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Decision support

Fueling the future: Overcoming the barriers to market development of renewable fuels in Germany using a novel analytical approach

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ABSTRACT

Germany has set ambitious targets for reducing greenhouse gas (GHG) emissions, namely by 65% until 2030 (compared to the 1990 level) and achieving climate neutrality by 2045. Although GHG emissions have decreased in most sectors, the transport sector has experienced failed reduction attempts. Renewable fuels are promising sustainable fuel alternatives that can replace current market-dominant fossil fuels to reduce GHG emissions. However, the market development of renewable fuels is hindered by various economic, environmental, technical, regulatory, and social barriers. Using a novel holistic approach, this study aims to analyze the market development barriers for renewable fuels in the German transport sector. First, a novel extension to the decision making trial and evaluation laboratory (DEMATEL) method is proposed using the Type-2 Neutrosophic Numbers (T2NN), which is improved by the K-means algorithm. Second, the maximum mean de-entropy algorithm is applied to convert the results of T2NN-DEMATEL into input for interpretive structural modeling (ISM). Next, a case study is conducted to analyze the impacts of barriers on different transport modes using the T2NN-based additive ratio assessment. Extensive sensitivity analyses are conducted to measure the impacts of different factors under different circumstances. The obtained results indicate that insufficient renewable energy policies and regulations, the lack of coordination in the supply chain, and high technology conversion challenges are the most significant barriers. Moreover, road and maritime transport are affected more than the aviation and rail sectors by the market development barriers.

1. Introduction

Climate change is the most critical ecological challenge the world is facing today. Especially in the transport sector, the persistent utilization of fossil fuels has posed a significant challenge by keeping greenhouse gas (GHG) emissions high (Zheng et al., 2019). Although various efforts had been made, the Paris Agreement explicitly called for unified action for the global reduction in emissions by shifting to renewable energies. Increasing energy consumption due to population growth, urbanization, and advancements in industries has become a great matter of concern for all countries, considering the unfavorable impacts of fossil fuels. The initialization of the Paris Agreement led to the introduction of several global policies to combat GHG emissions, including the Sustainable Development Goals (SDGs). On the global scale, the European Union (EU) is a pioneer in regulating and implementing the required measures to reduce GHG emissions across all sectors. For this purpose, the EU has made great efforts since the early 2010s to provide the required policy paradigms in order to regulate emission across all sectors. Specifically, the EU set two significant targets: to reduce GHG emissions by 55% (compared to the 1990 level) by 2030, and to achieve climate neutrality by 2050 (European Commission, 2021a). These targets are addressed by a portfolio of policies, while the Fit for 55 package and the EU Green Deal can be considered the pivots in the European policy framework (European Commission, 2021a, 2021c; Hainsch et al., 2022).

In Germany, as one of the key member states of the EU, the efforts to reduce emissions and move towards sustainability date back to the early 1990s, when the Electricity Feed-in Act was passed. At the time, Germany started to transition from fossil energies to renewable energies, a process now coined as the German Energiewende, driven by several policies, e.g., the Renewable Energy Act (EEG) (Hake, Fischer, Venghaus, & Weckenbrock, 2015; Joas, Pahle, Flachsland, & Joas, 2016). The Climate Action Plan is the current policy framework for decarbonization across all sectors in Germany (BMUV, 2016). Recently, the German government intensified its previous target to a 65%

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reduction in GHG by 2030 (compared to the EU's 55% target) and achieve climate neutrality by 2045 (5 years prior to the EU) (BMF, 2021). Germany has successfully decreased GHG emissions in several sectors, including energy, industry, households, agriculture, and waste. However, previous efforts to mitigate GHG emissions in the transport sector have not led to favorable developments. GHG emissions in the transport sector have stayed roughly at the level of 1990, with a minor decrease from 165 million tons of carbon equivalents to roughly 149 million tons of carbon equivalents in 2021 (an overall share of 19%) (Umweltbundesamt, 2022). Failure to achieve the previous targets in the German transport sector constitutes a key challenge to reducing total emissions to 438 million tons of carbon dioxide equivalents by 2030. Phasing out fossil fuels in the transport sector is the main obstacle to achieving emission reduction in the German transport sector. Moreover, the increase in the number of registered combustion engine-based vehicles, the failed target of 1 million registered electric vehicles (EVs) in 2020 (objective of the German Federal Government's National Electromobility Development Plan), and missing opportunities to support the deployment of renewable fuels are the further major challenges and obstacles that have hindered Germany from decreasing emissions.

Replacing fossil fuels with renewable fuels is an important milestone for Germany to address its high emissions in the transport sector (Hansen, Mathiesen, & Skov, 2019; Michalski, Poltrum, & Bünger, 2019). Renewable fuels cover a broad range of low-carbon and, in particular cases net-zero emission fuels. Advanced biofuels (second and third generation), Power-to-X (PtX) fuels, and hydrogen are the most well-known renewable fuel alternatives. The Renewable Energy Directive (RED) is the central EU framework supporting renewable fuels (Chiaramonti & Goumas, 2019; European Commission, 2021b; Long, Bose, O'Shea, Monaghan, & Murphy, 2021), which can be considered one of the initial EU policies addressing renewable energies (European Commission, 2009, 2018). Recently, within the Fit for 55 package, the EU launched significant initiatives, FuelEU Maritime and ReFuelEU Aviation, to exclusively support the implementation of renewable fuels in maritime and aviation (European Commission, 2021d, 2021f). Moreover, the Fit for 55 package also included a revision of the regulation on the deployment of alternative fuels infrastructures, which supports infrastructure requirements for renewable fuels (European Commission, 2021e). Nevertheless, various challenges represent barriers to the diffusion of renewable fuels in different transport modes. Although initial regulatory frameworks to support renewable fuels are provided by the German government and the EU, the fuel market dominated by fossil fuels remains an obstacle (Gordon, Balta-Ozkan, & Nabavi, 2023; Johnsson, Kjärstad, & Rootzén, 2019).

Understanding the dynamics affecting the market development of renewable fuels is significant to making them competitive with fossil fuels. However, renewable fuels are still in early development stages and currently face various technical, economic, environmental, social, and regulatory challenges that need to be addressed for a successful implementation (Klein-Marcuschamer & Blanch, 2015; Ueckerdt et al., 2021). Thus, investigating the market development barriers during the adoption and diffusion processes is crucial for strategic decision-making in favor of renewable fuels. The investigation of interactions among market development barriers for renewable fuels can be formulated as a multi criteria decision analysis (MCDA) problem (Cinelli, Kadziński, Miebs, Gonzalez, & Słowiński, 2022; Irawan, Jones, Hofman, & Zhang, 2023; Liu, Liao, & Yang, 2015; Sahoo & Goswami, 2023; Shao et al., 2020). The necessity to investigate market development barriers in a multi-dimensional framework considering social, environmental, economic, and political aspects has led to a formulation of the problem as an MCDA problem. In this regard, the decision making trial and evaluation laboratory (DEMATEL) and interpretive structural modeling (ISM) are two well-known techniques that can be used for the investigation of dynamics and interrelationships among market development barriers in a complex system (Mondal, Giri, & Roy, 2023; Trivedi, Jakhar, & Sinha, 2021).

For an MCDA problem, relying on decision-makers and experts to offer precise values for pairwise comparison is the most critical challenge (Chi & Chien, 2023; Lami & Todella, 2023; Wang, Jia, & Song, 2022; Yang et al., 2023). Fuzzy set theory is a well-known concept used to eliminate the ambiguity, impreciseness, and subjectivity of human judgment through the utilization of linguistic terms (Zadeh, Klir, & Yuan, 1996). Although traditional forms of fuzzy set theory have been frequently used for the investigation of MCDA problems, the concept of type-2 neutrosophic numbers (T2NNs) is one of the most recent and advanced uncertainty sets, with better performance at handling ambiguity and poor precision of information in real-world applications (Abdel-Basset, Saleh, Gamal, & Smarandache, 2019). In contrast to other fuzzy sets and neutrosophic sets, T2NN has definite advantages in processing complex, ambiguous, and indeterminate information. One of the primary advantages of T2NN is their triple-membership representation, which captures truth, indeterminacy, and falsity. Moreover, the T2NN takes it another step further and represents each membership function with triangular numbers for better and precise consideration of the information. Due to the structure of the T2NNs, it is possible to describe the degree of ambiguity and inconsistency inside a given set at a finer granularity, outperforming traditional neutrosophic sets and offering an improved decision support. This is especially useful in real-world situations where information is frequently layered and multi-dimensional. Next, the reliability and quality of the data used in the decision-making process can be better understood by the decision-makers. This, in turn, leads to more informed and robust decision outcomes. Contrarily, fuzzy sets and traditional neutrosophic sets do not offer this level of understanding of the nature of uncertainty and may offer less reliable support in difficult decision-making situations.

Therefore, a novel extension of DEMATEL based on T2NN (T2NN-DEMATEL) is presented in this study for a comprehensive investigation of market development barriers for renewable fuels using more flexible and accurate linguistic terms given the way of human thinking. DEMATEL enables a granular analysis, uncovering nuances and subtleties within a complex system. Traditional DEMATEL applies an average- or expert-based technique to identify a single threshold for the determination of interrelationships among market development barriers and the identification of impact types of barriers on each other. However, both techniques lack a rigorous scientific approach to determine a proper threshold for further elaboration, considering the possible subjectivity of data and information loss (Wu, Liao et al., 2022; Wu, Liu et al., 2022; Yong, Wu, Zhou, Tao, & Chen, 2023). Accordingly, a tool is required to replace the average- or expert-based techniques and highlight the characteristic of pairwise values in the total relation matrix of the T2NN-DEMATEL. This study improves the developed T2NN-DEMATEL using the K-means clustering algorithm to identify realistic thresholds to classify barriers into various impact groups with different degrees. To develop a better understanding of the impacts of barriers, four impact groups called relatively slight, slight, relatively strong, and strong are considered. The K-means algorithm offers a quantitative method for grouping data points into distinct groups, making it possible to define optimal thresholds quickly and easily, which can improve the data segmentation and decision-making procedures. Later, a sensitivity analysis is conducted to analyze the performance of the K-means algorithm in determining the impact groups using other clustering algorithms, namely the K-medoids and the Agglomerative Hierarchical algorithm.

Although the improved T2NN-DEMATEL by the K-means algorithm provides deep and detailed insights into dynamics within market development barriers, strategic decision-making requires tools to provide a macro-level analysis as well. In this regard, this study applies a well-known tool called ISM (Xu & Zou, 2020). ISM and DEMATEL are distinct yet related methodologies. To provide a micro-level view of the problem, DEMATEL primarily focuses on establishing complex causal interrelationships across all barriers. ISM, on the other hand, focuses on building significant interrelationships across barriers, capturing the impact of barriers from a macro-level perspective. The application of ISM emphasizes how well it can act as a complementary method to DEMATEL by offering a macro-level perspective for strategic policy-making purposes. While the macro-level perspective from the ISM drives broader strategies and policies, the micro-level perspective from DEMATEL focuses on specific actions and interventions. This dual-level analysis ensures that the decisions made are not only well-informed but also implementable at both micro- and macro-levels. Finally, the utilization of both DEMATEL and ISM can be useful in validating the results obtained by both methods. In other words, the consistency and reliability of the findings can be enhanced by contrasting the micro-level causal links discovered by DEMATEL with the macro-level interrelationships generated by the ISM.

Given the different nature of the input data used in ISM, previous studies have mainly used either the average-based threshold or an expert-based threshold to convert the results of DEMATEL as input for the ISM, or the results of ISM as input for the DEMATEL (Kumar & Dixit, 2018; Li & Tzeng, 2009; Manoharan, Pulimi, Kabir, & Ali, 2022; Wang, Cao, & Zhou, 2018). However, using average-based or expert-based thresholds raises concerns regarding the risk of overlooking potential impacts or focusing on the wrong impacts among barriers in the macro-level analysis. Moreover, utilizing the expert-based threshold lowers the time efficiency of the analysis and increases the possibility of subjectivity in the threshold value based on experts' professional backgrounds. To address this issue, the maximum mean de-entropy (MMDE) algorithm is used to convert the results of the T2NN-DEMATEL into input for the ISM with higher reliability and accuracy (Li & Tzeng, 2009). For this purpose, the MMDE algorithm determines an optimal threshold based on identifying the pairs (originating barrier and receiving barrier) with the highest mean de-entropy values. Furthermore, the cross-impact matrix multiplication applied to classification (MICMAC) analysis is used to classify the market development barriers in the macro-level analysis. In order to provide insightful information on the influence and dependence patterns within the ISM, the MICMAC assists in classifying elements as drivers, dependent, or autonomous. By classifying elements according to their functions and significance, this information improves the interpretability of the ISM outcomes and makes prioritization and decision-making more accurate. Essentially, the MICMAC contributes to a deeper understanding of the examined system by adding an additional layer of understanding to the dynamics and influence of the interrelated aspects of the ISM.

Although understanding the impacts of market development barriers for renewable fuels empowers policymakers to develop the required plans in favor of the sustainable transition in the transport sector, there is the need to develop proper frameworks for addressing the barriers considering different characteristics of transport modes, including road, rail, aviation, and maritime. In this regard, this study aims to conduct an analysis of the impacts of market development barriers in road, rail, aviation, and maritime. The goal is to analyze the degree to which a transport mode is affected by the barriers and sort them accordingly. Evaluating and sorting the transport modes against the identified market development barriers can be addressed as an MCDA ranking problem, where the barriers can be considered as decision criteria and transport modes can be accounted for as decision alternatives. Various MCDA ranking methods exist to tackle similar problems (Corrente, Greco, & Słowiński, 2016; Fernández, Figueira, Navarro, & Roy, 2017; Joshi & Kumar, 2016; Ru, Liu, Kadziński, & Liao, 2023). In this study, we apply additive ratio assessment (ARAS), which is one of the well-known MCDA methods, considering its reliability based on well-established and time-tested extensive applications. Its simplicity and transparency are two important features allowing decision-makers to comprehend the ranking process and the factors influencing the final decision. Additive ratio based ranking scores of ARAS provide a method that allows accounting for trade-offs between decision factors. In addition, ARAS has lower computational complexity compared to the existing ranking MCDA methods, outweighing the need for more complex and time-intensive methods. As mentioned before, MCDA problems are subject to the subjectivity and ambiguity of information offered by decision-makers and experts. So, a novel extension of ARAS based on the T2NNs (T2NN-ARAS) is suggested. For MCDA problems, weight coefficients play a significant role in determining the final performance of alternatives against decision criteria. For this purpose, weight coefficients for the decision criteria (market development barriers) are determined using the developed T2NN-DEMATEL. Later, the impact of weight coefficients is assessed by two different methods: Shannon's Entropy and CRiteria Importance Through Intercriteria Correlation (CRITIC). Both Shannon's Entropy and CRITIC are well-known objective methods to determine the weight coefficients that eliminate the potential bias of using subjective methods. Finally, the performance of T2NN-ARAS as a ranking MCDA method is compared with a T2NN-based aggregation method, T2NN-based weighted aggregated sum product assessment (WASPAS), and a T2NN-based technique for order of preference by similarity to ideal solution (TOPSIS).

The main contributions of this study are:

- Introducing a novel holistic analytical approach for barrier analysis.
- Applying the developed approach to identify and analyze the market development barriers for renewable fuels in Germany.
- Developing an advanced extension of DEMATEL (T2NN-DEMATEL) to provide higher flexibility to experts through accurate and reliable human-mode thinking lingual expressions.
- Improving T2NN-DEMATEL by using the K-means algorithm to classify barriers in appropriate impact groups.
- Utilizing the MMDE algorithm for the conversion of T2NN-DEMATEL results into input for the ISM.
- Suggesting a novel extension of ARAS (T2NN-ARAS) for the evaluation of transport modes against market development barriers.
- Conducting a sensitivity analysis based on the impacts of experts' opinions, comparing results of the K-means clustering algorithm with the K-medoids algorithm and the Agglomerative Hierarchical algorithm, measuring the impacts of the importance of market development barriers using Shannon's Entropy and CRITIC methods, and providing a comparative analysis for evaluation of transport modes based on T2NN-ARAS using three MCDA methods with the Spearman's rank correlation coefficient.
- Proposing recommendations to improve the market development of renewable fuels in Germany based on the obtained results.

All in all, the objective of this study is to address market development barriers for renewable fuels as potential pathways for decarbonizing the German transport sector. This objective is achieved through a holistic analytical approach that enables policymakers to investigate dynamics among multi-dimensional market development barriers, considering the opinions of experts. The approach is of benefit to policymakers given its applicability to both other regions as well as different sectors.

