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Multicriteria Sustainability Assessment of Transport Modes: A European Union Case Study for 2020

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Abstract: The transport sector, pivotal in sustaining economic activity and regional development, stands as a double-edged sword, enhancing competitiveness and mobility while posing substantial challenges to environmental sustainability. It remains heavily dependent on fossil fuels, characterized by inefficient infrastructure and scant emphasis on environmental stewardship. This trajectory not only undermines long-term viability but also exacerbates pollution levels, including greenhouse gases and air and noise pollutants, thus degrading environmental quality and posing health risks globally. Consequently, there is an imperative need for a paradigm shift towards sustainable transport practices. This study employs the Ranking Alternatives with Weights of Criterion (RAWEC) methodology to assess the sustainability of various transport modes within the European Union in 2020. Evaluation criteria included employment numbers, turnover, final energy consumption, greenhouse gas emissions, and transport-related fatalities. Criterion weight coefficients were calculated using the Standard Deviation Method, Entropy, and FANMA methods. The findings underscore the necessity for strategic adjustments in transportation planning and policy to align with sustainability objectives.

Keywords: Sustainability; Transportation modes; Ranking Alternatives with Weights of Criterion (RAWEC); FANMA; Entropy; Standard deviation method

1 Introduction

Transport presents a significant role in the economy due to its widespread presence across various stages of the production chain and at different geographic positions [1]. Nevertheless, transport is acknowledged as the sector experiencing the most rapid escalation in environmental pollution [2]. Excluding energy generation and industrial processing, transport emerges as a substantial contributor to pollution, exerting a significant impact on environmental degradation [3].

The transport sector stands as a primary source of emissions for ozone precursors, particulate matter, and acidifying substances. Forecasts suggest that the transport sector's proportion of national emissions could rise in the foreseeable future, as advancements in emission reduction from other sectors outpace those within transportation.

At the onset of the 21st century, sustainable development garnered comprehensive acknowledgment within transport policy, marking it as a fundamental long-term objective of European development. The paradigm shift introduced by the White Paper in 2001 [4] emphasized user orientation and other sociological factors, diverging from the prior focus primarily on the transport-environment ratio. Contrary to restricted mobility, the prevailing stance of the White Paper in 2006 [5] underscored that transport policy ought to endorse and enable mobility to foster economic growth.

The contemporary paradigm shift in the understanding of sustainable transportation revolves around the notion of "sustainable mobility." A sustainable transportation system is characterized by levels of fuel consumption, vehicle emissions, safety, congestion, and social and economic access that can be maintained indefinitely without inflicting significant or irreversible harm upon future generations worldwide [6].

According to the Environmental Directorate of the Organization for Economic Co-operation and Development (OECD), environmentally sustainable transportation is characterized by a system that safeguards public health and ecosystem integrity while meeting accessibility needs. This entails using renewable resources at a rate below their natural replenishment and utilizing non-renewable resources at a rate slower than the advancement of renewable substitutes [7].

In simpler terms, a sustainable transportation system is one that:

- Meets Basic Needs: Ensures that people and communities can safely access what they need, considering both human health and the health of the environment. This includes equitable access across generations.

- Is Affordable and Efficient: Provides transportation options that are economically viable and operate smoothly, contributing to a thriving economy. It also offers a variety of modes of transportation to suit different needs.

- Minimizes Environmental Impact: Reduces emissions and waste to levels that the Earth can handle without harm. This involves using resources responsibly, recycling and reusing materials, and minimizing noise and land use [8].

When assessing the sustainability of different transport modes, it's crucial to consider a range of indicators that cover economic, environmental, and social aspects. Transport mode can perform well in one aspect but poorly in another. Therefore, a comprehensive evaluation is necessary to understand the overall sustainability of each mode.

Multi-criteria decision-making (MCDM) is the process of making decisions when faced with many options that have conflicting qualities. This approach helps by simultaneously evaluating these options across multiple criteria or attributes. Key characteristics of such problems include having numerous criteria, which may conflict with each other, and each criterion having different units of measurement. The goal is to choose the best option from a set of finite alternatives based on these criteria [9].

Methods of MCDM enable us to assess the sustainability of various transportation modes by considering multiple indicators. These methods are valuable tools for decision-making in the transportation sector, helping us not only to evaluate the sustainability of individual modes, but also to rank entire transportation systems based on their sustainability performance.

