re = \left[\Omega_{ij}\right]_{m\times n}$ are defined similarly to the actual score of the criteria in *Step 2*. Based on the value of the actual score of alternatives, the alternatives are ranked, expression (12).

$$A_{ji}^{(1)} \geqslant A_{ji}^{(2)} \geqslant ... \geqslant A_{ji}^{(r)} \geqslant A_{ji}^{(r+1)} \geqslant ... \geqslant A_{ji}^{(m)}; \ \forall j, i \tag{12}$$

where $A_{ji}^{(r)}$ represents ith an alternative that is ranked within the jth criterion, which has been assigned the rank r.

In order to satisfy the condition that$A_{ji}^{(r)} \geqslant A_{ji}^{(r+1)}$, then the weight coefficients of the considered alternatives should meet the condition$\psi_{ji}^{(r)} \geqslant \psi_{ji}^{(r+1)}$, where $\psi_{ji}^{(r)}$ represents the weight coefficient ith the alternative that is ranked within the jth criterion. The weighting coefficients of successive criteria by rank should satisfy the condition from Eq. (13).

$$\begin{array}{l} \psi_{ji}^{(1)} - \psi_{ji}^{(2)} \geqslant 0; \\ \psi_{ji}^{(2)} - \psi_{ji}^{(3)} \geqslant 0; \\ \quad ... \\ \psi_{ji}^{(r)} - \psi_{ji}^{(r+1)} \geqslant 0; \\ \quad ... \\ \psi_{ji}^{(m-1)} - \psi_{ji}^{(m)} \geqslant 0. \end{array} \tag{13}$$

that is, Eq. (13) can be abbreviated as follows:

$$j\left(i\left(\psi_{ji}^{(r)} - \psi_{ji}^{(r+1)}\right)\right) \geqslant 0; \ \forall, j, i \tag{14}$$

where $\psi_{ji}^{(r)}$ represents the significance of ith alternative concerning the jth attribute at the rth rank.

Step 4: Creating a model for the calculation of weighting factors. To define the weight coefficients of alternatives and criteria, a multi-objective nonlinear mathematical model was defined in Eq. (15).

$$\begin{array}{l} Max\ Min\left\{ j\left(i\left(\psi_{ji}^{(r)} - \psi_{ji}^{(r+1)}\right)\right); , ji\psi_{ji}^{(m)} \right\}; \ \forall j, i \\ \quad s.t. \\ \quad \sum_{j=1}^{n} \sum_{i=1}^{m} \psi_{eji} = 1; \\ \quad \psi_{ji} \geqslant 0; \ \forall j, i \end{array} \tag{15}$$

The multi-objective nonlinear model in Eq. (15) can be transformed into a linear mathematical model for determining weight coefficients as follows:

$$\begin{array}{l} Max\ \varphi \\ s.t. \\ j\left(i\left(\psi_{ji}^{(r)} - \psi_{ji}^{(r+1)}\right)\right) \geqslant \varphi; \ \forall j, i \\ ji\psi_{ji}^{(m)} \geqslant \varphi; \ \forall j, i \\ \sum_{j=1}^{n} \sum_{i=1}^{m} \psi_{ji} = 1; \\ \psi_{ji} \geqslant 0; \ \forall j, i \end{array} \tag{16}$$

where $\psi_{ji}^{(r)}$ represents the weighting factor (significance) ith alternative concerning the jth attribute on the rth rank.

Table 1
The hierarchy of the evaluation criteria.

Main-criteria	Sub-criteria	Types
Economic Aspect (MC_1)		
C_1	Increasing fuel prices	Cost
C_2	Transshipment cost	Cost
C_3	Flexible use of resources	Benefit
Transportation Aspect (MC_2)		
C_4	Increased flexibility in transport choices	Benefit
C_5	Increased utilization of rail and inland waterway	Benefit
C_6	Optimal use of capacity on the network	Benefit
C_7	Road infrastructure load	Cost
Environmental Aspect (MC_3)		
C_8	Environmental regulations	Cost
C_9	Reduction in carbon footprint	Benefit
Organizational Aspect (MC_4)		
C_{10}	Complexity in planning	Cost
C_{11}	Willingness of the competitors to cooperate	Benefit
C_{12}	Data sharing platform availability	Benefit
C_{13}	Organizational cooperation capability	Benefit
C_{14}	Adaptable business models	Benefit

By solving model (16), we obtain the values of the weight coefficient of the ith alternative for each criterion j. Based on the value ofψ_{ji} , we can define the importance of alternatives and criteria, as follows:

a) The weighting coefficients of the alternatives are defined by applying the Eq. (17):

$$\psi_i = \sum_{j=1}^{n} \psi_{ij}; \ \forall i \tag{17}$$

b) The weighting coefficients of the criteria are defined by applying the Eq. (18):

$$\psi_j = \sum_{i=1}^{m} \psi_{ij}; \ \forall j \tag{18}$$

where ψ_i and ψ_j respectively represent the weighting coefficients of the alternatives and criteria.

6. Application of picture fuzzy OPA Multi-Criteria frame

This study is conducted to provide a decision-making mechanism for authorities in prioritizing sustainable freight transportation planning alternatives for the freight industry targeting zero-carbon emissions. To ground the assessments on reality, a case in the problem definition section is used by the experts in scoring.