The rest of the paper is organized as follows: Section 2 presents a literature review on studies related to market development of renewable fuels. Section 3 presents preliminaries and descriptions for the developed approach. A case study including context definition, barrier analysis, evaluation of transport modes and extensive sensitivity analyses are presented in Section 4. Managerial and regulatory insights are presented in Section 5. Finally, conclusion remarks are presented in Section 6.

2. Literature review

Recently, the market development analysis of fuels has become a growing field given the need to understand the critical dynamics affecting future energy markets. In this regard, investigating the impacts of barriers for market development (adoption and diffusion) is significant for policy-making and strategic decision-making. Considering the complexity of real-life markets, a comprehensive market development analysis of barriers should not only focus on technical barriers but also take economic, environmental, social, and political aspects into account. On the other hand, addressing market development barriers through quantitative and qualitative techniques is another concern that should be considered carefully. Thus, analyzing market development barriers comprehensively would require tools that can address such multi-dimensional and stakeholder-centered problems. Here, the most important recent studies addressing relevant problems are summarized.

Browne, O'Mahony, and Caulfield (2012) comprehensively analyzed barriers to alternative fuels under a policy framework to promote innovative fuel and vehicle technologies. Identified barriers were first categorized into financial, technical/commercial, institutional/administrative, public acceptability, regulatory, policy failures, and physical groups. Then, an evaluation framework was developed based on several criteria such as timeline, level of subsidiarity, type of required policy measure, actor, national relevance, and significance. Next, another evaluation framework was constructed for policy priorities based on timeline, type of policy, cost to consumer, cost to public, modal shift, GHG reduction potential, and impact on rural communities and socio-economic groups. Finally, the policies and regulations were categorized into several policy paradigms including technology-forcing (e.g., vehicle and fuel standards), economic (e.g., tax, subsidies, incentives), procurement (e.g. sustainable public transport), collaborative (e.g., network management, public–private partnership), and communication and diffusion (e.g., media publicity, awareness campaign) instruments. Scheelhaase, Maertens, and Grimme (2019) studied the potential of PtL (power-to-liquid) fuels in aviation. According to their findings, several barriers including high climate impact, limited availability, lack of investment, high investment risks, lack of incentives and regulations, certifying new fuels based on standards, high fuel cost, and lack of policies were hindering the adoption of PtL fuels in aviation. In this regard, introducing monetary and non-monetary incentives for development, production and utilization of synthetic fuels was significant for stabilizing the market for a new fuel. Demeulenaere (2019) applied rapid evidence assessment to investigate the utilization of automotive fleets for the diffusion of alternative fuels-based vehicles by identifying the barriers and enablers. Saccani, Pellegrini, and Guzzini (2020) investigated market development barriers for P2H (power-to-hydrogen) in Italy. Considering P2H production, storage, and transport to the final consuming points, barriers were categorized into economic, technical, operational, and social barriers. Economic barriers were exclusively concerned with investment and operative costs depending on the production technologies. The main technical barrier was related to the low efficiency of P2H fuels. Finally, operational and social barriers were concerned with lack of policies and strategies for P2H market regulations. Several recommendations were made to facilitate addressing the barriers through tax deduction, supporting incentives for the whole P2H supply chain, increasing R&D funding to improve the efficiency and safety of the fuels, and preparing a specific procedure for P2H projects. Social barriers seemed to be more complex and no suggestions were provided except increasing public awareness about the benefits of the P2H. Nouni et al. (2021) reviewed policy frameworks to identify opportunities and challenges against the development of alternative fuels including biofuels, CNG (compressed natural gas), biogas, EVs, hydrogen, and methanol in the Indian road transport sector. Results indicated that EVs and biofuels were reliable options for the current road transport while, CNG could be beneficial in short-term and hydrogen could play a significant role in the long-term. The challenges for each fuel were summarized as (i) ethanol and biodiesel suffer from suitable feedstock and storage infrastructures, (ii) CNG suffers from infrastructural requirements as well as high dependency on import LNG (liquefied natural gas), (iii) methanol is still not commercial in India so it lacks economic viability, (iv) electricity and hydrogen face various challenges such as technical properties regarding Li-ion batteries, driving range, refueling time and required infrastructures, cost of ownership, governmental support, operation and maintenance costs, and public acceptance. Using the barrier categories provided by Browne et al. (2012), Takman and Andersson-Sköld (2021) analyzed the opportunities and barriers for liquefied biogas for heavy trucks in Sweden. Environmental benefits, profitability, and new policies in favor of alternative fuels were some of the most important opportunities. On the other hand, financial issues, an unstable policy context, lack of infrastructure, and lack of knowledge in alternative fuels were the major barriers. To accelerate the market diffusion of alternative fuels in Sweden, improving knowledge generally in renewable energies and biogas value chains was suggested.

Gegg, Budd, and Ison (2014) identified drivers and barriers for market development of biofuels in aviation based on extensive qualitative interviews with 25 experts in aviation from Europe and North America. Main drivers were carbon reduction potential, energy security, unstable oil price, legislation, new business opportunities, and lack of alternative fuels. On the other hand, high production costs, lack of investment, sustainable feedstock supply, lack of policy and legislation, environmental challenges, and lack of supply chain certification were named as the most crucial barriers. Fenton and Kanda (2017) used a qualitative approach based on interviews to analyze the barriers to market diffusion of biogas in transport system of Basel, Switzerland and Odense, Denmark. The study identified 21 barriers under technology, system-level, actor-level, and business perspective. Results for Basel indicated that limited attention had been given to biogas in transport due to large-scale utilization of biogas for the heating. Although biogas was initially planned to be used in the transport sector, the shift to the heating sector put an obstacle for further development of biogas. Political actions promoting diesel and hybrid transport were the main reasons for the low development of biogas in transport. In Odense, the biogas was used in form of bio-natural gas where it was blended with natural gas. The city had made the required efforts to construct biogas plants for short-term demands. However, high investment for production plants and high taxes on natural gas were two main barriers for biogas in Denmark. Saravanan, Mathimani, Deviram, Rajendran, and Pugazhendhi (2018) conducted a comprehensive literature review on policy barriers for biofuels in India. Main policy barriers for biofuels were land-use challenges for the biofuel crops, technical difficulty in feedstock cultivation, the tax system, feedstock suitability based on the food vs. fuel debate as well as legal debates on the definition of biofuels in Indian policies. Funding for R&D for producing ethanol from different crops and increasing availability of feedstock using short generation biofuels crops, and a uniform tax system were effective ways to facilitate the development of biofuels in India. Leibensperger, Yang, Zhao, Wei, and Cai (2021) conducted an experimental study based on stakeholders' interactions for development of biofuels in the United States considering the producers, consumers, bio-refineries, rural communities, and the government. Several barriers were identified for producers including long-term contracts with bio-refineries, the existence of local markets, the willingness to take risks, high initial investment for growing bioenergy crops, and knowledge of bioenergy crops. Local communities identified unstable economy, resource constraints on future expansion, and impact of bio-refineries on quality of life and community standards as barriers for biofuels development.

Narwane, Yadav, Raut, Narkhede, and Gardas (2021) applied DEMATEL, ISM, and MICMAC to analyze the sustainable development of biofuels in India. They identified 38 barriers that affected the development of biofuels. A two-stage data collection was used for DEMATEL and ISM. As data aggregation in ISM is not possible compared to DEMATEL, the law of majority was used to construct the final reachability matrix. The results indicated that lack of governmental support for sustainable supply chain solutions, lack of subsidies and incentives to increase competitiveness of bio-energy, lack of support for entrepreneurial activities, and lack of biomass supply chain standards were the most critical barriers. One of the shortcomings of this study was the utilization of majority law to construct the final reachability matrix, where some experts' opinions may be ignored that can strongly affect the solutions. Irfan et al. (2022) suggested an integrated approach based on the Delphi technique, analytical hierarchy process (AHP) and TOPSIS under gray environment to analyze and prioritize the barriers for biomass energy barriers. The identified 24 barriers were categorized into technological & infrastructural, economic & financial, political & institutional, and cultural & behavioral groups. Results indicated that technological complexity was the most important barrier that can be addressed through providing funding for the R&D. Raj, Dan, and Kumar (2023) used an integrated MCDA approach based on DEMATEL and TOPSIS for a feasibility analysis of alternative fuels-based vehicles in India. Fourteen factors were identified to measure the feasibility based on economic, environmental, social, and technical aspects. Using DEMATEL, factors were categorized into cause and effect groups, and their relative weight coefficients were identified. With the obtained weight coefficients, experts were invited to evaluate EVs, hydrogen vehicles, solar vehicles, and biofuels-based vehicles against the identified factors. The results indicated that EVs were favored over other alternative fuels vehicles. An important limitation of this study was related to the limited list of alternative fuels-based vehicles and technologies that were evaluated. Moreover, no factor addressed the political perspective for the alternative fuels-based vehicles.

Although various studies have been conducted to address the analysis of barriers in the context of renewable fuels, no study has aimed to generally address their market development considering biofuels, PtX fuels as well as hydrogen in Germany. As discussed, various approaches have been suggested; however, this study presents a robust approach addressing shortcomings of previous approaches in the literature through improved T2NN-DEMATEL by the K-means algorithm, the MMDE algorithm, ISM, and T2NN-ARAS.

3. Methodology

This section presents the preliminaries and steps for the implementation of the developed approach.

3.1. T2NN-DEMATEL improved by K-means algorithm

Between 1972 and 1976, the Geneva research center of the Battelle Memorial Institute developed the DEMATEL method as a mathematical approach for analyzing causal relationships in complex systems through the use of graphs and pairwise information to resolve related issues and challenges more efficiently. DEMATEL uses input data regarding the interactions of critical factors to build up cause and effect groups in a structured, hierarchical manner. From a systematic perspective, DEMATEL conducts a micro-level analysis by incorporating all interactions among the critical factors to understand systems' behavior. In this regard, DEMATEL has been known as a reliable technique to address various multi-dimensional problems in different systems across multiple sectors, such as e.g., renewable energy development (Dinçer, Yüksel, & Eti, 2023; Narwane et al., 2021), urban planning (Ferreira, Spahr, Sunderman, Govindan, & Meidutė-Kavaliauskienė, 2022), industrial management (Nezhad, Nazarian-Jashnabadi, Rezazadeh, Mehraeen, & Bagheri, 2023; Singh & Bhanot, 2020), and transport management (Trivedi et al., 2021).

A novel extension of DEMATEL method under the T2NNs (Appendix A) can be applied using the following steps:

Step 1. Establishment of an initial direct-relation matrix (A). Experts are supposed to provide a pairwise matrix for rating the relationships among barriers using the linguistic T2NN scale in Table 1. Thus, the initial matrix will be an $n \times n$ which can be called as $X^e = [x_{ij}^e]$, where e denotes the expert and x_{ij} represents relationship between barrier i and j. Next, collected data from experts are aggregated into a single initial direct-relation matrix where all experts are considered equal (Eq. (1)).

Table 1
Linguistic scale for relationship among barriers.

Linguistic term	T2NN value
No influence (NI)	$<(0.1,\ 0.2,\ 0.2),(0.7,\ 0.8,\ 0.9),(0.55,\ 0.85,\ 0.95)>$
Low influence (LI)	$<(0.4,\ 0.3,\ 0.25),(0.45,\ 0.55,\ 0.4),(0.45,\ 0.6,\ 0.55)>$
Medium influence (MI)	$<(0.65,\ 0.55,\ 0.55),(0.4,\ 0.45,\ 0.55),(0.35,\ 0.4,\ 0.35)>$
High influence (HI)	$<(0.8,\ 0.75,\ 0.7),(0.2,\ 0.15,\ 0.3),(0.15,\ 0.1,\ 0.2)>$
Extreme influence (EI)	$<(0.9,\ 0.85,\ 0.9),(0.1,\ 0.15,\ 0.1),(0.05,\ 0.05,\ 0.1)>$

$$a_{ij} = \frac{1}{E}\sum_{e=1}^{E} x_{ij}^e \tag{1}$$

where E denotes total number of experts and a_{ij} shows the aggregated value for the elements of matrix A.

Step 2. T2NN values in the aggregated initial direct-relation matrix are converted to crisp values via Eq. (A.8).

Step 3. Normalization of the aggregated initial direct-relation matrix into normalized direct-relation matrix (D) (Eq. (2)).

$$D = A\pi \tag{2}$$

where

$$\pi = Min\left[\frac{1}{max\sum_{j=1}^{n} a_{ij}}, \frac{1}{max\sum_{i=1}^{n} a_{ij}}\right] \tag{3}$$

Step 4. Computation of total relation matrix (T) using the matrix D (Eq. (4)).

$$T = D(I - D)^{-1} \tag{4}$$

where I denotes the identity matrix.

Step 5. Determination of prominence $(r+c)$ and relation $(r-c)$ values using Eqs. (5)–(6).

$$R = [r_i]_{n\times 1} = \left[\sum_{j=1}^{n} t_{ij}\right]_{n\times 1} \tag{5}$$

$$C = [c_i]_{1\times n} = \left[\sum_{i=1}^{n} t_{ij}\right]_{1\times n} \tag{6}$$

Using prominence $(r+c)$ and relation $(r-c)$ values, barriers can be categorized into cause and effect groups such that barriers with positive $(r-c)$ are placed in the cause group and barriers with negative $(r-c)$ are considered in the effect group. In the same way, $(r-c)$ values can be used to sort the barriers from highest importance to lowest importance. Next, average value of the total relation matrix is used to convert its values into binary 0–1 values in order to derive the interrelationships among barriers.

Step 6. Although an average-based threshold or an expert-based threshold is mainly used to elaborate the causal relationships, the lack of scientific justification on using an average-based or expert-based threshold may lead to biased results through missing information. On the other hand, the average-based or expert-based threshold classifies the causal relationships into two groups by ignoring smaller causal relationships and keeping the larger ones. Nevertheless, a detailed understanding of all causal relationships is critical in real-life applications in order to detect different degrees of causality through several thresholds. Therefore, the K-means algorithm is used to analyze the results of T2NN-DEMATEL with better thresholds. The K-means algorithm is one of the most well-known efficient clustering methods in the fields of data mining and machine learning. The K-means is an unsupervised clustering algorithm that aims to determine the optimal set of points that minimizes the distances from each point to its nearest center. The algorithm partitions a set of data into k cluster such that each data point is allocated to only one cluster. For a data set in the form of $X = \{x_j\}$, K-means algorithm first starts by randomly choosing the m data points to be the center of clusters. Next, every m is clustered into k clusters based on minimum squared error criterion measuring the distance between a data point and the cluster center. The new mean of each cluster is computed, and the procedure continues until the cluster centers remain unchanged. At this point, the within-cluster sum of squares (WCSS) is calculated using Eq. (7).

$$WCSS(C_i) = \sum_{x_j \in C_i} || x_j - \alpha_i || \tag{7}$$

where C_i denotes cluster i, and α_i indicate the mean of data points in cluster C_i.

The main goal is to minimize the sum of the squared error within k clusters based on Eq. (8).

$$\min(WCSS(C_i)) = arg \min_{c} \sum_{i=1}^{k} \sum_{x_j \in C_i} || x_j - \alpha_i ||^2 \tag{8}$$

Next, to generate a new partition by assigning observed data points to their closest cluster center, Eq. (9) must hold for the sum of squared error.

$$C_i^t = x_j \ : || x_j - m_i^t || \leq || x_j - m_{i*}^t || \tag{9}$$

where m_i^t denotes the mean of ith cluster in tth iteration, and C_i^t shows all data points in the ith cluster in tth iteration.

Finally, the new mean centers are determined based on Eq. (10).

$$m_i^{t+1} = \frac{1}{| C_i^{t+1} |} \sum_{x_j \in C_i^t} x_j \tag{10}$$

where m_i^{t+1} indicates the mean of the ith cluster in tth iteration, and C_i^{t+1} shows all data points in the ith cluster in tth iteration.

Thresholds are determined based on the identified clusters for a detailed elaboration of the total relation matrix of T2NN-DEMATEL (Wu, Liao et al., 2022; Wu, Liu et al., 2022; Yong et al., 2023). The identified thresholds are used to classify the impact degrees of barriers on each other using four groups of slight, relatively slight, relatively strong, and strong (Wu, Liu et al., 2022).