There exist several globally recognized top-tier methods of MCDM, often referred to as "higher-level" methods. Some of the most well-known methods for MCDM include TOPSIS (Technique for Order Preference by Similarity to Ideal Solutions) [10–14], AHP (Analytic Hierarchy Process) [10, 13, 15–17], EDAS [18–22], VIKOR (Višekriterijumsko kompromisno rangiranje) [12], MABAC (Multi-Attributive Border Approximation Area Comparison) [15, 23], MAIRCA (Multi-Attributive Ideal-Real Comparative Analysis) [24], SAW (Simple Additive Weighting) [25], and so on.

Certainly, establishing clear criteria and assigning weight coefficients are essential for effective decision-making [26]. Additionally, it's vital to assign weight coefficients to each criterion, indicating their relative significance in the decision-making process. Weight coefficients, which assign importance to different criteria in MCDM, can be determined using various methods such as entropy [14, 25], CRITIC (CRiteria Importance Through Intercriteria Correlation) [27], FUCOM (FUll COnsistency Method) [27], and so on.

The primary goal of this paper is to compare different transportation modes within the European Union for 2020 in terms of their sustainability. To rank these modes, the paper will utilize the RAWEC method, starting with sustainability indicators specific to transportation. Also, the influence of the weight coefficients obtained by the methods of entropy, FANMA, and standard deviation on the ranking of alternatives will be examined.

2 Literature Review

Sustainable transport has evolved from being narrowly defined as solely environmental sustainability to encompassing a broader range of dimensions. One of the frequently cited definitions comes from the Brundtland Commission's Report, which defines sustainable transport as meeting current transportation and mobility needs without jeopardizing the ability of future generations to fulfill their own needs. This definition emphasizes the intergenerational equity aspect of sustainability, highlighting the importance of ensuring that our transportation systems are viable and accessible for both present and future generations [28].

The Council of the European Union offers a more comprehensive definition of sustainable transport, which encompasses various dimensions. According to this definition, a sustainable transport system: Ensures that the basic access and developmental needs of individuals, businesses, and societies are met safely, while also promoting human and ecosystem health and ensuring equity across generations; Is affordable, operates fairly and efficiently, provides a choice of transport modes, and fosters a competitive economy and balanced regional development; Limits emissions and waste within the Earth's capacity to absorb them, utilizes renewable resources at sustainable rates, and minimizes the use of nonrenewable resources while reducing impacts on land and noise generation. This definition underscores the multifaceted nature of sustainable transportation, emphasizing its role in promoting social equity, economic prosperity, and environmental stewardship [29].

At the European Conference of Ministers of Transport in 2004, a concise definition of sustainable transportation was provided: "A sustainable transport system is accessible, safe, environmentally friendly, and affordable." This definition highlights key aspects of sustainability in transportation, emphasizing the importance of accessibility for all, safety, environmental responsibility, and affordability [30].

Awasthi et al. [31] examined four MCDM techniques, namely TOPSIS, VIKOR, SAW, and GRA, to assess the sustainability of urban transportation projects. In the comparison between TOPSIS and VIKOR, it was found that the hybrid electric bus emerges as the most suitable alternative for Taiwan's urban areas in the short and medium term. This suggests that the hybrid electric bus is identified as the best compromise alternative fuel mode for sustainable urban transportation in Taiwan [12].

Kolak and Feyzioglu [32] utilized both the TOPSIS and MACBETH (Measuring Attractiveness by a Categorical Based Evaluation Technique) methods to assess the sustainability of transport networks in several European countries.

Bojković et al. [33] presented an MCDM outranking approach called the ELECTRE method for evaluating transport sustainability on a macro level. Additionally, the authors applied a modified version of the ELECTRE (ELimination Et Choix Traduisant la REalité; Elimination and Choice Corresponding to Reality) method for assessing transport sustainability at the macro level.

Jeon et al. [34] analyzed three scenarios regarding transportation and land use at the urban level. The authors employed the simple weighted average method along with composite sustainability indices and various performance measures to conduct their evaluation.

A cross-country assessment of transport sustainability was conducted using a multi-criteria approach rooted in the outranking concept introduced by Roy [35].

Puška et al. [36] presented a novel MCDM method under the title RAWEC. The simplicity and concise nature of the RAWEC method set it apart from other MCDM methods. This method over alternative approaches is motivated by the goal of simplifying decision-making processes. While many newer methods add complexity with extra steps that complicate calculations, the RAWEC method was developed to streamline this process. Its design aims to minimize steps and avoid intricate computations. The method consists of just four straightforward steps, with the first two being foundational and applicable to all methods.