In the case study discussed in this paper, four alternatives were evaluated using the picture fuzzy OPA methodology: Alternative 1 - Multimodal transport; Alternative 2 - Logistic hubs; Alternative 3 - Synchromodality, and Alternative 4 - Unimodality. For the evaluation of alternatives, 14 criteria were identified, which were grouped within four clusters, as given in Table 1. The experts from academia and the sector are interviewed, and the literature is reviewed in constructing the set of criteria and the set of alternatives. Each alternative is evaluated according to the decision criteria by four decision-makers using face-to-face interviews.

The evaluation of alternatives was performed using the picture fuzzy OPA methodology, which was implemented through the steps presented in the next section:

6.1. Proposed model results

Steps 1 and 2: Four experts participated in the researchE_e $(e = 1, 2, ..., 4)$.

Expert 1—A manager in a logistic company with 7 years of experience (male), Expert 2—A logistics company owner (transportation engineer) with 12 years of experience (male), Expert 3—An academician in

Table 2
Fuzzy scale for evaluation of criteria and alternatives.

Linguistic Term	Picture Fuzzy Number
Extremely low (EL)	<0.1,0.1,0.8>
Very low (VL)	<0.1,0.2,0.7>
Low (L)	<0.2,0.3,0.6>
Middle low (ML)	<0.2,0.3,0.5>
Below middle (BM)	<0.3,0.2,0.5>
Middle (M)	<0.4,0.2,0.4>
Above middle (AM)	<0.5,0.2,0.3>
Middle high (MH)	<0.6,0.1,0.3>
High (H)	<0.7,0.1,0.2>
Very high (VH)	<0.8,0.2,0.1>
Extremely high (EH)	<0.9,0.1,0.1>

Table 3
Evaluation of criteria.

Crit.	Experts			
	E_1	E_2	E_3	E_4
C_1	VH	H	EH	H
C_2	L	MH	H	EH
C_3	AM	VH	M	VH
C_4	MH	H	AM	H
C_5	ML	VH	BM	H
C_6	H	VH	VH	MH
C_7	M	MH	M	ML
C_8	BM	H	H	MH
C_9	BM	VH	EH	VH
C_{10}	L	H	M	MH
C_{11}	VH	BM	L	AM
C_{12}	EH	H	ML	H
C_{13}	BM	AM	BM	MH
C_{14}	MH	MH	BM	AM

Table 4
Aggregated linguistic matrix.

Criteria	Aggregated value	Criteria	Aggregated value
C_1	<0.776,0.119,0.151>	C_8	<0.569,0.119,0.312>
C_2	<0.596,0.132,0.330>	C_9	<0.673,0.168,0.223>
C_3	<0.605,0.200,0.236>	C_{10}	<0.484,0.157,0.395>
C_4	<0.629,0.119,0.252>	C_{11}	<0.425,0.221,0.404>
C_5	<0.483,0.186,0.349>	C_{12}	<0.621,0.132,0.267>
C_6	<0.724,0.141,0.179>	C_{13}	<0.423,0.168,0.408>
C_7	<0.410,0.186,0.404>	C_{14}	<0.502,0.141,0.356>

a school of transportation and logistics with 18 years of experience (male), Expert 4—An academician (transportation engineer) with 27 years of experience (male).

Using the picture fuzzy scale presented in Table 2, the experts evaluated the criteria shown in Table 1.

Based on expert assessments, four linguistic matrices $\Im^t = \left[\wp_j^t\right]_{n\times 1}$ ($1\leqslant t\leqslant 4$) were formed with expert evaluations of the significance of the criteria as given in Table 3.

Using Eq. (6), expert assessments were combined, and an aggregated linguistic matrix was obtained, which is presented in Table 4.

When defining the aggregate values of expert assessments, the vector of expert weight coefficients $\varpi_e = 0.25$ ($e = 1, 2, ..., 4$) was adopted. Therefore, an example of the calculation of the aggregated value for criterion C_1 is presented in the following section:

$$\wp_1 = \left\langle \begin{array}{c} (0.8+0.2)^{0.25}\cdot(0.7+0.1)^{0.25}\cdot(0.9+0.1)^{0.25}\cdot(0.7+0.1)^{0.25} - \\ (0.2)^{0.25}\cdot(0.1)^{0.25}\cdot(0.1)^{0.25}\cdot(0.1)^{0.25}, \\ (0.2)^{0.25}\cdot(0.1)^{0.25}\cdot(0.1)^{0.25}\cdot(0.1)^{0.25}, \\ 1-(1-0.1)^{0.25}\cdot(1-0.2)^{0.25}\cdot(1-0.1)^{0.25}\cdot(1-0.2)^{0.25} \end{array} \right\rangle$$
$$= \langle 0.776, 0.1119, 0.151\rangle$$

The remaining aggregated picture fuzzy values from Table 4 were defined similarly. The criteria ranking was performed using the actual score elements. The actual scores of the criteria are given in Table 5.

Table 5
Actual scores for criteria.