3.2. MMDE-ISM-MICMAC

DEMATEL provides a micro-level perspective of the interactions of the barriers in a complex system, while a macro-level perspective of the system may be required for strategic policy-making. In this regard, ISM is one of the well-established statistical macro-level techniques to analyze the interrelationships among barriers to understand the challenges and issues needed to address the system properly (Warfield, 1974). Soon after its development, ISM showed very successful performance in addressing complex problems and has been applied for various applications such as e.g., transport (Trivedi et al., 2021), energy management (Xu & Zou, 2020), and supply chain management (Ali, Hossen, Mahtab, Kabir, Paul, et al., 2020). In contrast to the DEMATEL that gets different values to establish the initial matrix, the ISM gets only 0 and 1 values based on four possible relationships between factors to construct structural self-interaction matrix (SSIM). For two barriers B_1 and B_2, four relationship values are possible according to

- V: Barrier B_1 will facilitate to attain Barrier B_2;
- A: Barrier B_2 will facilitate to attain Barrier B_1;
- X: Barriers B_1 and B_2 will facilitate to attain each other;
- O: Barriers B_1 and B_2 have no relation.

where V and X get 1 and A and O are shown by 0 in the SSIM.

Considering the input type of the ISM, data collection must be repeated to collect the required data for the ISM using the above-mentioned format. To decrease the complexity of the data collection process, a threshold value may be determined to utilize the aggregated initial direct-relation matrix for the SSIM. Although there are several ways to determine a threshold value, a scientific technique is required to avoid any potential subjectivity and bias leading to the wrong solutions. For this purpose, the MMDE algorithm developed by Li and Tzeng (2009) is a well-known technique that can be used to determine a robust threshold value. The MMDE algorithm can be implemented based on the following steps.

Step 1. Conversion of the $n \times n$ total relation matrix (D) into an ordered set $T = \{t_{11}, t_{12}, \dots, t_{nn}\}$ from largest to smallest value. Next, all ordered values are transformed into ordered triplets in the form of (t_{ij}, x_i, x_j) where x_i denotes dispatch node (affecting barrier), and x_j represents receiver node (affected barrier).

Step 2. Constructing an ordered dispatch node set based on dispatch nodes in the initial ordered set, which can be shown as T^{D_i}.

Step 3. Beginning with the first element of T^{D_i}, the probability of different elements can be determined in each set. First, the value of t is determined by assigning it as 1 and then increasing the value from 1 to $C(T_{D_i})$ (cardinal number of an ordered set) in increments of 1. Later, the mean de-entropy value of set $T_t^{D_i}$ is determined by $MDE_t^{D_i} = \frac{H_t^{D_i}}{N(T_t^{D_i})}$, where $H_t^{D_i}$ denotes the de-entropy value of set $T_t^{D_i}$, and $N(T_t^{D_i})$ shows cardinal number of different elements in a set. In this regard, the entropy function can be defined as Eq. (11).

$$H(p_1, p_2, \dots, p_n) = -\sum_{i=1}^{n} p_i log(p_i) \tag{11}$$

where

$$\sum_{i=1}^{n} p_i = 1 \tag{12}$$

$$p_i log(p_i) = 0 \quad if \quad p_i = 0 \tag{13}$$

De-entropy function can be defined accordingly based on Eq. (14).

$$H^D = H(\frac{1}{n}, \frac{1}{n}, \dots, \frac{1}{n}) - H(p_1, p_2, \dots, p_n) \tag{14}$$

The probability of a dispatch node shown as x_i can be determined using $p_i = \frac{k}{m}$, where m is the cardinality of an order set, and k is the frequency of element x_i.

Step 4. The MMDE value and its corresponding $T_t^{D_i}$ are identified and denoted as $T_{max}^{D_i}$.

Step 5. A similar procedure is applied for an ordered receiver node set T^{Re}. Next, the MMDE value and its corresponding set is represented by T_{max}^{Re}.

Step 6. The first element in set T^* is selected as the subset T^{Th} which includes all elements in $T_{max}^{D_i}$ and T_{max}^{Re}, the minimum influence value in T^{Th} is the threshold value with $1 < C(T^{Th}) < C(T^*)$.

Step 7. Using the threshold value from the MMDE algorithm, the initial reachability matrix is constructed by 1 and 0 values. In this regard, elements larger than the threshold value in the total relation matrix are changed to 1 and the rest to 0 in the initial reachability matrix.

Step 8. The final reachability matrix is constructed after checking transitivity within the matrix. According to the new matrix, driving and dependence power values are determined.

Step 9. The final reachability matrix is then used for level partitioning with reachability and antecedent sets. The antecedent set comprises the factor itself and other factors that may aid in reaching it. The reachability set for a given factor includes the factor itself and other factors it may help to accomplish. The intersection of these sets is then calculated for each factor. The first level is the factor for which the reachability and intersection sets are equal. This element is then isolated from the other factors in preparation for the subsequent level of iteration. Until all levels of each factor have been established, the same level-iteration process is repeated.

Step 10. Using multiplication properties of matrices, MICMAC analysis is used to analyze the driving power and dependence power of barriers in order to categorize them under four groups including autonomous barrier, dominated/ dependent barrier, relay/linkage barrier, and independent barrier (Azadnia, Onofrei, & Ghadimi, 2021; Narwane et al., 2021; Warfield, 1974).

3.3. T2NN-ARAS

For the evaluation of transport modes against the market development barriers, an MCDA ranking method is required. ARAS, developed by Zavadskas and Turskis (2010), is one of the well-known MCDA methods that can be used for multi-criteria ranking, sorting, and prioritization problems. A decade after its development, ARAS has been used in various decision-making, evaluation, and assessment problems in different applications such as energy management (Mishra, Rani, Cavallaro, & Mardani, 2022), or the evaluation of EVs (Ghenai, Albawab, & Bettayeb, 2020).

To improve the accuracy and preciseness of the traditional ARAS in dealing with uncertain information, a novel extension of ARAS using T2NNs can be applied using the following steps.

Step 1. For an MCDA problem with n criteria and m alternatives, the initial decision matrix is constructed by each expert, $X^e = [x^e_{ij}]$, using the linguistic T2NN scale in Table B.1. Later, all decision matrices are aggregated to a single aggregated initial decision matrix based on equal experts' contributions (Eq. (A.10)).

Step 2. T2NN values in the aggregated initial decision matrix are converted to crisp values by applying Eq. (A.8).

Step 3. According to the nature of criteria, e.g., whether a criterion is beneficial or non-beneficial for the goal of the problem, normalization of the aggregated initial decision matrix can be computed using Eqs. (15) and (16) for beneficial and non-beneficial criteria, respectively.

$$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}} \tag{15}$$

$$r_{ij} = \frac{\frac{1}{x_{ij}}}{\sum_{i=1}^{m} \frac{1}{x_{ij}}} \tag{16}$$

Step 4. The normalized weighted decision matrix is constructed using the normalized decision matrix and the weight vector as Eq. (17).

$$u_{ij} = r_{ij} w_j \tag{17}$$

Step 5. The optimality function value for each alternative is determined using Eq. (18).

$$L_i = \sum_{j=1}^{n} u_{ij} \tag{18}$$

Step 6. To rank the alternatives, the optimality degree is calculated compared to the most optimal value of each criterion according to Eq. (19).

$$V_i = \frac{L_i}{L_{i^*}} \tag{19}$$

The ranking order of alternatives can be determined based on V_i values in descending order.

Fig. 1 represents all steps to address the proposed problem using the developed approach.

4. Case study

This section presents a case study and the results obtained by the developed approach for analyzing the dynamics of market development barriers for renewable fuels in Germany. The main objective of this section is to conduct a comprehensive analysis of market development barriers for renewable fuels in Germany in order to support the 2030 emission reduction and 2045 climate neutrality targets. In this regard, the most important goals can be summarized as (a) identifying barriers, (b) understanding how barriers affect each other, (c) identifying barriers with the highest influence on the others, and (d) determining the transport modes most strongly affected by the barriers. Considering the relevant policies in the EU and Germany, as well as the German transport sector, the problem is structured accordingly. For this purpose, a micro-level barrier analysis is conducted using the T2NN-DEMATEL improved by the K-means algorithm, and a macro-level barrier analysis is conducted using the MMDE-ISM-MICMAC. Finally, the study seeks to rank transport modes against market development barriers using the T2NN-ARAS.

Table 2
A summary of the relevant policies and targets.

Policy	Targets for 2030	Targets for 2050 (2045 Germany)
FuelEU maritime	Reducing GHG emissions intensity by 6% (compared to 2020),	Reducing GHG emissions by 75% (compared to 2020),
ReFuelEU aviation	Minimum share of renewable fuels by 6%,	Minimum share of renewable fuels by 70%,
Alternative fuels infrastructure regulation	Recharging stations at least every 60 km (passenger cars and trucks), hydrogen and liquefied methane refueling stations at least every 200 km, accessibility of 90% of ships to renewable fuels (electricity mainly), accessibility of all airports to electricity supply	–
CO_2 emission standards for cars and vans	Cars: limit of 95 g/km (2021–2024), −15% for 2025–2029, Vans: limit of 147 g/km (2021–2024), −15% for 2025–2029,	Cars: −55% for 2030–2034 and −100% for 2050, Vans: −50% for 2030–2034 and −100% for 2050,
Renewable energy directive (RED III)	Achieving at least a 42.5% share of renewable energy in the EU's final energy consumption,	–
National hydrogen strategy	Increasing electrolyzer capacity to 5 GW, reaching a share of 10% hydrogen in aviation,	–
Renewable energy act (EEG)	Increasing the share of electricity generation out of renewable sources by at least 80%,	–
European strategy for low-emission mobility	Promoting the deployment of low-emission vehicles and alternative fuels, developing the necessary infrastructure,	–
Mobility and fuels strategy of the german government (MFS)	Increasing share of renewable energies for 18% of gross final energy consumption by 2020,	Increasing the share by 60%,

4.1. Policy framework in Germany

The policy framework for renewable fuels in Germany is a mix of national policies and EU policies. Regarding German policies, several policies in different contexts have been passed for various renewable fuels, specifically for biofuels and hydrogen. Table 2 presents a short summary of the most significant and relevant policies addressing renewable fuels in the EU and Germany. Understanding the targets of the relevant policies regarding emission reduction is of high significance to identify the barriers and formulate the problem.

4.2. Context definition

Renewable fuels include a broad range of fuels covering, e.g., PtX fuels, biofuels, ammonia, and hydrogen. In the EU's journey towards climate neutrality, renewable fuels play a significant role in decarbonizing the transport sector. Although renewable fuels provide potential options for replacing fossil fuels, no serious improvement has been observed in their large-scale production and utilization so far. According to the European Alternative Fuels Observatory (EAFO), roughly

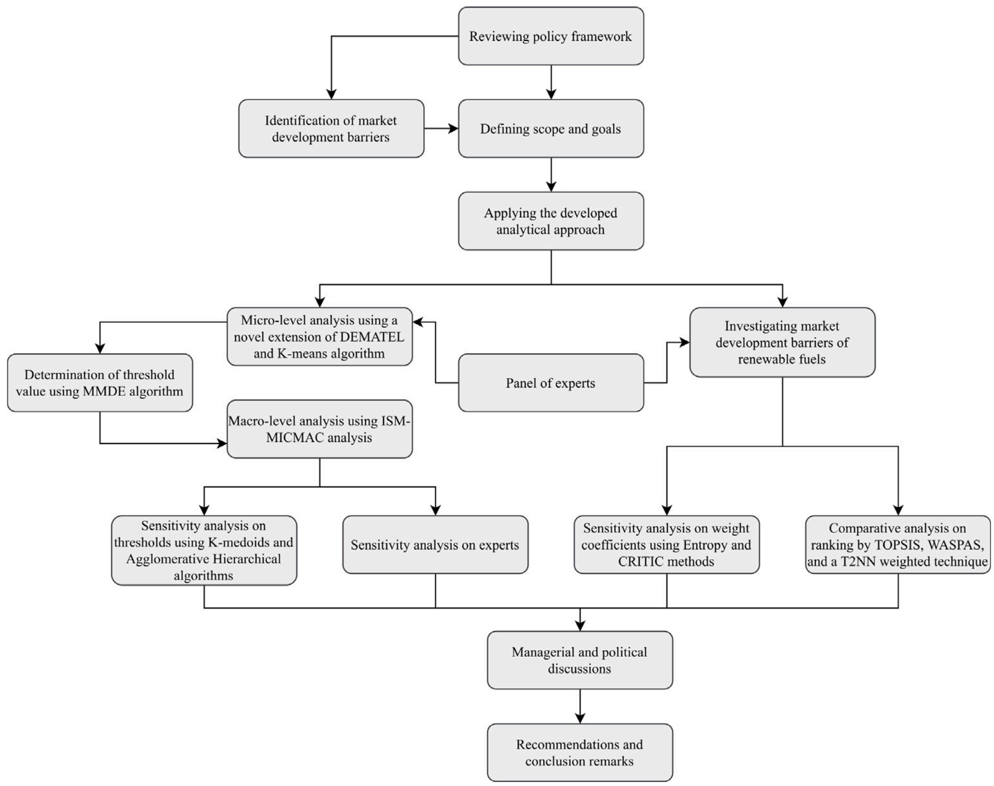


Fig. 1. A flowchart of the proposed problem.

3 thousands alternative fuels passenger cars were registered in Germany by mid-January 2024, which accounts for 4.65% of the total fleet (European Commission, 2024). In the EU, almost 17 thousands alternative fuels passenger cars were registered, accounting for 5.4% of the total fleet. Of the registered vehicles, EVs account for a large share with a total of over 8 thousands cars while the rest were related to hydrogen, LNG, LPG (liquefied petroleum gas), and CNG. For maritime and aviation, Germany within the EU pursues several strategies to deploy renewable fuels in order to decrease GHG emissions; however, renewable fuels are used in these transport modes in very limited cases (European Commission, 2024). However, the road to climate neutrality passing through renewable fuels is so far not well developed, and at the current pace reaching the targets would not be possible. An important factor that plays a key role is the low market development of renewable fuels in Germany. Thus, this study aims to analyze the barriers hindering the adoption and diffusion of renewable fuels in the German transport sector. Considering the potential role of EVs in decarbonizing the transport sector, specifically road transport, many studies have been conducted to address different aspects of the adoption and diffusion of EVs (Li, Wang, & Xie, 2022; Mersky, Sprei, Samaras, & Qian, 2016; Rezvani, Jansson, & Bodin, 2015). However, research on other renewable fuels including PtX fuels, biofuels, ammonia, and hydrogen is insufficient. Therefore, this study concentrates on addressing market development barriers for renewable fuels with a focus on PtX fuels, biofuels, and hydrogen. In this regard, identifying barriers is a critical task to conceptualize the problem properly.

For this purpose, ten major market development barriers are identified based on a literature review considering not only technical barriers, but also social, environmental, economic, and multi-sector regulatory aspects. High initial costs (B1) include investment costs, capital costs, storage and recharging costs as well as high capital costs of the existing energy generating system using renewable sources, logistics costs, and operational costs (Browne et al., 2012; Dominković, Bačeković, Pedersen, & Krajačić, 2018; Mirza, Ahmad, Harijan, & Majeed, 2009; Solangi, Longsheng, & Shah, 2021). Lack of public acceptance (B2) is an important barrier that can be defined as people's unwillingness to adopt renewable fuels considering the costs, tax, and technical characteristics compared to fossil fuels (Adhikari, Mithulananthan, Dutta, & Mathias, 2008; Mirza et al., 2009; Solangi et al., 2021). Insufficient consumer awareness (B3) expresses the unawareness of people regarding the benefits of renewable fuels considering the lack of information and knowledge on their advantages for a low-GHG transport system (Luthra, Kumar, Garg, & Haleem, 2015; Solangi et al., 2021). High technology conversion challenges (B4) show technical challenges in life cycle and fuel chain analysis of renewable fuels with various renewable sources (Luthra et al., 2015; Narwane et al., 2021; Saccani et al., 2020). Lack of technological and market infrastructure (B5) is another important barrier, which addresses commercialization challenges of renewable fuels considering the lack of research & development, and recharging infrastructures required for fuel availability (Luthra et al., 2015; Mirza et al., 2009; Solangi et al., 2021). Insufficient renewable energies policies and regulations (B6) represent a significant barrier that concern the lack of policies addressing renewable fuels in different modes (Abdmouleh, Alammari, & Gastli, 2015; Browne et al., 2012; Elavarasan, Afridhis, Vijayaraghavan, Subramaniam, & Nurunnabi, 2020; Kim, 2021). Insufficient coordination (B7), as a barrier, concerns the lack of coordination and collaboration among multiple agents such as energy generators, politicians, or production sites within a fuel supply chain Luthra et al. (2015), Solangi et al. (2021). Low feedstock availability (B8) is a critical barrier that covers the availability of required raw material in terms of energy sources such as renewable electricity, biomass, and carbon feedstock. Single-source provision of fuel production systems is a danger that can cause volatility in availability of renewable electricity considering the seasonal and technical limitation of renewable sources such as wind and solar energies (Browne et al., 2012; Hammond, Kallu, & McManus, 2008; Roszkowska & Szubska-Włodarczyk, 2022; Solangi et al., 2021). High environmental challenges (B9) include ecological issues, e.g., direct and indirect land-use issues or water-use during the production of renewable fuels (Kumar et al., 2020; Panoutsou et al., 2021; Wang et al.,

Table 3
Multi-expert direct relationship matrix.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
B1	NI, NI, NI, NI, NI, NI	NI, MI, HI, MI, MI, MI	NI, MI, MI, LI, EI, MI	HI, EI, HI, EI, NI, MI	HI, EI, HI, HI, HI, MI	LI, MI, HI, HI, NI, MI	HI, EI, LI, EI, NI, LI	LI, HI, EI, HI, NI, HI	EI, HI, EI, HI, NI, LI	EI, LI, MI, LI, NI, MI
B2	NI, LI, MI, NI, LI, HI	NI, NI, NI, NI, NI, NI	EI, HI, HI, HI, MI, EI	NI, LI, LI, NI, LI, NI	LI, HI, EI, HI, LI, MI	LI, EI, MI, EI, LI, HI	MI, HI, HI, MI, NI, MI	NI, MI, MI, HI, LI, NI	NI, MI, HI, MI, NI, LI	NI, MI, EI, MI, NI, HI
B3	NI, LI, LI, LI, LI, MI	EI, HI, EI, EI, HI, EI	NI, NI, NI, NI, NI, NI	NI, MI, NI, LI, LI, NI	NI, MI, HI, MI, LI, HI	NI, HI, MI, HI, LI, HI	LI, MI, HI, MI, NI, LI	NI, HI, MI, NI, LI, NI	NI, MI, HI, HI, NI, LI	NI, MI, HI, HI, NI, HI
B4	EI, EI, LI, EI, HI, MI	NI, MI, MI, MI, NI, MI	NI, HI, LI, MI, NI, MI	NI, NI, NI, NI, NI, NI	HI, MI, MI, EI, HI, MI	LI, EI, LI, HI, NI, HI	HI, EI, HI, HI, NI, LI	MI, MI, EI, MI, NI, MI	HI, HI, HI, MI, HI, MI	MI, MI, MI, HI, NI, MI
B5	EI, EI, HI, EI, LI, HI	LI, MI, EI, HI, NI, EI	LI, MI, MI, MI, NI, HI	EI, EI, MI, HI, LI, EI	NI, NI, NI, NI, NI, NI	LI, MI, HI, MI, NI, HI	HI, HI, HI, HI, NI, MI	NI, HI, HI, LI, NI, NI	MI, HI, MI, HI, NI, LI	HI, MI, MI, EI, NI, HI
B6	EI, HI, EI, HI, LI, HI	EI, MI, MI, MI, NI, HI	EI, LI, MI, LI, NI, HI	EI, MI, LI, MI, MI, MI	EI, MI, EI, HI, MI, HI	NI, NI, NI, NI, NI, NI	EI, HI, HI, MI, LI, MI	HI, HI, HI, HI, NI, NI	MI, EI, HI, EI, NI, HI	LI, LI, HI, LI, NI, HI
B7	HI, EI, MI, HI, LI, NI	LI, HI, HI, HI, NI, HI	MI, MI, MI, MI, NI, MI	NI, HI, MI, HI, LI, NI	LI, HI, HI, HI, LI, LI	NI, MI, MI, HI, MI, HI	NI, NI, NI, NI, NI, NI	MI, HI, HI, LI, MI, NI	NI, MI, MI, HI, NI, NI	HI, MI, MI, LI, NI, LI
B8	HI, HI, HI, HI, HI, HI	NI, MI, LI, LI, LI, LI	NI, HI, LI, NI, NI, LI	EI, HI, EI, HI, NI, HI	NI, MI, LI, LI, NI, HI	NI, HI, HI, HI, NI, HI	HI, LI, HI, NI, NI, NI	NI, NI, NI, NI, NI, NI	NI, HI, EI, MI, NI, MI	LI, NI, MI, NI, NI, MI
B9	HI, HI, HI, HI, LI, LI	NI, EI, EI, EI, LI, EI	NI, MI, EI, MI, NI, LI	HI, MI, HI, HI, NI, MI	NI, HI, MI, HI, NI, LI	LI, HI, MI, EI, MI, LI	NI, MI, MI, LI, NI, NI	NI, HI, HI, HI, NI, HI	NI, NI, NI, NI, NI, NI	NI, LI, MI, LI, NI, LI
B10	NI, LI, LI, MI, NI, LI	EI, HI, EI, HI, NI, LI	MI, MI, HI, HI, NI, MI	NI, HI, HI, MI, NI, LI	NI, HI, HI, HI, NI, LI	MI, LI, EI, LI, NI, MI	NI, NI, MI, NI, NI, MI	NI, NI, EI, NI, NI, NI	NI, MI, MI, MI, NI, MI	NI, NI, NI, NI, NI, NI

B1: High initial costs, B2: Lack of public acceptance, B3: Insufficient consumer awareness, B4: High technology conversion challenges, B5: Lack of technological and market infrastructure, B6: Insufficient renewable energies policies and regulations, B7: Insufficient coordination, B8: Low feedstock availability, B9: High environmental challenges, B10: Low travel range.

2019; Why et al., 2019). Low travel range (B10) highlights the range limit of renewable fuels considering the technical properties (Browne et al., 2012; Demeulenaere, 2019; Ghadikolaei et al., 2021; Melaina & Bremson, 2008).

To investigate the aforementioned barriers, a panel of six experts (five male and one female) from academia with expertise in research & development of renewable fuels is established.

4.3. Results of improved T2NN-DEMATEL

As discussed earlier, DEMATEL aims to provide a micro-level perspective of the dynamics of systems. Thus, the results of DEMATEL can provide deep and detailed information about the interactions of barriers in order to improve the market development of renewable fuels in the German transport sector.

According to the defined steps of the T2NN-DEMATEL in Section 3.1, experts were invited to express their opinions on interactions among barriers using linguistic terms in Table 1. Table 3 represents the initial evaluations including linguistic terms for each pairwise comparison. Linguistic terms in pairwise comparison between barrier B1 and B2 (high initial costs and the lack of public acceptance) is represented as (NI, MI, HI, MI, MI, MI), which shows opinions of experts 1–6, respectively.

Based on step 1 of the T2NN-DEMATEL, experts' opinions are aggregated to construct a single initial direct relation matrix using Eq. (A.10) where all experts have equal contribution. Later, the aggregated direct relation matrix is converted into crisp values using Eq. (A.8). The final aggregated direct relation matrix is shown in Table 4.

Eqs. (2)–(3) are used to construct the normalized direct relation matrix which is reported in Table 5.

Finally, the total relation matrix in Table 6 is determined using Eq. (4).

Table 7 represents the final results determined by calculating prominence ($R_i + C_i$) and relevance ($R_i - C_i$) values using Eqs. (5) and (6). Based on the prominence and relevance values, the barrier "insufficient renewable energy policies and regulations" is determined as the most important barrier followed by high technology conversion challenges, and insufficient coordination in the supply chain. In a systematic perspective, market development barriers are categorized into cause and effect groups. Insufficient renewable energy policies and regulations, high technology conversion challenges, insufficient coordination in the supply chain, and lack of technological and market

Table 4
Final aggregated direct relation matrix.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
B1	0.192	0.590	0.452	0.776	0.803	0.623	0.719	0.738	0.669	0.423
B2	0.496	0.192	0.823	0.321	0.719	0.747	0.641	0.521	0.521	0.641
B3	0.425	0.873	0.192	0.357	0.623	0.668	0.548	0.466	0.580	0.648
B4	0.810	0.478	0.521	0.192	0.746	0.687	0.738	0.632	0.750	0.590
B5	0.833	0.733	0.570	0.810	0.192	0.623	0.722	0.531	0.623	0.717
B6	0.814	0.678	0.644	0.653	0.799	0.192	0.733	0.690	0.776	0.582
B7	0.703	0.708	0.532	0.580	0.670	0.641	0.192	0.623	0.492	0.548
B8	0.804	0.425	0.437	0.803	0.496	0.690	0.531	0.192	0.641	0.389
B9	0.724	0.808	0.569	0.684	0.580	0.680	0.389	0.690	0.192	0.392
B10	0.392	0.765	0.641	0.580	0.630	0.593	0.352	0.431	0.478	0.192

Table 5
Normalized aggregated direction relationship matrix.

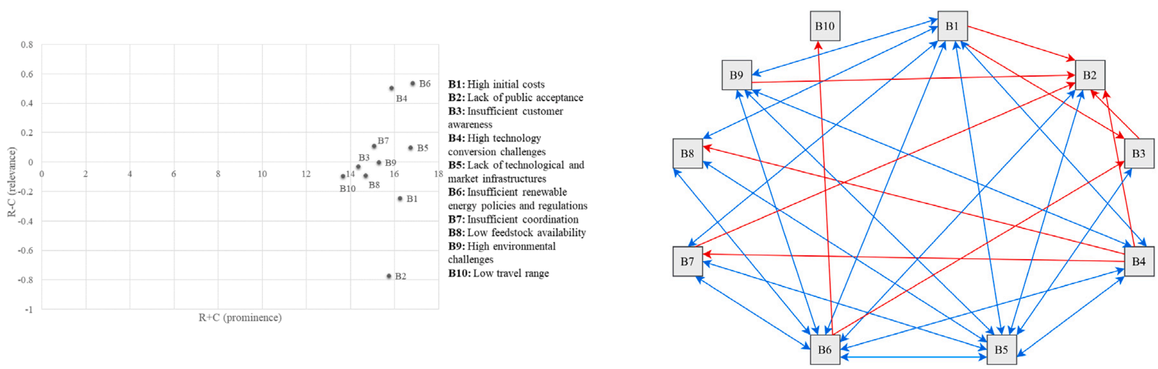
	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
B1	0.029	0.090	0.069	0.118	0.122	0.095	0.110	0.113	0.102	0.065
B2	0.076	0.029	0.125	0.049	0.110	0.114	0.098	0.079	0.079	0.098
B3	0.065	0.133	0.029	0.054	0.095	0.102	0.083	0.071	0.088	0.099
B4	0.123	0.073	0.079	0.029	0.114	0.105	0.113	0.096	0.114	0.090
B5	0.127	0.112	0.087	0.123	0.029	0.095	0.110	0.081	0.095	0.109
B6	0.124	0.103	0.098	0.100	0.122	0.029	0.112	0.105	0.118	0.089
B7	0.107	0.108	0.081	0.088	0.102	0.098	0.029	0.095	0.075	0.083
B8	0.123	0.065	0.067	0.122	0.076	0.105	0.081	0.029	0.098	0.059
B9	0.110	0.123	0.087	0.104	0.088	0.104	0.059	0.105	0.029	0.060
B10	0.060	0.117	0.098	0.088	0.096	0.090	0.054	0.066	0.073	0.029

Table 6
Total relation matrix.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
B1	0.795	0.847	0.731	0.823	0.883	0.843	0.797	0.790	0.804	0.698
B2	0.784	0.744	0.740	0.711	0.821	0.810	0.739	0.713	0.736	0.688
B3	0.744	0.809	0.627	0.687	0.779	0.771	0.699	0.679	0.716	0.664
B4	0.897	0.851	0.755	0.757	0.893	0.868	0.814	0.791	0.830	0.734
B5	0.920	0.906	0.783	0.861	0.838	0.882	0.832	0.796	0.833	0.771
B6	0.944	0.925	0.814	0.866	0.948	0.846	0.856	0.841	0.877	0.773
B7	0.825	0.825	0.709	0.758	0.827	0.807	0.686	0.738	0.743	0.683
B8	0.813	0.757	0.669	0.764	0.775	0.785	0.710	0.653	0.739	0.636
B9	0.833	0.842	0.718	0.776	0.819	0.817	0.721	0.752	0.704	0.665
B10	0.703	0.756	0.658	0.683	0.743	0.724	0.640	0.641	0.669	0.568

Table 7
A Summary of results obtained by the T2NN-DEMATEL.

Barrier	R_i	C_i	$R_i + C_i$	$R_i - C_i$	Group	Rank
B1 (High initial costs)	8.010	8.257	16.267	−0.247	Effect	9
B2 (Lack of public acceptance)	7.487	8.261	15.749	−0.774	Effect	10
B3 (Insufficient consumer awareness)	7.174	7.205	14.380	−0.031	Effect	6
B4 (High technology conversion challenges)	8.191	7.687	15.878	0.503	Cause	2
B5 (Lack of technological and market infrastructure)	8.421	8.325	16.746	0.096	Cause	4
B6 (Insufficient renewable energy policies and regulations)	8.690	8.155	16.845	0.535	Cause	1
B7 (Insufficient coordination)	7.601	7.493	15.094	0.108	Cause	3
B8 (Low feedstock availability)	7.301	7.394	14.695	−0.093	Effect	7
B9 (High environmental challenges)	7.646	7.650	15.296	−0.004	Effect	5
B10 (Low travel range)	6.786	6.880	13.666	−0.095	Effect	8



(a) Degree of influence.

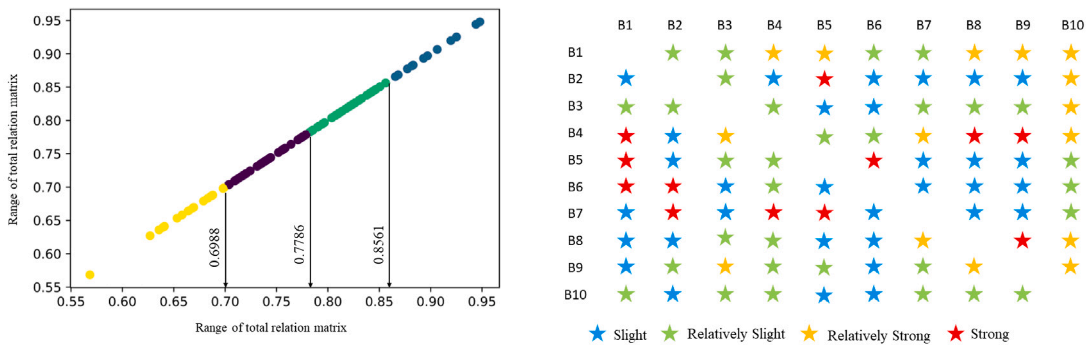
(b) Cause and effect relationships among market development barriers.

Fig. 2. Interrelationships between barriers based on final results of the T2NN-DEMATEL.

infrastructure are determined as causes of barriers. High costs, lack of public acceptance, insufficient consumer awareness, low feedstock (raw material) availability, high environmental challenges e.g., ecological land issues and water use, and low travel range are chosen as effects. Market development barriers in the cause category highlight the need to consider them for future policy-making to improve the market development of renewable fuels in Germany.

Fig. 2(a) visualizes the results on the prominence and relevance within a 2D graph showing insufficient renewable energy policies and regulations (B6), and high technology conversion challenges (B4) are the most dominant barriers. On the other hand, both B6 and B4 are placed in a very close distance from each other, which explains how both are strongly interconnected. To provide a complete view on how barriers interact with each other, an average-based threshold is used to determine the threshold value in the total relation matrix. The average value of all elements of the total relation matrix is 0.773. Using the threshold value, the interactions among barriers can be determined in the total relation matrix by replacing values with 0 and 1 when they are smaller or larger than the threshold value. Fig. 2(b) represents the network of interactions among barriers through one-side and double-side arrows. One important insight from the generated network is connectivity of insufficient renewable energy policies and regulations (B6) with all barriers as the main cause. On the other hand, low travel range (B10) does not directly affect any barriers. Moreover, the lack of technological and market infrastructure (B5), high costs (B1), and high technology conversion challenges (B4) are three other barriers with high impact on other barriers. Most impacts between insufficient renewable energy policies and regulations (B6) and other barriers are shown by double-arrows, denoting that insufficient renewable energy policies and regulations (B6) and all other barriers are effecting each other at the same time. From another point of view, the lack of technological and market infrastructure (B5) is affected by multiple barriers, more than any other barrier, explaining how the lack of technological and market infrastructure is influenced by several barriers. Again, low travel range (B10) is only affected by insufficient renewable energy policies and regulations (B6), which highlights the importance of policies and regulations for addressing low travel range.