Crit.	μ_j^+	ν_j^-	$\widehat{\Psi}_j$	∂_j	Rank
C_1	0.0000	0.0000	1.0000	1.039	1
C_2	0.1797	0.1785	0.6419	0.658	7
C_3	0.1705	0.0848	0.7447	0.714	6
C_4	0.1461	0.1002	0.7537	0.783	4
C_5	0.2929	0.1972	0.5099	0.495	10
C_6	0.0519	0.0279	0.9203	0.934	2
C_7	0.3658	0.2527	0.3814	0.370	14
C_8	0.2065	0.1606	0.6330	0.658	8
C_9	0.1028	0.0715	0.8257	0.816	3
C_{10}	0.2918	0.2430	0.4652	0.465	11
C_{11}	0.3501	0.2527	0.3972	0.373	13
C_{12}	0.1550	0.1160	0.7290	0.748	5
C_{13}	0.3521	0.2569	0.3910	0.386	12
C_{14}	0.2734	0.2050	0.5216	0.530	9

Table 6
Evaluation of alternatives.

Criteria	A_1	A_2	A_3	A_4
C_1	AM, L, EL, VL	L, VL, VL, ML	VL, EL, ML, L	VH, EH, L, EL
C_2	M, VL, EL, VL	EL, EL, ML, BM	M, VH, VL, ML	VH, VH, L, EL
C_3	EH, VH, VH, H	AM, VH, MH, VH	VH, VH, EH, MH	VL, VL, H, M
C_4	EH, EH, EH, VH	EL, H, H, VH	EL, H, VH, H	EL, EL, AM, M
C_5	M, MH, H, H	M, EL, L, MH	EH, EH, EH, VH	EL, EL, M, M
C_6	VL, H, VH, VH	H, BM, EH, H	EH, MH, H, H	BM, VL, M, BM
C_7	VL, VL, BM, L	VL, VH, EL, ML	EL, EL, M, L	BM, EH, VL, VL
C_8	EH, VL, L, L	M, L, M, BM	AM, EL, EL, L	VH, VH, BM, VL
C_9	VL, H, H, H	H, H, VH, MH	EH, EH, EH, VH	VL, VL, M, BM
C_{10}	L, H, VL, L	EH, EL, EL, BM	ML, H, L, VL	EH, H, L, BM
C_{11}	L, VL, EH, H	AM, EH, L, VH	EH, VL, VH, MH	VL, VL, M, M
C_{12}	VL, EH, H, VH	H, AM, EH, H	EH, L, AM, H	VL, VL, BM, MH
C_{13}	H, EH, VH, H	VH, BM, EH, VH	EH, M, H, H	VL, VL, M, AM
C_{14}	M, AM, H, H	EH, MH, EH, VH	EH, AM, VH, MH	VL, BM, L, BM

Where the actual score of the C_1 criterion is obtained by applying the following calculations:

(1). Calculate the positive ideal solution

$$\wp^+ = \langle \mu^+, \eta^+, \nu^+ \rangle = \left\langle \begin{array}{c} \max\limits_{1\leqslant j\leqslant 14}(0.776, 0.596, 0.605, 0.629, ..., 0.502), \\ \min\limits_{1\leqslant j\leqslant 14}(0.119, 0.132, 0.200, 0.119, ..., 0.141), \\ \min\limits_{1\leqslant j\leqslant 14}(0.151, 0.330, 0.236, 0.252, ..., 0.356) \end{array} \right\rangle$$
$$= \langle 0.776, 0.119, 0.151\rangle$$

(1) Calculate positive and negative goal differences for $\wp_1 = \langle \mu_1, \eta_1, \nu_1 \rangle$

$$\mu_1^+ = \mu^+ - \mu_1 = 0.776 - 0.776 = 0.00$$

$$\nu_1^- = \nu_1 - \nu^+ = 0.151 - 0.151 = 0.00$$

(2) Calculate the actual score for C_1

$$\partial_1 = \frac{1.00}{1-(0.156-0.119)} = 1.039$$

Table 7
Aggregate home matrix.

Criteria	A_1	A_2	A_3	A_4
C_1	<0.195,0.186,0.640>	<0.142,0.245,0.634>	<0.144,0.206,0.669>	<0.406,0.157,0.495>
C_2	<0.154,0.168,0.678>	<0.160,0.157,0.684>	<0.326,0.221,0.467>	<0.376,0.186,0.495>
C_3	<0.804,0.141,0.126>	<0.668,0.168,0.206>	<0.773,0.141,0.155>	<0.288,0.168,0.544>
C_4	<0.881,0.119,0.100>	<0.479,0.119,0.417>	<0.479,0.119,0.417>	<0.219,0.141,0.640>
C_5	<0.601,0.119,0.280>	<0.296,0.157,0.572>	<0.881,0.119,0.100>	<0.205,0.141,0.654>
C_6	<0.532,0.168,0.336>	<0.633,0.119,0.267>	<0.718,0.1,0.203>	<0.261,0.200,0.539>
C_7	<0.166,0.221,0.634>	<0.230,0.186,0.595>	<0.174,0.157,0.687>	<0.292,0.168,0.551>
C_8	<0.317,0.206,0.544>	<0.326,0.221,0.482>	<0.187,0.157,0.675>	<0.422,0.200,0.410>
C_9	<0.507,0.119,0.374>	<0.699,0.119,0.203>	<0.881,0.119,0.1>	<0.205,0.200,0.595>
C_{10}	<0.289,0.206,0.557>	<0.257,0.119,0.634>	<0.289,0.206,0.532>	<0.512,0.157,0.384>
C_{11}	<0.432,0.157,0.458>	<0.583,0.186,0.310>	<0.536,0.141,0.358>	<0.224,0.200,0.576>
C_{12}	<0.559,0.141,0.336>	<0.699,0.119,0.203>	<0.571,0.157,0.33>	<0.253,0.168,0.579>
C_{13}	<0.776,0.119,0.151>	<0.673,0.168,0.223>	<0.668,0.119,0.233>	<0.241,0.200,0.559>
C_{14}	<0.560,0.151,0.280>	<0.790,0.126,0.155>	<0.682,0.151,0.206>	<0.206,0.226,0.584>

Table 8
Priority of alternatives.