An important challenge of using the average-based threshold is the loss of information on impacts between barriers whose values in the total relation matrix fall under the threshold value. Moreover, information loss happens in another direction when the average-based threshold is used such that this technique fails to show the degree of influence between barriers. In Fig. 2(b), only links are drawn based on whether two barriers affect each other, but to what degree remains unclear. In this regard, to elaborate the total relation matrix more, the K-means algorithms is used to classify the total relation values in the total relation matrix (Table 6) into a suggested classification by Wu, Liu et al. (2022) named as slight, relatively slight, relatively strong, and strong clusters based on impacts of barriers. The K-means algorithm, applied using the scikit-learn library in Python 3.6, determined the thresholds as 0.6988, 0.7786, and 0.8561. Fig. 3(a) shows the distribution of total relation values in the total relation matrix, clusters, and thresholds. For better visualization, Fig. 3(b) illustrates the impact of barriers for each pair using colored symbols under slight, relatively slight, relatively strong, and strong categories. Based on the clustering results, high technology conversion challenges (B4), next to insufficient renewable energy policies and regulations (B6), and lack of technological and market infrastructure (B5) have the strongest impact frequency. Low feedstock availability (B8) and the lack of public acceptance (B2) are two barriers in terms of strong impact frequency. Insufficient renewable energy policies and regulations (B6) are only affected strongly by lack of technological and market infrastructure (B5), which highlights high significance of technological and infrastructural aspects on the policy framework. The rest of the barriers have a slight impact on insufficient renewable energy policies and regulations (B6) while high initial costs (B1), and high technology conversion challenges (B4) show relatively slight impact on insufficient renewable energy policies and regulations (B6). Moreover, high initial costs (B1) is the strongest affected barrier mainly by high technology conversion challenges (B4), lack of technological and market infrastructure (B5), and



(a) Identified thresholds using K-means algorithm. (b) Impact of barriers based on the thresholds.

Fig. 3. Categorization of barriers using the K-means algorithm.

insufficient renewable energy policies and regulations (B6) showing that high costs related to renewable fuels are dramatically influenced by lack of polices, lack of market infrastructures, and technological conversion challenges.

4.4. Results of MMDE-ISM-MICMAC

As discussed earlier, ISM can be used to analyze the macro-level perspective of interactions among market development barriers. This way, deep macro-level results can be useful for upper-level policy-making, acting as complementary to the micro-level results obtained by T2NN-DEMATEL. However, an important challenge regarding the ISM is related to its input data format which differs from the input data of T2NN-DEMATEL. In this regard, two possible ways exist to implement the ISM, either by collecting data from experts and aggregating them based on most common input or using the total relation matrix of T2NN-DEMATEL. To reduce the complexity of the computational analysis and re-involvement of experts, we decided to use the latter. To use the total relation matrix, a threshold must be determined to convert the elements in Table 6 into 0 and 1 values. In DEMATEL method, an average-based or an expert-based technique can be used for this purpose. Following the previous discussion on challenges related to these techniques, a scientific and logical technique can provide better input and consequently more reliable results.

To do so, the MMDE algorithm is applied in Python. After sorting the 100 total relation values, 100 sets are generated based on the combination of corresponding out-going barriers (dispatch-node) and in-going barriers (receiver-node) of a total relation value. Finally, the MMDE value for each set of dispatch-node and receiver-node is calculated according to the procedure of the MMDE algorithm in Section 3.2. The results of the MMDE algorithm indicate that (B6,B6,B6,B5) and (B5,B1,B2,B1,B2,B1) are the dispatch-nodes and receiver-nodes with the maximum MMDE values of 0.065 and 0.029, respectively. Fig. 4 presents MMDE values for 100 dispatch-node sets and receiver-node sets, where the MMDE value in dispatch-node and receiver-node sets are highlighted in the graph. According to the results, insufficient renewable energy policies and regulations (B6) and lack of technological and market infrastructure (B5) are chosen for the dispatch-node, while lack of technological and market infrastructure (B5), high initial costs (B1), and lack of public acceptance (B2) are selected for the receiver-node. Therefore, the possible pair of nodes will be (B6,B5), (B6,B1), (B6,B2), (B5,B1), and (B5,B2). Among the identified sets, (B5,B2) has the minimum value of 0.906. Therefore, the threshold for converting the total relation matrix is 0.906. Values above the threshold are changed to 1 and the rest are kept 0. Table 8 shows the initial reachability matrix.

Following the construction of the initial reachability matrix, the final reachability matrix is determined by including the transitivity

Table 8
Initial reachability matrix.

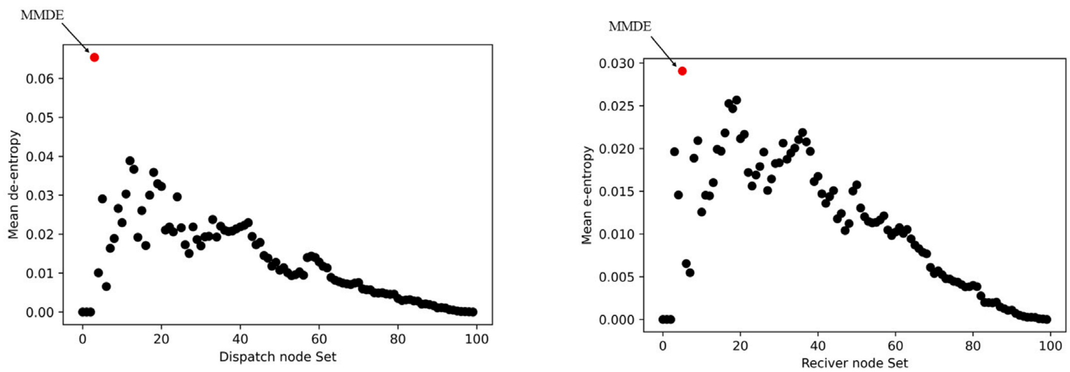
	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
B1	0	0	0	0	0	0	0	0	0	0
B2	0	0	0	0	0	0	0	0	0	0
B3	0	0	0	0	0	0	0	0	0	0
B4	0	0	0	0	0	0	0	0	0	0
B5	1	0	0	0	0	0	0	0	0	0
B6	1	1	0	0	1	0	0	0	0	0
B7	0	0	0	0	0	0	0	0	0	0
B8	0	0	0	0	0	0	0	0	0	0
B9	0	0	0	0	0	0	0	0	0	0
B10	0	0	0	0	0	0	0	0	0	0

Table 9
Final reachability matrix.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10	Driving power
B1	1	0	0	0	0	0	0	0	0	0	1
B2	0	1	0	0	0	0	0	0	0	0	1
B3	0	0	1	0	0	0	0	0	0	0	1
B4	0	0	0	1	0	0	0	0	0	0	1
B5	1	0	0	0	1	0	0	0	0	0	2
B6	1	1	0	0	1	1	0	0	0	0	4
B7	0	0	0	0	0	0	1	0	0	0	1
B8	0	0	0	0	0	0	0	1	0	0	1
B9	0	0	0	0	0	0	0	0	1	0	1
B10	0	0	0	0	0	0	0	0	0	1	1
Dependence power	3	2	1	1	2	1	1	1	1	1	

in the matrix through consideration of the transitivity rule. The transitivity rule checks if high initial costs (B1) is associated to lack of public acceptance (B2), and B2 is connected to insufficient consumer awareness (B3), then B1 is inevitably connected to B3. Table 9 shows the final reachability matrix. Table 9 also represents driving power and dependence power of each barrier based on the total number of links that a barrier holds to other barriers or is affected by other barriers, respectively. Results indicate that insufficient renewable energy policies and regulations (B6) has the highest driving power and high costs (B1) has the highest dependence power.

Using the final reachability matrix, barriers can be partitioned based on the reachability set, antecedent set, and intersection set. Level I includes the barriers with identical reachability set and intersection set. In the next iteration, barriers involved in the level I are eliminated from the rest of barriers. This procedure is continued for identifying the levels of all barriers. Table 10 presents the full partitioning iterations for the barriers. The level of all barriers are determined in three iterations. According to the final results, insufficient renewable energy



(a) Mean de-entropy values of dispatch nodes with a maximum Mean de-entropy value 0.0654

(b) Mean de-entropy values of receiver nodes with a maximum Mean de-entropy value 0.0290

Fig. 4. Mean de-entropy values obtained from MMDE algorithm.

Table 10
Iteration-level partition of market development barriers.

Barriers	Reachability set	Antecedent set	Intersection	Level	Barriers	Reachability set	Antecedent set	Intersection	Level
		Iteration 1					Iteration 2		
B1	1,	1, 5, 6,	1,	1	B1		5, 6,		1
B2	2,	2, 6,	2,	1	B2		6,		1
B3	3,	3,	3,	1	B3				1
B4	4,	4,	4,	1	B4				1
B5	1, 5,	5, 6,	5,		B5	5,	5, 6,	5,	2
B6	1, 2, 5, 6,	6,	6,		B6	5, 6,	6,	6,	
B7	7,	7,	7,	1	B7				1
B8	8,	8,	8,	1	B8				1
B9	9,	9,	9,	1	B9				1
B10	10,	10,	10,	1	B10				1
		Iteration 3					Final iteration-level partition of barriers		
B1		6,		1	B1	1,	1, 5, 6,	1,	1
B2		6,		1	B2	2,	2, 6,	2,	1
B3				1	B3	3,	3,	3,	1
B4				1	B4	4,	4,	4,	1
B5		6,		2	B5	5,	5, 6,	5,	2
B6	6,	6,	6,	3	B6	6,	6,	6,	3
B7				1	B7	7,	7,	7,	1
B8				1	B8	8,	8,	8,	1
B9				1	B9	9,	9,	9,	1
B10				1	B10	10,	10,	10,	1

policies and regulations (B6) is placed in level III, lack of technological and market infrastructure (B5) is categorized in level II, and the rest of the barriers are in level I. Placement of the insufficient renewable energy policies and regulations (B6) in the highest level shows its significance among all barriers followed by the lack of technological and market infrastructure (B5) in the second level. In a macro-level analysis, the ISM indicates that the rest of the barriers have lower significance compared to B6 and B5, and equally affect the market development process.

To illustrate the results of the ISM, Fig. 5 shows the interactions among barriers on a macro-level perspective. Insufficient renewable energy policies and regulations (B6), as the most important barrier, directly affect lack of technological and market infrastructure (B5) and lack of public acceptance (B2) and indirectly high initial costs (B1). The rest of the barriers do not show any potential interaction on a macro-level perspective. Once again, insufficient renewable policies and regulations shows its dominant effect on the system by highlighting the significant role of regulating the market for renewable fuels, increasing positive public acceptance, and reducing supply chain costs. Furthermore, the MICMAC analysis suggests that all barriers show autonomous behavior, indicating that all barriers significantly and separately affect the market development process on a macro-level perspective and needs to be addressed.

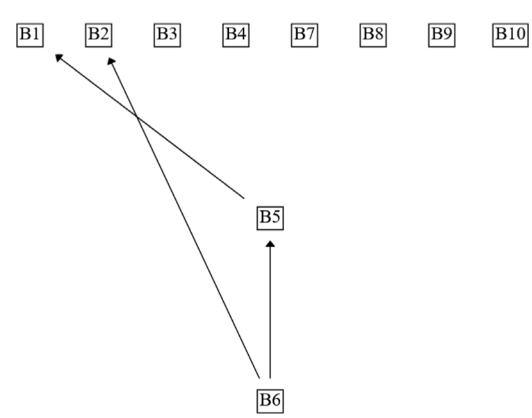


Fig. 5. Macro-level cause and effect relationships among market development barriers.

4.5. Effects by transport mode

Under real-life circumstances, different market and technical characteristics of each transport mode play a crucial role in adoption

Table 11
Experts evaluations on impact of barriers for market development of renewable fuels.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
Aviation	VH, H, M, H, VH, H	M, H, L, M, L, H	VL, H, L, H, H, H	H, H, H, H, VH, VH	L, H, M, H, M, H	EH, VH, M, H, VH, EH	VL, M, M, H, M, H	EL, M, M, M, VH, VH	VL, H, M, M, VH, VH	L, H, M, H, VH, EH
Maritime	EH, H, M, H, H, H	M, M, M, M, L, M	EL, M, L, H, M, M	H, H, H, H, M, VH	M, M, M, M, H, H	EH, VH, M, H, VH, EH	VL, M, M, H, H, H	EL, M, M, M, VH, VH	VL, H, M, H, VH, EH	M, H, M, H, H, EH
Road	VH, EH, EH, EH, M, EH	M, EH, EH, EH, H, VH	L, EH, EH, EH, L, VH	H, M, H, H, L, H	L, VH, VH, VH, VH, EH	EH, VH, EH, H, L, VH	VL, M, H, H, M, EH	EL, VH, VH, VH, H, VH	VL, H, H, VH, M, VH	VL, VH, H, VH, M, VH
Rail	H, EH, EH, H, M, VH	M, H, M, EH, H, H	EL, VH, VH, EH, H, H	H, M, H, M, L, H	L, H, H, H, H, VH	EH, VH, VH, H, M, VH	VL, M, M, H, H, VH	EL, H, H, H, H, VH	VL, H, M, VH, VL, VH	VL, L, H, L, M, M

Table 12
Final evaluation results of T2NN-ARAS.

Modes	L_i	V_i	Rank
Aviation	0.246	1.171	4
Maritime	0.252	1.200	2
Road	0.253	1.205	1
Rail	0.248	1.178	3

and diffusion of new fuels based on the global standards, economic prospects, and environmental benefits. For this purpose, the identified barriers in previous parts are used to measure how each transport mode is affected in order to show how policies should be considered in the proper way.

At this point, transport modes are considered as alternatives, and market development barriers are accounted as the evaluation criteria. To decrease the bias and subjectivity in weight coefficients of the evaluation criteria, prominence values in T2NN-DEMATEL method are used to obtain the final weight coefficients. By utilizing prominence values derived by DEMATEL, we are addressing the inherent biases and dependencies across criteria as well as bringing this important insight into the MCDA process. To provide a more accurate and context-aware ranking, this method makes use of the data gathered from DEMATEL to assign weights that reflect the relative importance and effect of each criterion in the decision-making process. By considering the dynamic relationships within the set of criteria, it improves the robustness and validity of the MCDA model, assisting in improved decision support and supporting more efficient solutions.

The weight coefficient of each barrier is determined by dividing its prominence value to total summation of prominence values. According to the obtained results, weight coefficients of barriers are $B6 = 0.109 > B5 = 0.108 > B1 = 0.105 > B4 = 0.103 > B2 = 0.102 > B9 = 0.099 > B7 = 0.098 > B8 = 0.095 > B3 = 0.093 > B10 = 0.088$. In the next step, the experts were invited to construct the initial decision matrix using the linguistic scale in Table B.1. Table 11 presents the initial decision matrix including all six experts.

Next, the aggregated evaluation matrix was constructed using Eq. (A.10) based on the linguistic terms in Table B.1. Later, Eq. (A.8) is used to determine the crisp values of the T2NN elements in the evaluation matrix. Finally, the aggregated evaluation matrix was derived (Table C.1). The evaluation matrix is normalized and the weighted evaluation matrix is constructed by multiplication of weight vector obtained from T2NN-DEMATEL with the normalized matrix. Finally, the scores for all transport modes are calculated (Table 12). According to the final results, the road transport is affected more than other transport modes followed by maritime and rail modes. The aviation is the least affected mode by the market development barriers for deployment of renewable fuels. The difference among score of road and maritime transport is very small, revealing very similar behaviors in the adoption and diffusion of renewable fuels.

4.6. Sensitivity analysis

This section presents several sensitivity analyses to understand effects of possible changes in the results under different circumstances and performance of the developed approach.

4.6.1. Scenario-based micro-level analysis

DEMATEL highly depends on the experts' opinions to classify the barriers into cause and effect groups as well as to identify the importance of barriers. Thus, a sensitivity analysis is conducted to measure the impact of input data on the final results based on each experts' opinions, and a scenario-based analysis is provided by varying the importance of experts.