Criteria	Priorities				Criteria	Priorities			
	1st	2nd	3rd	4th		1st	2nd	3rd	4th
C_1	A4	A2	A1	A3	C_8	A4	A2	A1	A3
C_2	A4	A3	A2	A1	C_9	A3	A2	A4	A1
C_3	A1	A3	A2	A4	C_{10}	A4	A2	A3	A1
C_4	A2	A4	A2	A3	C_{11}	A2	A4	A3	A1
C_5	A3	A1	A4	A2	C_{12}	A2	A4	A3	A1
C_6	A3	A2	A4	A1	C_{13}	A1	A2	A3	A4
C_7	A4	A2	A1	A3	C_{14}	A2	A3	A1	A4

where

$\widehat{\Psi}_1 = (1-\mu_1^+) - \nu_1^- = (1-0.0) - 0.0 = 1.0$ and.

$$\overline{\eta} = \frac{1}{14}\sum_{j=1}^{14}(0.119+0.132+0.200+0.119+\ldots+0.141) = 0.156$$

The actual scores of the remaining criteria are calculated similarly.

Step 3: In this step, the experts evaluated the alternatives under defined criteria. To consider the alternatives, the experts used the linguistic scale from Table 2. Expert assessments are presented within the home matrices $\Re^t = \left[\Omega_{ij}^t\right]_{4\times 14}$ $(1\leqslant t\leqslant 4)$ given in Table 6.

Using Eq. (6), expert assessments were combined in Table 7.

Alternatives are ranked using actual scores, as presented in Table 8. Actual scores of alternatives are given in Table A1 (Appendix).

Step 4: Using Eqs. (12) - (16), the OPA linear model is defined and presented in the following section:

$$Max\ \varphi$$
$$s.t.$$
$$\begin{array}{lcl}
1\cdot(1\cdot(\psi_{1,A4}-\psi_{1,A2}))\geqslant\varphi; & & 13\cdot(1\cdot(\psi_{11,A2}-\psi_{11,A4}))\geqslant\varphi;\\
1\cdot(2\cdot(\psi_{1,A2}-\psi_{1,A1}))\geqslant\varphi; & & 13\cdot(2\cdot(\psi_{11,A4}-\psi_{11,A3}))\geqslant\varphi;\\
1\cdot(3\cdot(\psi_{1,A1}-\psi_{1,A3}))\geqslant\varphi; & & 13\cdot(3\cdot(\psi_{11,A3}-\psi_{11,A1}))\geqslant\varphi;\\
1\cdot(4\cdot\psi_{1,A3})\geqslant\varphi; & & 13\cdot(4\cdot\psi_{11,A1})\geqslant\varphi;\\
2\cdot(1\cdot(\psi_{6,A3}-\psi_{6,A2}))\geqslant\varphi; & & 14\cdot(1\cdot(\psi_{7,A4}-\psi_{7,A2}))\geqslant\varphi;\\
2\cdot(2\cdot(\psi_{6,A2}-\psi_{6,A4}))\geqslant\varphi; & \&\ldots\& & 14\cdot(2\cdot(\psi_{7,A2}-\psi_{7,A1}))\geqslant\varphi;\\
2\cdot(3\cdot(\psi_{6,A4}-\psi_{1,A1}))\geqslant\varphi; & & 14\cdot(3\cdot(\psi_{7,A1}-\psi_{7,A3}))\geqslant\varphi;\\
2\cdot(4\cdot\psi_{6,A1})\geqslant\varphi; & & 14\cdot(4\cdot\psi_{7,A3})\geqslant\varphi;\\
3\cdot(1\cdot(\psi_{9,A3}-\psi_{9,A2}))\geqslant\varphi; & & \\
3\cdot(2\cdot(\psi_{9,A2}-\psi_{9,A4}))\geqslant\varphi; & & \sum_{j=1}^{14}\sum_{i=1}^{4}\psi_{ji}=1;\\
3\cdot(3\cdot(\psi_{9,A4}-\psi_{9,A1}))\geqslant\varphi; & & \psi_{ij}\geqslant 0;\ \forall j,i\\
3\cdot(4\cdot\psi_{9,A1})\geqslant\varphi; & &
\end{array}$$

By solving the linear model and applying Eq. (17), we determine the significance of alternatives as follows:

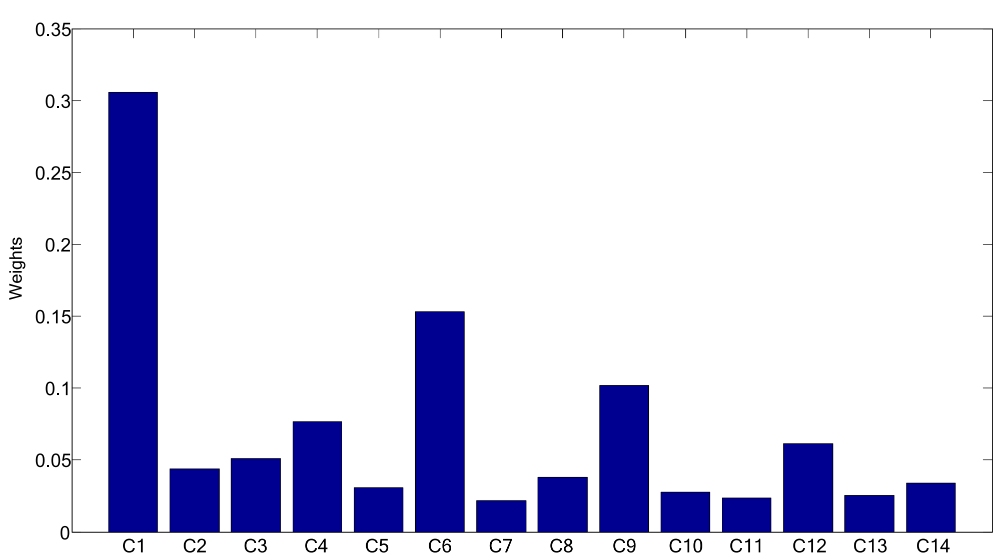

Fig. 3. Criteria weighting coefficients.

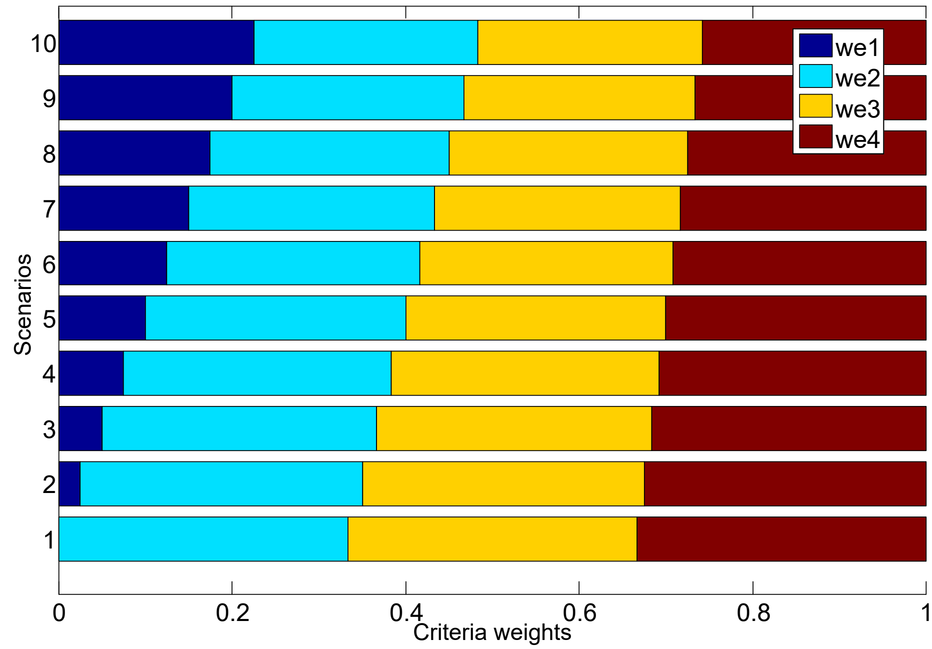

Fig. 4. New weight vectors.

$$\psi_i = \begin{matrix} A1 \\ A2 \\ A3 \\ A4 \end{matrix} \begin{bmatrix} 0.0253 \\ 0.2230 \\ 0.2244 \\ 0.2432 \end{bmatrix}$$

Based on the significance of the alternatives, we can define the following rank $A_4 > A_3 > A_2 > A_1$.

6.2. Sensitivity analysis

In addition to the importance of alternatives, using Eq. (18), we can define the weighting coefficients of the criteria Fig. 3.

When defining AS criteria and alternatives, the same values of weighting coefficients were adopted for all experts ($\varpi_e = 0.25$, $e = 1, 2, \ldots, 4$). Since the aggregation of expert estimates was performed using the PF operator for geometric weight averaging (Eq. (6)), it was expected that the weight coefficients of experts affect the change in the value of AS criteria/alternatives. Therefore, in the following part, the change in the value of the vector of expert weight coefficients is simulated.

Based on the recommendations of Kahraman (2002), new weight vectors were generated, and their influence on changes in the rankings of alternatives was analyzed. The new vectors of weight coefficients were obtained based on the variation of the value of the weight coefficient of the first expert (ϖ_1). The amount of change in the generated vectors of weights of the experts was defined based on the methodology

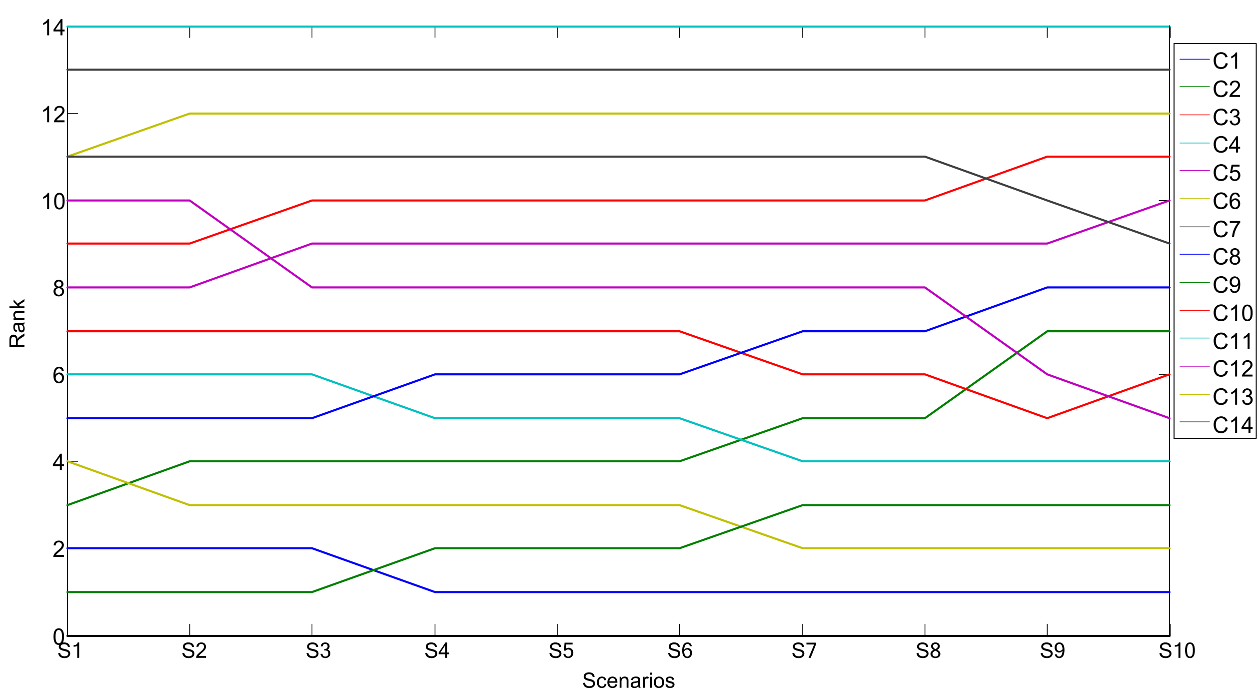

Fig. 5. Changing the rank of criteria through ten scenarios.

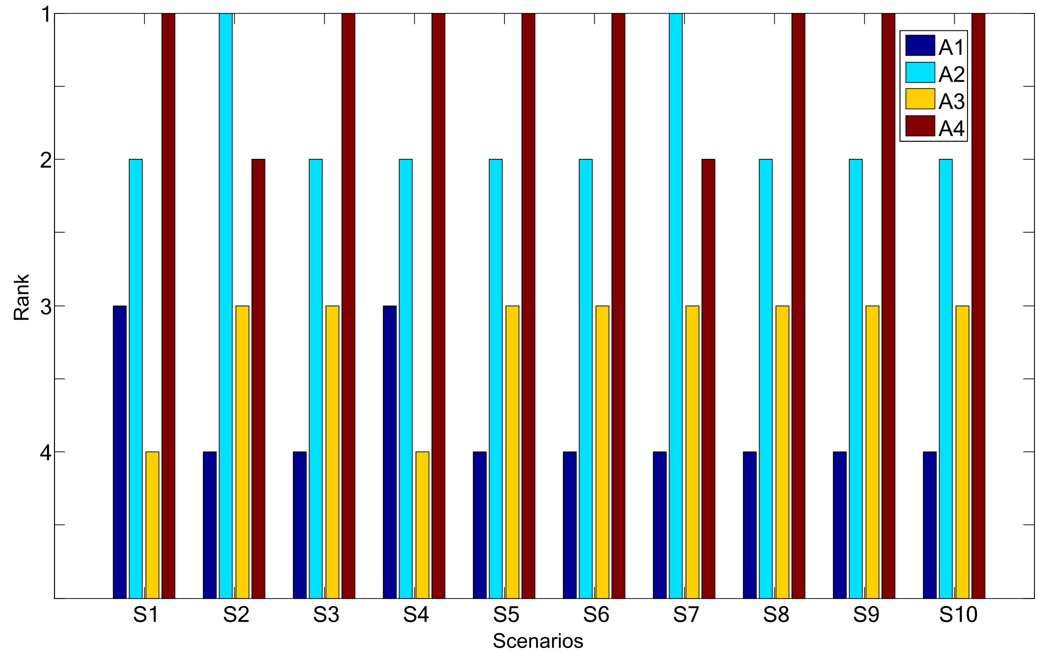

Fig. 6. Results of linear models through scenarios.

of Kahraman (2002). Thus, the weight coefficient limits of change ϖ_1 are defined according to the following $-0.25 \leq \Delta w_s \leq 0.75$. Each of the defined intervals is divided into ten sequences that represent scenarios. Based on the obtained limit values and proportions for defining the relationship between the weights of the criteria (Bakır et al., 2021), new vectors of weighting coefficients were generated in each scenario, Fig. 4.

After the calculation of new vectors of weight coefficients, the influence of each newly generated vector on the ranks of criteria and alternatives was analyzed. Fig. 5 shows the change in the criteria rankings through ten scenarios.

It can be seen from Fig. 6 that changes in the weights of experts affect the change in the rank of criteria. Similar changes are happening with alternatives. To consider the impact of these changes on the final results of the multi-criteria model, ten new linear models were generated. By solving models, the ranks of alternatives were obtained through the scenarios shown in Fig. 6.