To do so, a scenario-based framework is used to investigate possible changes in the results under different scenarios with different weighting of the experts' opinions. For this purpose, six scenarios are defined where in each scenario an expert is preferred over others. In this regard, an importance weight of 0.35 is assigned to the preferred expert in each scenario, while the others are considered at a lower uniform weight of 0.13. Results of the scenario-based DEMATEL are shown in Table 13. Compared to the initial results, scenario 1, 3, and 5 choose insufficient renewable energy policies and regulations (B6) as the most important barrier dominantly affecting the whole system. Scenario 2, 4, and 6 suggest high technology conversion challenges (B4) as the most significant barrier. Low travel range (B10) is found to be the least important barrier in all scenarios. The number of causes and effects are same in all scenarios except scenario 6, where six barriers are identified as the causes. In all scenarios, B6 and B4 are identified as the main causes. In the same way, lack of public acceptance (B2) is selected as an effect in all scenarios. High costs (B1) is determined as an effect in all scenarios except scenario 3, where higher preference is given to expert 3. While experts 2 and 3 believe that low travel range is a cause, the rest of experts disagree by considering it as an effect of other barriers. Lack of technological and market infrastructure (B5) is considered as a cause in all scenarios except for scenario 5, where high preference to expert 5 leads to B5 into the effect group.

Similar to Section 4.3, an average-based technique is utilized to determine a threshold value in the total relation matrix of each scenario in order to depict the interactions among the barriers. Fig. 6 shows interactions among barriers for all six scenarios.

4.6.2. K-means vs. K-medoids vs. Agglomerative Hierarchical algorithm

Clustering algorithms vary a lot based on their mathematical structure and suitability for specific tasks. One of the main drawbacks of the K-means algorithm is its sensitivity to outliers considering its center-based average procedure. For this purpose, a sensitivity analysis is conducted to analyze the total relation matrix using the K-medoids and the Agglomerative Hierarchical algorithm.

First the results are compared to the results of the K-medoids algorithm. Although the K-medoids is very similar to the K-means, the K-medoids forms clusters based on the distance to medoids, while the K-means forms cluster according to the distance of data points to each centroid. In other words, the K-means seeks to minimize the total squared error, whereas the K-medoids aims to minimize the sum of dissimilarities between points in each cluster from its center. A description of the K-medoids clustering algorithm is presented in Appendix D.

The K-medoids algorithm is applied using the scikit-learn library of Python, and results are shown in Fig. 7. Fig. 7(a) illustrates the distribution of elements in the total relation matrix and the identified thresholds. Identified thresholds are 0.7040, 0.7640, and 0.8172, which

Table 13
Scenario-based T2NN-DEMATEL results.

	Scenario 1				Scenario 2				Scenario 3			
Barrier	R+C	R-C	Group	Rank	R+C	R-C	Group	Rank	R+C	R-C	Group	Rank
B1	9.537	−0.318	Effect	9	23.249	−0.222	Effect	8	19.790	0.085	Cause	4
B2	9.014	−0.573	Effect	10	22.268	−0.929	Effect	10	19.574	−0.783	Effect	10
B3	8.190	−0.236	Effect	8	20.672	−0.075	Effect	7	17.765	0.058	Cause	6
B4	9.443	0.251	Cause	2	22.937	0.678	Cause	1	19.004	0.501	Cause	2
B5	9.762	0.199	Cause	3	23.822	0.139	Cause	4	20.428	0.078	Cause	5
B6	10.019	0.869	Cause	1	23.665	0.383	Cause	2	20.426	0.603	Cause	1
B7	8.982	−0.148	Effect	6	21.880	0.253	Cause	3	18.633	−0.149	Effect	8
B8	8.445	0.068	Cause	4	21.347	−0.291	Effect	9	18.711	−0.563	Effect	9
B9	8.623	0.055	Cause	5	22.139	−0.068	Effect	6	19.227	−0.132	Effect	7
B10	7.868	−0.167	Effect	7	18.910	0.131	Cause	5	17.652	0.301	Cause	3
	Scenario 4				Scenario 5				Scenario 6			
Barrier	R+C	R-C	Group	Rank	R+C	R-C	Group	Rank	R+C	R-C	Group	Rank
B1	21.749	−0.131	Effect	8	17.019	−0.568	Effect	9	14.715	−0.287	Effect	8
B2	20.828	−1.069	Effect	10	16.359	−0.741	Effect	10	14.592	−0.816	Effect	10
B3	18.967	0.181	Cause	3	14.787	0.313	Cause	3	13.405	−0.176	Effect	7
B4	21.267	0.776	Cause	1	16.604	0.500	Cause	2	14.153	0.605	Cause	1
B5	22.466	0.032	Cause	5	17.275	−0.250	Effect	8	15.349	0.241	Cause	4
B6	22.396	0.163	Cause	4	17.286	0.567	Cause	1	15.594	0.350	Cause	3
B7	20.168	0.593	Cause	2	15.437	0.310	Cause	4	13.254	0.090	Cause	5
B8	19.065	−0.371	Effect	9	15.072	−0.088	Effect	7	13.160	0.424	Cause	2
B9	20.925	−0.044	Effect	6	15.582	0.039	Cause	5	13.584	0.059	Cause	6
B10	18.103	−0.127	Effect	7	13.645	−0.082	Effect	6	12.705	−0.490	Effect	9

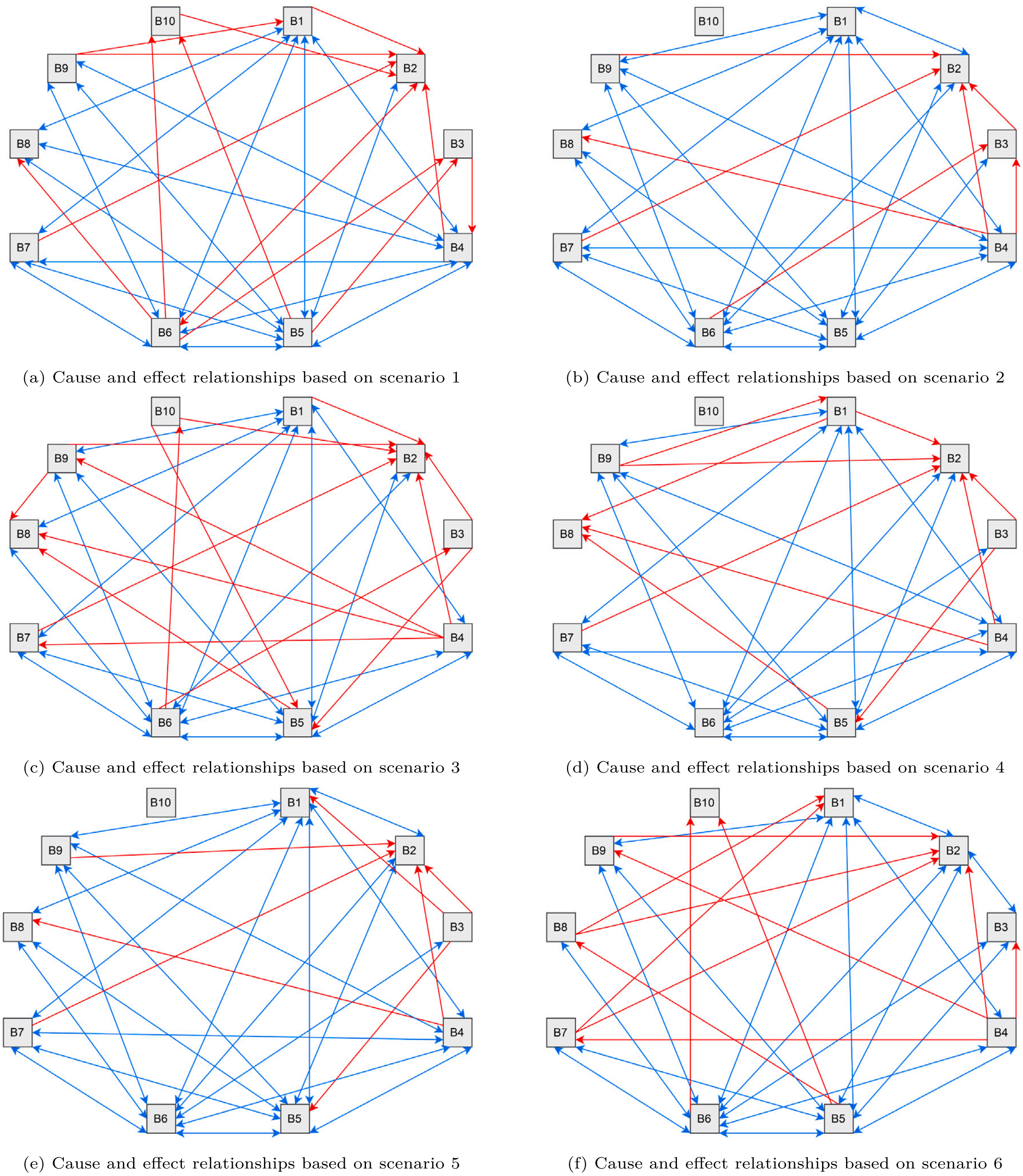
are completely different compared to the thresholds obtained by the K-means algorithm. Under such changes, the categorization of barriers based on pairwise impacts are represented in Fig. 7(b). With a glance at Fig. 7(b), K-medoids shows less conservative behavior compared to the K-means algorithm. According to the results, insufficient coordination (B7) strongly affects six barriers, while lack of renewable energy policies and regulation (B6) and lack of technological and market infrastructures (B5) only affects five and four barriers strongly, respectively. Lack of public acceptance (B2) and high initial costs (B1) are two barriers which are strongly impacted by other barriers. The results of the K-medoids indicate that lack of public acceptance (B2) and high initial costs (B1) are major effects among market development barriers. Thus, Germany could prevent high costs in renewable fuel supply chains and increase public acceptance by addressing major cause barriers, which turn to be high technology conversion challenges (B4), lack of technological and market infrastructure (B5), insufficient renewable energy policies and regulations (B6), insufficient coordination (B7), and high environmental challenges (B9). Another difference between results of the K-medoids and the K-means is related to impact of barriers on low travel range (B10). Although most of the barriers had relatively strong impact on low travel range (B10) in the results obtained by the K-means algorithm, low travel range (B10) is affected relatively strong only by insufficient renewable energy policies and regulations (B6) and insufficient coordination (B7), while other barriers show mainly slight impact on low travel range (B10) in the results of the K-medoids algorithm.

Second, the Agglomerative Hierarchical algorithm is used for the categorization of the barriers' impacts. The Agglomerative Hierarchical algorithm is a bottom-up approach to clustering. It starts with each data point as its own cluster and then iteratively merges clusters until a single cluster or a desired number of clusters is achieved. The Agglomerative Hierarchical algorithm differs from the K-means and the K-medoids in terms of approach, characteristics, and suitability for various types of data and applications. The main difference is that the Agglomerative Hierarchical algorithm does not have a concept of centroids or medoids as it builds a hierarchy by merging clusters. Moreover, the Agglomerative Hierarchical algorithm can handle clusters of various shape and sizes, including non-convex clusters, while other algorithms assume clusters to be convex. On the other hand, the K-means and the K-medoids have lower computational complexity compared to the Agglomerative Hierarchical algorithm. The procedure for implementation of the Agglomerative Hierarchical algorithm is presented in Appendix E.

The Agglomerative Hierarchical algorithm is applied using the scikit-learn library of Python, and results are shown in Fig. 8. Fig. 8(a) illustrates the distribution of elements in the total relation matrix and the identified thresholds. Identified thresholds are 0.6879, 0.7965, and 0.8654, which are different compared to the thresholds determined by the K-means and the K-medoids algorithms. Under such changes, the categorization of barriers based on pairwise impacts are represented in Fig. 8(b). Fig. 8(b) shows that most barriers have a relatively slight effect on each other followed by relatively strong effect. Results also indicate that insufficient renewable energy policies and regulation (B6) strongly affect five barriers, followed by lack of technological and market infrastructure (B5) and high technology conversion challenges (B4), which affect three barriers. Unlike the results of the K-medoids, where insufficient coordination (B7) strongly affected six barriers, B7 does not strongly affect any barrier based on the Agglomerative Hierarchical algorithm. At the same time, lack of technological and market infrastructure (B5) is strongly affected by others, which is quite similar to the results of the K-means algorithm. Obstacles in the renewable fuels supply chain can be handled by focusing on tackling the major identified challenges; high technology conversion challenges (B4), lack of technological and market infrastructure (B5), insufficient renewable policies and regulations (B6), and high initial costs (B1). Unlike the K-means algorithm, the Agglomerative Hierarchical algorithm highlights strong impacts of initial costs (B1) on market infrastructure (B5) and insufficient coordination (B7). An important difference is also visible in the strong impact of the lack of policies and regulation (B6) on environmental challenges (B9).

4.6.3. Robustness of results: impact of weight coefficients & ranking method

MCDA methods, in general, are very sensitive to the input data as well as the methods' structure and any changes may lead to different final solutions. In this regard, two different tests are designed to measure the impact of weight coefficients and ranking methods on the obtained results from the T2NN-ARAS. First, the impact of weight coefficients of market development barriers on the final ranking order of transport modes is measured using the results from the T2NN-DEMATEL with Shannon's Entropy (Pichler & Schlotter, 2020; Shannon, 2001), CRITIC (Diakoulaki, Mavrotas, & Papayannakis, 1995), and combined CRITIC-Entropy (Torkayesh, Ecer, Pamucar, & Karamaşa, 2021) (Fig. 9). In the next step, the results of T2NN-ARAS



(a) Cause and effect relationships based on scenario 1

(b) Cause and effect relationships based on scenario 2

(c) Cause and effect relationships based on scenario 3

(d) Cause and effect relationships based on scenario 4

(e) Cause and effect relationships based on scenario 5

(f) Cause and effect relationships based on scenario 6

Fig. 6. Cause and effect relationships in different scenarios.

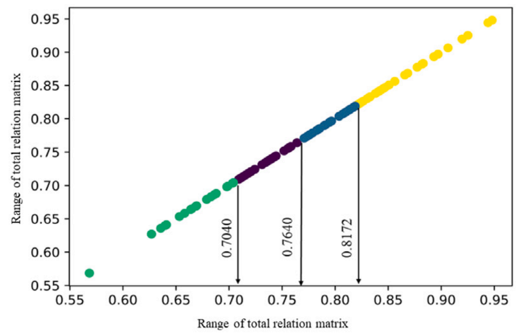
are compared with the results of the T2NN-WASPAS (Gokasar, Deveci, & Kalan, 2022), T2NN-TOPSIS (Abdel-Basset et al., 2019), and a T2NN-aggregated technique.

Fig. 9(a) represents the weight coefficients obtained by DEMATEL and weight coefficients obtained by Shannon's Entropy, CRITIC, and combined CRITIC-Entropy using an aggregation operator. According to the results, DEMATEL and CRITIC identify insufficient renewable energy policies and regulations (B6) as the most important market development barrier while Entropy and CRITIC-Entropy assign the highest coefficient to low feedstock availability (B8). On the other hand, CRITIC determines low feedstock availability (B8) as the second most important barrier while in the initial results, low feedstock availability (B8) is among the three least important barriers. Detailed results of all obtained weight coefficients are shown in Fig. 9(a). To measure the similarity and difference between ranking order under weight coefficients obtained by DEMATEL with other methods, the Spearman correlation coefficient is used based on Eq. (20).

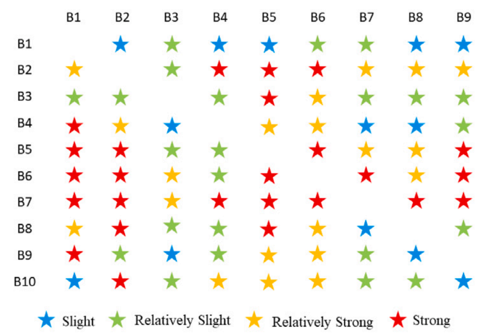
$$\rho = 1 - \frac{6\sum d_i^2}{n(n^2-1)} \tag{20}$$

where n shows the number of samples, and d_i represent the ranking order of alternative i.