From Fig. 6, we can see that the new weighting vectors change the final significance of alternatives. In six scenarios, the initial ranking of alternatives was confirmed, while in four scenarios, the initial ranking was violated. In scenarios S2 and S7, there were changes in the ranks of the dominant alternatives (A_4 and A_2). Furthermore, in scenarios S1 and S4, the ranking of alternatives A_1 and A_3 was disturbed, while in the dominant alternatives, there were no changes. To consider the statistical correlation of changes, the Spearman coefficient was applied (Sałabun and Urbaniak, 2020). The value of ϕ through the scenarios ranges from $0.8 \leq \phi \leq 1.0$, which indicates a high correlation of results (see Fig. 7).

The results in Fig. 7 indicate that the changes in rankings that occurred in the four scenarios are not statistically significant. The average value of ϕ through scenarios is 0.92, showing a significant correlation. Based on the presented analysis, we can conclude that the initial solution is credible and that alternatives A_4 and A_3 represent the best solutions from the considered set.

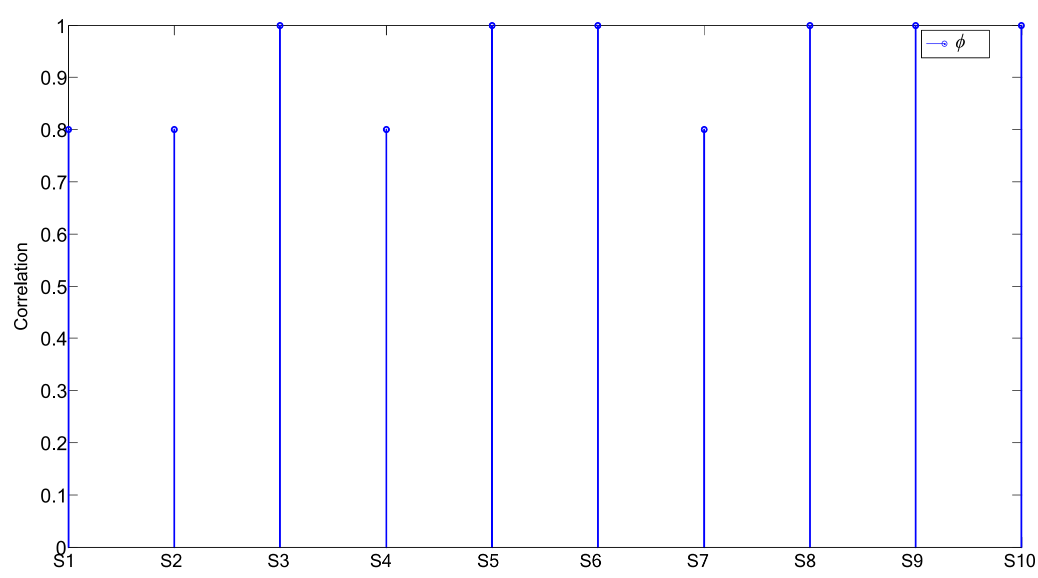

Fig. 7. Correlation of ranks across scenarios.

7. Results and discussion

According to the findings, the multimodal transport system is the least advantageous one among the alternatives. There is a growing need for integrated systems, which necessitates the integration of information, assets, and prospects. Integrating intelligent transportation systems is that separate legal restrictions and strategies for multimodal transportation stakeholder cooperation are delicate, reasonable, and significant difficulties within cross-border regions (Kramarz et al., 2021).

Synchromodality is the following least advantageous alternative. Synchromodal planning issues emerge at both the tactical and operational levels. The issues are complex. One must choose and arrange the activities to be provided, assign capacity and technology, and consider the logistics of the commodities. Challenges that cope with problems every day in a logistic system are considered in operational scheduling problems. This implies that these issues include unpredictability and stochasticity, which adds to their complexity (Guo et al., 2017).

Providing logistic hubs is the second most advantageous one. A nation's economic health is becoming heavily reliant on an adequate freight transportation infrastructure. Hubs provide the logistical solutions to support modal shifts, hence reducing roadway congestion and enhancing freight movement efficiency (Herr, 2008). Inland hubs are necessary for a much more effective freight distribution system and can help improve a town's sustainability and financial development (Long and Grasman, 2012). For example, Taiwan has used logistic hubs to promote corporate business activities and goals (Trappey et al., 2008).

Unimodality is the most advantageous alternative among the others. Transportation features, such as travel expenses and quality standards, are used as benchmarks to assess road networks. The entire transit from town to town is handled by the same vehicle, with no need for a transit point in unimodality. Unimodal road network involves cargo gathering in the starting location, and transportation from the starting location to the destination. Multimodal transportation is a competitive mode and may be adopted as an option for unimodal transportation to attain rising transport demands (Zgonc et al., 2019). A system's resilience is defined as its capacity to devote resources to respond to disruption and, as a result, reduce the volume and breadth of negative consequences (Jansuwan et al., 2021).

8. Policy implications

Because of the increased need for goods transportation, environmental challenges are gaining prominence in the supply chain. Traffic congestion in cities causes environmental degradation and higher prices. Cities become less attractive places to live because of rapid congestion, with a specific issue being the poor effect on health. There is a huge international movement toward the development of sustainable transportation (Ćirović et al., 2014).

The utilization of urban consolidation centers aims to reduce truck traffic and pollutant emissions. Many European nations, notably the United Kingdom, France, and Italy, have shown renewed focus on the notion of urban transshipment centers in the late 1990 s and early 2000 s. UCCs have the potential to reduce the overall distance traveled in metropolitan areas, as well as GHGs and local air quality issues related to these excursions. During the 1990 s, local freight operators and transport companies operating together in many towns and cities produced experiments and operational systems for German city logistics (Allen et al., 2012). In some situations, this entailed the construction of new transshipment centers, whilst in others, facilities were used and companies merely agreed on how to divide traffic (Crainic and Laporte, 1997; Crainic et al., 2004).

Substantial advancements, notably in engine and energy technology, are required. There is a need to statistically investigate approaches to low-emission freight transportation to influence potential policymaking (Yan et al., 2021).

9. Conclusion

Freight transportation strikes at the heart of manufacturing processes and economic growth (Jansuwan et al., 2021). The authorities of the European Union have claimed that current traffic habits are unsustainable in terms of climate change, economic efficiency, safety, and rising road congestion. According to the results, the most advantageous mode of transportation for freight businesses is unimodality. The whole transit from town to town is managed by a single vehicle in unimodal road transport, eliminating the requirement for a transit station. Unimodal truck transportation is appropriate for the shortest delivery lengths since there are no additional shipping costs or wait times, resulting in less logistical effort than multimodal transport.

Considering criteria weighting coefficients, increasing fuel prices, optimal use of capacity on the network, and reduction in carbon footprint are seen to be the most important criteria, which play a big role in the prioritization of alternatives. Based on the importance weights of the criteria and expert views, unimodality is selected to be the most advantageous alternative, even though integrating different transportation modes is believed to be a sustainable alternative (Givoni and Banister, 2010). The reason behind unimodality being the most advantageous rather than multimodality may be related to the fact that integration of transportation modes is not being properly sustained in many regions.

One limitation of the OPA methodology is that the prioritization of alternatives and criteria is done based on predefined ranks. In this study, the ranks of alternatives were defined based on the actual score of alternatives. For example, looking at the actual score of alternatives A_1 and A_3 under criteria C_1, we get 2.320 for A_1 and 2.374 for A_3. Therefore, alternative A_1 is third-ranked, while alternative A_3 is fourth-ranked based on the obtained values. However, if we look at actual scores, alternative A_1 has only 2.3% over alternative A_3. Therefore, it is necessary to direct future research to improve the OPA linear model that will allow the consideration of actual scores of alternatives/criteria instead of their ranks. Also, future research needs to be directed towards the implementation of rough sets and fuzzy rough sets in the OPA methodology. This would allow for an objective treatment of inaccuracies in expert estimates.

Another limitation of the study is regarding the transportation dynamics of different regions. For regions, which conduct many of their transportation needs through railway or sea transportation modes, the results of this study may change. So, the location of the study is very important considering the development of various transportation systems in the region. Therefore, the alternatives of this study should be revised according to the location of implementation.

A special emphasis is being made on minimizing CO_2 levels through a better planning process. The increasing amount of freight transport and the greenhouse effect are the primary indicators that developing a more sustainable and effective transportation network is a priority (Solvay et al., 2018). Multiple policies, including market regulations, subsidies to rail businesses, intermodal connections, and equipment assets, have been implemented at the European and national levels to aid in the modal shift to freight rail transit. Therefore, there is a need for a systematic study of low-emission freight transportation options to affect possible policies.

Freight transportation companies have increased their studies in achieving zero carbon emission. Considering these studies, optimization of freight transportation systems, directing freight transportation into more environmentally friendly modes, and setting up emission targets are seen to be the few of many methods for achieving sustainable freight transportation. Studies such as ours, which identify the important criteria that need to be considered for achieving the aim of zero carbon emission, bring various alternatives together and implement MCDM methods to advantage prioritize these alternatives, show great potential in aiding freight transportation authorities and impact of this study is demonstrated by these factors.

Considering the methodology and the opportunities brought by this study, a gap is filled in the literature by providing a guide for freight transportation authorities. However, there are still subjects related to this study that can be further developed. For instance, in future studies, different case studies can be examined with different alternatives and criteria. By doing so, this study can be made applicable in different regions.

CRediT authorship contribution statement

Dragan Pamucar: Methodology, Software, Validation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Muhammet Deveci:** Conceptualization, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Ilgin Gokasar:** Conceptualization, Validation, Formal analysis, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Luis Martínez:** Validation, Writing – original draft, Writing – review & editing. **Mario Köppen:** 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.

Acknowledgement

None

Appendix

See Table A1

Table A1
Actual score of alternatives.

Criteria	A_1	A_2	A_3	A_4
C_1	2.302	2.203	2.371	1.281
C_2	2.383	2.247	2.008	1.334
C_3	1.169	1.269	1.237	1.459
C_4	1.041	1.644	1.792	1.613
C_5	1.519	1.998	1.049	1.642
C_6	1.671	1.328	1.309	1.501
C_7	2.315	2.087	2.373	1.462
C_8	2.089	1.890	2.348	1.215
C_9	1.715	1.192	1.049	1.609
C_{10}	2.129	2.100	2.104	1.058
C_{11}	1.888	1.467	1.681	1.572
C_{12}	1.632	1.192	1.624	1.529
C_{13}	1.204	1.281	1.406	1.539
C_{14}	1.555	1.042	1.367	1.595

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