The Spearman correlation coefficient between T2NN-DEMATEL and CRITIC is 0.5394, between T2NN-DEMATEL and Shannon's Entropy is −0.563, and between T2NN-DEMATEL and CRITIC-Entropy is −0.309. Similar to the previous elaboration, the high correlation coefficient between T2NN-DEMATEL and CRITIC denotes a close similarity between the results of the two methods, specifically by identifying insufficient renewable policies and regulations (B6) as the most significant barrier. Diverse weight coefficients obtained by different methods highlight

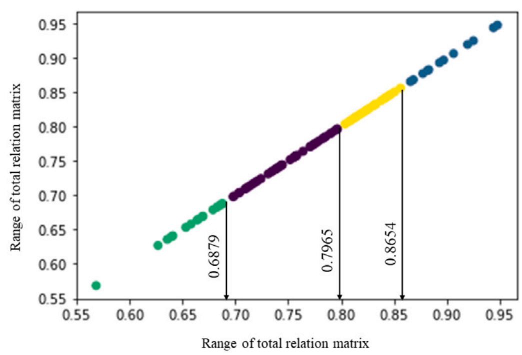


(a) Identified thresholds using K-medoids algorithm.

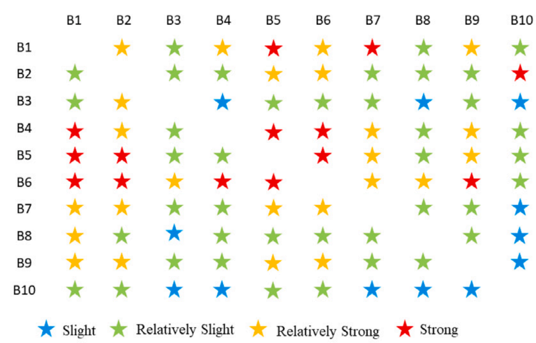


(b) Impact of barriers based on the thresholds.

Fig. 7. Categorization of barriers using the K-medoids algorithm.

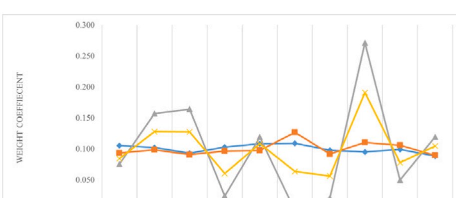


(a) Identified thresholds using the Agglomerative Hierarchical algorithm.



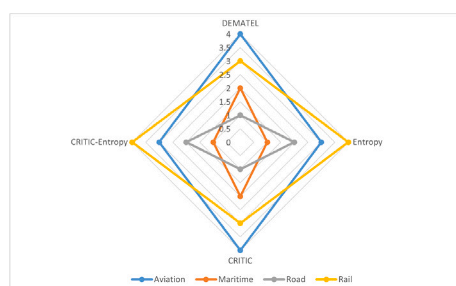
(b) Impact of barriers based on the thresholds.

Fig. 8. Categorization of barriers using the Agglomerative Hierarchical algorithm.

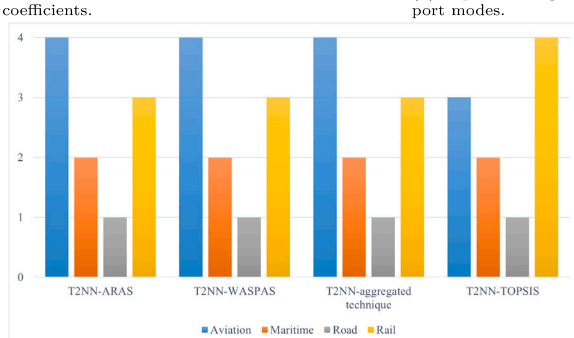


	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
DEMATEL	0.105	0.102	0.093	0.103	0.108	0.109	0.098	0.095	0.099	0.088
CRITIC	0.093	0.098	0.091	0.096	0.097	0.127	0.092	0.110	0.106	0.089
Entropy	0.075	0.157	0.164	0.024	0.119	0.000	0.020	0.271	0.049	0.119
CRITIC-Entropy	0.084	0.128	0.127	0.060	0.108	0.063	0.056	0.191	0.078	0.104

(a) Scenarios for weight coefficients.



(b) Impact of weight coefficients on ranking order of transport modes.



(c) Comparative analysis on the ranking MCDA methods.

Fig. 9. Sensitivity analysis on robustness of results.

the importance of utilization of a mixed-method for determination of weight coefficients in order to mitigate any subjectivity by using a single method. Although weight coefficients vary in all method, the impacts on the final ranking order of transport modes are slight. Fig. 9(b) illustrates how transport modes are ranked under different weight coefficients. Using weight coefficients of T2NN-DEMATEL and CRITIC, the road transport is ranked first, while it drops to the second place when weight coefficients of Shannon's entropy and CRITIC-Entropy are used. In this case, the different weight coefficients by Shannon's entropy and CRITIC-Entropy lead to a slightly different ranking order where maritime transport is found to be affected more by the market development barriers. The correlation between T2NN-DEMATEL and Shannon's Entropy is 0.6, between DEMATEL and CRITIC it is 1, and between DEMATEL and CRITIC-Entropy it is 0.6. Obtaining a correlation coefficient of 1 shows that the ranking order obtained using weight coefficients of T2NN-DEMATEL and CRITIC is fully similar. Fig. 9(b) illustrates that even assigned with low coefficient for insufficient renewable policies and regulations (B6), top ranked transport modes experiences very slight changes, such that road drops to second place and maritime rises to the first place.

As mentioned before, T2NN-WASPAS, T2NN-TOPSIS and a weighted T2NN aggregator are used to conduct a comparative analysis. Fig. 9(c) represents the ranking order of all four transport modes by different methods. All methods agree on road transport being the most affected sector. The results obtained by the T2NN-ARAS have a Spearman correlation coefficient of 1 with the T2NN-WASPAS, and T2NN-based aggregation technique showing that all results are consensus. However, the correlation between T2NN-ARAS and the T2NN-TOPSIS is 0.8 with aviation being determined as the third and rail as the fourth affected modes. One of the major reasons behind such differences may stem from the structure of TOPSIS, which applies a distance-based function, while ARAS utilizes a ratio-based weighted function.

5. Discussions

5.1. Methodological insights

Barrier analysis is a complex and multi-dimensional process that requires reliable tools to analyze the barriers in a comprehensive system covering all possible interrelationships. The suggested approach combines cutting-edge methodologies, including ISM, the MMDE algorithm, T2NN-DEMATEL improved by the K-means algorithm, and the T2NN-MCDA (T2NN-ARAS). This combination of methods provides a thorough and reliable framework for identifying and comprehending the main barriers for renewable fuels in Germany. Below, we offer details on the effectiveness of our suggested approach.

The interdependencies between the detected barriers can be more precisely and accurately analyzed with the use of the T2NN-DEMATEL, which is improved by the K-means algorithm. We tackle the inherent uncertainties and ambiguity involved with subjective evaluations by using the T2NNs, which handles uncertain information with reliable and flexible functions. Moreover, the utilization of the T2NN enables us to prioritize and compare the barriers, facilitating the identification of critical obstacles that require immediate attention. On the other hand, by combining related data points, the K-means method improves the interdependency matrix's quality and lowers the risk of bias in the results, further increasing the accuracy of DEMATEL. In this regard, the K-means algorithm empowers policymakers to classify the results into various impact groups in order to get detailed understanding of the barriers' interactions. Later, a sensitivity analysis is conducted using the K-medoids and the Agglomerative Hierarchical algorithms to measure the performance of the K-means in categorizing interrelationships into different effect groups.

ISM is a well-known and reliable tool for a deeper analysis of barriers in a macro-level perspective. To reduce the subjectivity of input data by collecting another round of data and act time-efficiently, the conversion of DEMATEL results to the ISM input is a common task, which is usually completed based on an average-based threshold or by experts. To avoid any possible subjectivity of the average threshold or expert-driven threshold, the MMDE algorithm can be used, which ensures robust estimation of the threshold value. For large-scale barrier analysis problems with high number of barriers, the MMDE can be used as a systematic technique reducing any manual adjustment to determine the threshold, specifically for multi-expert analyses where finding a consensus threshold is a difficult task. Next, the MICMAC analysis is also included in the developed holistic approach, where it aims to categorize the barriers allowing for a deeper understanding of the relationships and interactions. In other words, the analysis pinpoints the barriers with the highest driving power and dependence, indicating the key obstacles that require immediate attention and intervention. This information is crucial for policymakers and stakeholders to formulate targeted strategies and actions to address the most influential and interconnected barriers effectively.

All in all, a barrier analysis requires reliable tools to prevent any false and misleading results, which can consequently negatively affect the policy-making. The barrier analysis is improved in accuracy, dependability, and comprehensiveness thanks to the developed integrated approach that also offers insightful information on the main obstacles and their interdependencies. By using the developed approach, decision-makers and stakeholders may design effective strategies to overcome the identified barriers and support policymakers in aiming to address main barriers in the system. In case of the renewable fuels, the barrier analysis can be of high significance for policymakers considering the cross-sectoral stakeholders' opinions over multi-aspect barriers. Thus, a robust and comprehensive approach is required for detecting the main barriers and shaping the future policy framework.

5.2. Managerial implications

Based on the obtained results, insufficient renewable energy policies and regulations (B6), high technology conversion challenges (B4), and insufficient coordination in renewable fuel supply chain (B7) are three barriers with highest contribution against the market development of renewable fuels in Germany. Germany is mostly regulated by major national policies such as the EEG, the National Hydrogen Strategy, and NPM as well as the European policies including the RED III, FuelEU Maritime, and ReFuelEU Aviation. The adoption process to the recent policies has taken longer than what it should have, national policies are exclusively focused on electrification and hydrogen development, and other renewable fuels are inclusively addressed in the MFS and Climate Action Plan. Lack of policy framework for renewable fuels, specifically for PtX fuels, is the most significant challenge for their low deployment in Germany. Germany has recently launched the PtL roadmap for sustainable aviation fuels and the PtX roadmap for sustainable maritime fuels (ammonia, methanol, synthetic natural gas) (BMDV, 2021). Nevertheless, both roadmaps are in very early steps and currently face several technological challenges regarding the fuel production, fuel pricing, fuel transport, and engine suitability to new fuels. Thus, Germany needs strict regulation for renewable fuels, specifically PtX fuels, to maximize its current capacity in order to reduce the risks of failing the 2030 target. On the other hand, the National Hydrogen Strategy contributes more to the aviation providing the goal of supplying 200 kilo tons of Kerosene for German aviation by 2030 (BMWK, 2020). For maritime, Germany is collaborating with various countries in Africa, the Middle East, and South America to supply the required demand for inland and international maritime mode by 2030. Another important challenge of the policy framework in Germany is related to the infrastructures of renewable fuels that need a specific policy as the FTIP 2030 mainly addresses EVs (BMDV, 2016). Thus, Germany is advised to accordingly update the FTIP 2030 in order to be aligned with the new policies within the Fit for 55 and the

Climate Action Plan. The same problem holds for the national policies supporting biofuels.

High technology conversion challenges (B4) are the second most important market development barrier for renewable fuels in Germany. Currently, process efficiency of the renewable fuels is questioned compared to other fuel alternatives. In this regard, various R&D projects are conducted worldwide to improve the energy conversion technologies to enhance the energy efficiency of renewable fuels (BMBF, 2022). Allocation of adequate funding for the R&D projects can be considered the most critical pathway to address the high technology conversion challenges and improve the renewable fuels supply chain.

Insufficient coordination in the supply chain (B7) is another significant barrier ahead of renewable fuels, which can be considered for various supply chain processes and stakeholders such as energy generators, politicians, consumers, and production facilities. Ensuring the availability of renewable electricity by increasing its share in the total electricity generation and building a robust power grid are two vital milestones to improve the coordination for the power generators. Development of communication systems connecting various stakeholders in the supply chain is another crucial way of improving the coordination. According to the results of ISM, it can be understood that addressing regulatory and policy challenges would play a significant role in the whole system. Moreover, the lack of public acceptance is found to be a serious barrier against the development of renewable fuels in Germany. Supported by the lack of consumer awareness, public acceptance is the most important social barrier with strong effects on other barriers. Increasing awareness of consumers on benefits of renewable fuels as well as disadvantages of fossil fuels, and enhancing monetary incentives specifically for maritime and aviation sectors are effective ways to improve public awareness and therefore increase public acceptance.

6. Conclusions

Renewable fuels including PtX fuels, hydrogen, and biofuels are potential fuel alternatives for the decarbonizing the German transport sector. Germany is planning to promote renewable fuels to achieve GHG emissions reduction target by 2030 and climate neutrality by 2045. Considering the insufficient and minor decreasing trend in GHG emissions in the German transport sector, deployment of renewable fuels to achieve the targets is unavoidable. However, the promotion of renewable fuels is currently hindered by the market-dominant fossil fuels as well as other technical, economic, social, environmental, and regulatory challenges.

For this purpose, this study aims to conduct a comprehensive analysis on market development barriers for renewable fuels in Germany. To do so, a novel holistic analytical approach is suggested. First, a new extension of DEMATEL called T2NN-DEMATEL is used to investigate the barriers to understand the dynamics among them. Results of T2NN-DEMATEL are first elaborated based on an average-based technique used for determining the threshold value; later, the K-means algorithm is applied to classify the interactions among barriers under different impact groups. In the next step to understand the behavior of barriers in a macro-level perspective, the MMDE algorithm is used to convert the results of T2NN-DEMATEL into input for a macro-level analysis using the ISM. A case study is investigated for impact assessment of market development barriers in aviation, maritime, road and rail using the T2NN-ARAS method. Finally, three sensitivity analysis tests are designed to measure the impact of changes in the final results. For this purpose, a scenario-based test is used to measure the possible impact of divergent expert evaluations on the ranking order of barriers, and interactions among barriers. Next, the K-medoids and the Agglomerative Hierarchical algorithms are applied to show effect of clustering algorithms on the classification of barriers based on impact degrees. Then, Shannon's Entropy and CRITIC are utilized to highlight the impact of weight coefficients of barriers on determining the most affected transport mode by the market development barriers. At the end, three MCDA methods are used with similar data to show the consistency of results obtained by the T2NN-ARAS.

Results of the T2NN-DEMATEL indicate that insufficient renewable energy policies and regulations for renewable fuels, high technology conversion challenges, and insufficient coordination in the supply chain are most important market development barriers for renewable fuels in Germany. Moreover, barriers are categorized into cause and effect groups to highlight the cause barriers that affect the system and lead to effect barriers. In this regard, high technology conversion challenges, lack of technological and market infrastructure, insufficient renewable energy policies and regulations, and insufficient coordination are categorized as cause barriers. On the other hand, the rest of the barriers are identified as the effect barriers. Later, the K-means algorithm is applied to classify interactions among barriers under slight, relatively slight, relatively strong, and strong categories. Lack of coordination, technological conversion challenges, insufficient policies and regulation, and lack of technological and market infrastructure have the strongest impact on other barriers.

For the macro-level analysis, the MMDE was used to determine the optimal threshold value to convert the total relation matrix into the reachability matrix. The results of the ISM showed that insufficient renewable energy policies and regulations, lack of technological and market infrastructure, high costs, and lack of public acceptance are the major challenges for market development of renewable fuels, where insufficient policies and regulations plays the key role among all four. The rest of the barriers show independent influence on the market development process. Furthermore, the MICMAC analysis indicated that all market development barriers currently express autonomous behavior, highlighting the importance of addressing all barriers to succeed in the diffusing renewable fuels. The results of the case study show that road and maritime are the most affected transport modes in Germany. Aviation is the least affected sector; thus, adoption and diffusion of renewable fuels in aviation is supported more than in other sectors.

Although this study addresses an important problem within the German transport and energy sectors, several limitations exist that may be addressed in future studies. To consolidate the opinions of experts from academia and industry, one may address the same problem with the developed approach with larger numbers of experts from academia and industry. For a large-scale analysis of market development barriers, various clustering algorithms can be implemented for categorization of interactions among barriers. This study uses the weight coefficients determined by T2NN-DEMATEL for the evaluation of transport modes using the T2NN-ARAS. In future studies, subjective weight coefficients can be determined by experts using techniques such as best worst method. Moreover, the same problem can be addressed for other sectors such as industry, agriculture, and waste management. Market development, adoption and diffusion processes, has different characteristics in different transport modes. Thus, a future direction should be addressing the same problem for a specific renewable fuel in a specific transport mode.

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Appendix A. Preliminaries of T2NN

As an extension of the traditional single-valued neutrosophic set (SVNS), Abdel-Basset et al. (2019) introduced the T2NN providing more flexibility and accuracy to express uncertain information. The T2NN can be defined as follows.

Definition 1. A T2NN set $\widetilde{Z}$ in $\widetilde{X}$ can be defined as (A.1).

$$\widetilde{Z} = \{\widetilde{x}, \kappa_{\widetilde{Z}}(\widetilde{x}), \lambda_{\widetilde{Z}}(\widetilde{x}), \mu_{\widetilde{Z}}(\widetilde{x})\rangle \mid \widetilde{x} \in \widetilde{X}\} \tag{A.1}$$

where, $\kappa_{\widetilde{Z}}(\widetilde{x}) : \widetilde{X} \to \kappa[0,1], \lambda_{\widetilde{Z}}(\widetilde{x}) : \widetilde{X} \to \lambda[0,1]$, and $\mu_{\widetilde{Z}}(\widetilde{x}) : \widetilde{X} \to \mu[0,1]$. In this regard, first component of a T2NN set can be shown as Eq. (A.2).

$$\kappa_{\widetilde{Z}}(\widetilde{x}) = \left(\kappa_{\kappa_{\widetilde{Z}}}(\widetilde{x}), \kappa_{\lambda_{\widetilde{Z}}}(\widetilde{x}), \kappa_{\mu_{\widetilde{Z}}}(\widetilde{x})\right) \tag{A.2}$$

The second function can be represented as Eq. (A.3).

$$\lambda_{\widetilde{Z}}(\widetilde{x}) = \left(\lambda_{\kappa_{\widetilde{Z}}}(\widetilde{x}), \lambda_{\lambda_{\widetilde{Z}}}(\widetilde{x}), \lambda_{\mu_{\widetilde{Z}}}(\widetilde{x})\right) \tag{A.3}$$

Finally, the third component is defined based on Eq. (A.4).

$$\mu_{\widetilde{Z}}(\widetilde{x}) = \left(\lambda_{\kappa_{\widetilde{Z}}}(\widetilde{x}), \mu_{\lambda_{\widetilde{Z}}}(\widetilde{x}), \mu_{\mu_{\widetilde{Z}}}(\widetilde{x})\right) \tag{A.4}$$

For a T2NN set, the following condition must hold. $\kappa_{\widetilde{Z}}(\widetilde{x}) = \left(\kappa^1_{\widetilde{Z}}(\widetilde{x}), \kappa^2_{\widetilde{Z}}(\widetilde{x}), \kappa^3_{\widetilde{Z}}(\widetilde{x})\right), \lambda_{\widetilde{Z}}(\widetilde{x}) = \left(\lambda^1_{\widetilde{Z}}(\widetilde{x}), \lambda^2_{\widetilde{Z}}(\widetilde{x}), \lambda^3_{\widetilde{Z}}(\widetilde{x})\right)$, and $\mu_{\widetilde{Z}}(\widetilde{x}) = \left(\mu^1_{\widetilde{Z}}(\widetilde{x}), \mu^2_{\widetilde{Z}}(\widetilde{x}), \mu^3_{\widetilde{Z}}(\widetilde{x})\right)$, where $\kappa_Z(\widetilde{x}), \lambda_{\widetilde{Z}}(\widetilde{x})$ and $\mu_{\widetilde{Z}}(\widetilde{x})$ are $\widetilde{X} \to [0,1]$. For every $\widetilde{x} \in \widetilde{X} : 0 \le \kappa^1_{\widetilde{Z}}(\widetilde{x}) + \lambda^1_{\widetilde{Z}}(\widetilde{x}) + \mu^1_{\widetilde{Z}}(\widetilde{x}) \le 3$.

Definition 2. For two T2NNs denoted as $\widetilde{Z_1}$ and $\widetilde{Z_2}$, arithmetic operations can be calculated using Eqs. (A.5)–(A.7).

$$\begin{aligned}\widetilde{Z}_1 \oplus \widetilde{Z}_2 = &< (\kappa_{\kappa_{\widetilde{Z}_1}}(x) + \kappa_{\kappa_{\widetilde{Z}_2}}(x) - \kappa_{\kappa_{\widetilde{Z}_1}}(x) \times \kappa_{\kappa_{\widetilde{Z}_2}}(x), \kappa_{\lambda_{\widetilde{Z}_1}}(x)\\ &+ \kappa_{\lambda_{\widetilde{H}_2}}(x) - \kappa_{\lambda_{\widetilde{Z}_1}}(x) \times \kappa_{\lambda_{\widetilde{Z}_2}}(x),\\ &\kappa_{\mu_{\widetilde{Z}_1}}(x) + \kappa_{\mu_{\widetilde{Z}_2}}(x) - \kappa_{\mu_{\widetilde{Z}_1}}(x) \times \kappa_{\mu_{\widetilde{Z}_2}}(x)), (\lambda_{\kappa_{\widetilde{Z}_1}}(x)\\ &\times \lambda_{\kappa_{\widetilde{Z}_2}}(x), \lambda_{\lambda_{\widetilde{Z}_1}}(x) \times \lambda_{\lambda_{\widetilde{Z}_2}}(x),\\ &\lambda_{\mu_{\widetilde{Z}_1}}(x) \times \lambda_{\mu_{\widetilde{Z}_2}}(x)), (\mu_{\kappa_{\widetilde{Z}_1}}(x) \times \mu_{\kappa_{\widetilde{Z}_2}}(x), \mu_{\lambda_{\widetilde{Z}_1}}(x)\\ &\times \mu_{\lambda_{\widetilde{Z}_2}}(x), \mu_{\mu_{\widetilde{Z}_1}}(x) \times \mu_{\mu_{\widetilde{Z}_2}}(x)) >\end{aligned} \tag{A.5}$$

$$\begin{aligned}\widetilde{Z}_1 \otimes \widetilde{Z}_2 = &\langle(\kappa_{\kappa_{\widetilde{Z}_1}}(x) \times \kappa_{\kappa_{\widetilde{Z}_2}}(x), \kappa_{\lambda_{\widetilde{Z}_1}}(x) \times \kappa_{\lambda_{\widetilde{Z}_2}}(x), \kappa_{\mu_{\widetilde{Z}_1}}(x) \times \kappa_{\mu_{\widetilde{Z}_2}}(x)),\\ &(\lambda_{\kappa_{\widetilde{Z}_1}}(x) + \lambda_{\kappa_{\widetilde{Z}_2}}(x) - \lambda_{\kappa_{\widetilde{Z}_1}}(x) \times \lambda_{\kappa_{\widetilde{Z}_2}}(x),\\ &\lambda_{\lambda_{\widetilde{Z}_1}}(x) + \lambda_{\lambda_{\widetilde{Z}_2}}(x) - \lambda_{\lambda_{\widetilde{Z}_1}}(x) \times \lambda_{\lambda_{\widetilde{Z}_2}}(x),\\ &\lambda_{\mu_{\widetilde{Z}_1}}(x) + \lambda_{\mu_{\widetilde{Z}_2}}(x) - \lambda_{\mu_{\widetilde{Z}_1}}(x) \times \lambda_{\mu_{\widetilde{Z}_2}}(x)),\\ &(\mu_{\kappa_{\widetilde{Z}_1}}(x) + \mu_{\kappa_{\widetilde{Z}_2}}(x) - \mu_{\kappa_{\widetilde{Z}_1}}(x) \times \mu_{\kappa_{\widetilde{Z}_2}}(x),\\ &\mu_{\lambda_{\widetilde{Z}_1}}(x) + \mu_{\lambda_{\widetilde{Z}_2}}(x) - \mu_{\lambda_{\widetilde{Z}_1}}(x) \times \mu_{\lambda_{\widetilde{Z}_2}}(x),\\ &\mu_{\mu_{\widetilde{Z}_1}}(x) + \mu_{\mu_{\widetilde{Z}_2}}(x) - \mu_{\mu_{\widetilde{Z}_1}}(x) \times \mu_{\mu_{\widetilde{Z}_2}}(x))\rangle\end{aligned} \tag{A.6}$$

$$\begin{aligned}\theta\widetilde{Z} = \langle &\left(1 - (1 - \kappa_{\kappa_{\widetilde{Z}}}(x))^\theta, 1 - (1 - \kappa_{\lambda_{\widetilde{Z}}}(x))^\theta, 1 - (1 - \kappa_{\mu_{\widetilde{Z}}}(x))^\theta\right),\\ &\left((\lambda_{\kappa_{\widetilde{Z}}}(x))^\theta, (\lambda_{\lambda_{\widetilde{Z}}}(x))^\theta, (\lambda_{\mu_{\widetilde{Z}}}(x))^\theta\right),\\ &\left((\mu_{\kappa_{\widetilde{Z}}}(x))^\theta, (\mu_{\lambda_{\widetilde{Z}}}(x))^\theta, (\mu_{\mu_{\widetilde{Z}}}(x))^\theta\right)\rangle\end{aligned} \tag{A.7}$$

Definition 3. The score function and accuracy of $\widetilde{Z}_1$, represented by $S(\widetilde{Z}_1)$ and $A(\check{A}_1)$ can be computed using Eqs. (A.8)–(A.9).

$$\begin{aligned}S(\widetilde{H}) = \frac{1}{12}\langle 8 &+ \left(\kappa_{\kappa_{\widetilde{Z}}}(x) + 2\kappa_{\lambda_{\widetilde{Z}}}(x) + \kappa_{\mu_{\widetilde{Z}}}(x)\right)\\ &- \left(\lambda_{\kappa_{\widetilde{Z}}}(x) + 2\lambda_{\lambda_{\widetilde{Z}}}(x) + \lambda_{\mu_{\widetilde{Z}}}(x)\right) - \left(\mu_{\kappa_{\widetilde{Z}}}(x) + 2\mu_{\lambda_{\widetilde{Z}}}(x) + \mu_{\mu_{\widetilde{Z}}}(x)\right)\rangle\end{aligned} \tag{A.8}$$

$$\begin{aligned}A\left(\widetilde{Z}_1\right) = \frac{1}{4}\Big\langle &\left(\kappa_{\kappa_{Z_1}}(\widetilde{x}) + 2\left(\kappa_{\lambda_{Z_1}}(\widetilde{x})\right) + \kappa_{\mu_{Z_1}}(\widetilde{x})\right)\\ &- \left(\mu_{\kappa_{Z_1}}(\widetilde{x}) + 2\left(\mu_{\lambda_{Z_1}}(\widetilde{x})\right) + \mu_{\mu_{Z_1}}(\widetilde{x})\right)\Big\rangle\end{aligned} \tag{A.9}$$

Definition 4. Let $S\left(\widetilde{Z}_i\right)$ and $A\left(\widetilde{Z}_i\right)$ represent the score and accuracy functions, for the T2NNs $\widetilde{Z}_i (i = 1, 2)$, respectively. Comparison of two T2NNs can be made based on following statements.

- If $S\left(\widetilde{Z}_1\right) > S\left(\widetilde{Z}_2\right)$, then $\widetilde{Z}_1 > \widetilde{Z}_2$,
- If $S\left(\widetilde{Z}_1\right) = S\left(\widetilde{Z}_2\right), A\left(\widetilde{Z}_1\right) > A\left(\widetilde{Z}_2\right)$ then $\widetilde{Z}_1 > \widetilde{Z}_2$,
- If $S\left(\widetilde{Z}_1\right) = S\left(\widetilde{Z}_2\right), A\left(\widetilde{Z}_1\right) = A\left(\widetilde{Z}_2\right)$ then $\widetilde{Z}_1 = \widetilde{Z}_2$

Definition 5. For a series of T2NNs in form of $\widetilde{Z}$ with a weight vector of $\gamma = (\gamma_1, \dots, \gamma_p)^T$ while γ can take only values between 0 and 1 and total sum of weight vector must equal to 1, Type-2 Neutrosophic Number Weighted Averaging (T2NNWA) operator can be determined as follows.

$$\begin{aligned}&T2NNWA_\gamma(\check{Z}_1, \dots, \check{Z}_l, \dots, \check{Z}_p)\\ &= \gamma_1\check{Z}_1 \oplus \cdots \oplus \gamma_l\check{Z}_l \oplus \cdots \oplus \gamma_p\check{Z}_p = \bigoplus_{l=1}^{p}\gamma_l\check{Z}_l\\ &= \left(1 - \prod_{l=1}^{p}(1 - \kappa_{\kappa_{\check{Z}_l}}(x))^{\gamma_l},\ 1 - \prod_{l=1}^{p}(1 - \kappa_{\lambda_{\check{Z}_l}}(x))^{\gamma_l},\ 1 - \prod_{l=1}^{p}(1 - \kappa_{\mu_{\check{Z}_l}}(x))^{\gamma_l}\right),\\ &\left(\prod_{l=1}^{p}(\lambda_{\kappa_{\check{Z}_l}}(x))^{\gamma_l}, \prod_{l=1}^{p}(\lambda_{\lambda_{\check{Z}_l}}(x))^{\gamma_l}, \prod_{l=1}^{p}(\lambda_{\mu_{\check{Z}_l}}(x))^{\gamma_l}\right),\\ &\left(\prod_{l=1}^{p}(\mu_{\kappa_{\check{Z}_l}}(x))^{\gamma_l}, \prod_{l=1}^{p}(\mu_{\lambda_{\check{Z}_l}}(x))^{\gamma_l}, \prod_{l=1}^{p}(\mu_{\mu_{\check{Z}_l}}(x))^{\gamma_l}\right)\end{aligned} \tag{A.10}$$

Appendix B. T2NN linguistic scale

See Table B.1.

Appendix C. Evaluation of transport modes

See Table C.1.

Appendix D. K-medoids algorithm

For a data set in the form of $X = \{x_j\}$, the K-medoids can be implemented as follows. First the Euclidean distance can be determined using Eq. (D.1).

$$Distance(x_j, \alpha_i) = ((x_{j1} - \alpha_{j1})^2 + (x_{j2} - \alpha_{j2})^2 + \cdots + (x_{jm} - \alpha_{jm})^2)^{\frac{1}{2}} \tag{D.1}$$

Later, the sum of distances between cluster center points and corresponding data points is used to determine the absolute error as Eq. (D.2).

$$Error = \sum_{i=1}^{k}\sum_{j}^{n} Distance(x_j, \alpha_i) \tag{D.2}$$

This procedure continues until the center points stay the same.

Appendix E. Agglomerative hierarchical algorithm

The algorithm can be summarized as follows:

1. Start with each data point as its own cluster:

   Clusters = $\{1, 2, 3, \dots, N\}$

   where N is the number of data points.
2. Compute the pairwise distance (similarity) between all clusters.
3. Merge the two closest clusters into a single cluster:

   $C_i = \{C_j, C_k\}$

   where C_i is the new cluster, and C_j and C_k are the clusters being merged.
4. Update the set of clusters:

   Clusters = Clusters $\setminus \{C_j, C_k\} \cup \{C_i\}$

5. Repeat steps 2–4 until only one cluster remains or the desired number of clusters is reached.

Table B.1
Linguistic scale for evaluations.

Linguistic terms	T2NN value
Extremely low (EL)	$<(0.2,\ 0.2,\ 0.1),(0.65,\ 0.8,\ 0.85),(0.45,\ 0.8,\ 0.7)>$
Very low (VL)	$<(0.35,\ 0.35,\ 0.1),(0.5,\ 0.75,\ 0.8),(0.5,\ 0.75,\ 0.65)>$
Low (L)	$<(0.5,\ 0.3,\ 0.5),(0.5,\ 0.35,\ 0.45),(0.45,\ 0.3,\ 0.6)>$
Medium (M)	$<(0.4,\ 0.45,\ 0.5),(0.4,\ 0.45,\ 0.5),(0.35,\ 0.4,\ 0.45)>$
High (H)	$<(0.6,\ 0.45,\ 0.5),(0.2,\ 0.15,\ 0.25),(0.1,\ 0.25,\ 0.15)>$
Very high (VH)	$<(0.7,\ 0.75,\ 0.8),(0.15,\ 0.2,\ 0.25),(0.1,\ 0.15,\ 0.2)>$
Extremely high (EH)	$<(0.95,\ 0.9,\ 0.9),(0.1,\ 0.1,\ 0.05),(0.05,\ 0.05,\ 0.05)>$

Table C.1
Final aggregated evaluation matrix.

	B1	B2	B3	B4	B5	B6	B7	B8	B9	B10
Aviation	0.319	0.333	0.302	0.306	0.316	0.348	0.380	0.413	0.387	0.351
Maritime	0.312	0.392	0.369	0.304	0.341	0.348	0.353	0.413	0.360	0.342
Road	0.354	0.348	0.356	0.308	0.353	0.346	0.367	0.368	0.363	0.377
Rail	0.339	0.326	0.338	0.326	0.300	0.346	0.371	0.326	0.397	0.401

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