3 MCDM Methodology and Input Data

In MDCM, a conflict between different criteria can often be observed, which is the essence of every decision-making situation. When the criteria are mutually conflicting, the solution to the multi-criteria problem requires the application of complex procedures for choosing one preferred variant or determining the order of the variants.

3.1 The Entropy Method

The entropy method involves calculating the weights of objective criteria using Shannon's concept of entropy applied to the data in the decision matrix [37]. The method determines the weight coefficients of objective criteria by measuring the uncertainty in the decision matrix's information content. It does so by assessing the mutual contrast among individual criteria values across alternatives for each criterion and then across all criteria simultaneously. This method is considered objective because it derives the weight values directly from the criteria values of the alternatives, thus removing any issues related to subjectivity, lack of expertise, or the absence of a decision-maker. Also, the nature and orientation of the criteria are not important. In the initial step, the criteria values of the alternatives are normalized, resulting in a normalized decision matrix.

The entropy values represent the information contained in the normalized decision matrix for each criterion, ensuring that they fall within the range of 0 to 1 by introducing a constant. Subsequently, the divergence level is calculated based on the average information content across all criteria. Finally, the relative weights of the criteria are determined by simple additive normalization, providing a measure of the contrast intensity among the criteria.

3.2 The FANMA Method

The FANMA method calculates criteria weighting coefficients by employing the principle of distance from the ideal point, and this technique is called early weight normalization [38]. This method is based on the principle of ideal point distance and weighted normalized values. The initial values are normalized in the first step of the process. Based on the decision matrix, each element of the matrix needs to be brought to a value between 0 and 1, and then it can be said that all criteria have the same metric. Additionally, through the normalization process, the decision matrix is converted into a new matrix of weights. The ideal solution is defined as an artificial variant and represents the ideal value of the criteria. The squared distance can serve as a measure of how far each alternative is from the ideal point. Once the required recalculations are completed, the resulting vector is obtained, which is used to determine the values of the weighting coefficients.

3.3 The Standard Deviation Method

The approach of the standard deviation method coincides with the entropy method, where less importance is assigned to the criteria according to which the alternatives have a smaller range of values compared to the criteria where the values of the alternatives differ more significantly [39]. After normalizing the decision matrix, taking into account the normalized values for each criterion, the standard deviation is determined. The weight coefficients' values are directly linked to the standard deviation of the alternative's values toward the criteria.

3.4 The RAWEC Method

At the beginning, the formation of the decision matrix marks the initial step in all MCDM methodologies. During this step, the various alternatives under consideration are assessed based on the predefined criteria, resulting in the creation of an initial decision matrix.

The second step is the normalization process of the decision matrix, which is a crucial step in MCDM, including the RAWEC method [36]. When the initial decision matrix is normalized, a process known as double normalization is employed by applying Eqs. (1)-(2) [36]:

For criteria that are maximized, the normalized values are calculated as follows:

$$n_{ij} = \frac{x_{ij}}{x_{j\,\max}}, \quad n^*_{ij} = \frac{x_{j\,min}}{x_{ij}} \tag{1}$$

For the criteria to be minimized, the normalized values are calculated as follows:

$$n_{ij} = \frac{x_{j\,min}}{x_{ij}}, \quad n^*_{ij} = \frac{x_{ij}}{x_{j\,max}} \tag{2}$$

In Eqs. (1) and (2), $x_{j\,min}$ denotes the minimum value among alternatives for a specific criterion, while $x_{j\,max}$ denotes the maximum value among alternatives for the same criterion.

In the subsequent third step, the weighting of the normalized decision matrix is combined with the calculation of deviations from the criteria weights [36]. This is achieved by applying Eqs. (3) and (4):

$$v_{ij} = \sum_{i=1}^{n} w_j \cdot (1 - n_{ij}) \tag{3}$$

$$v^*_{ij} = \sum_{i=1}^{n} w_j \cdot \left(1 - n^*_{ij}\right) \tag{4}$$

where, w_j represents the weight coefficients.

For the first value (v_{ij}), a smaller deviation is desirable, while for the second value ($v^*{}_{ij}$), a larger deviation is preferable. Using these deviations, the final values of the alternatives are calculated [36].

Lastly, in the fourth step, the ranking of alternatives by the RAWEC method is computed [36]. This is achieved by applying Eq. (5):

$$Q_i = \frac{v^*_{ij} - v_{ij}}{v^*_{ij} + v_{ij}} \tag{5}$$

The results of the RAWEC method are values in a range between -1 and 1 [36]. Ranking the alternatives involves arranging them in descending order of assessment values, where the alternative with the highest value represents the ideal selection [36].

3.5 The Input Data

Indicators are quantitative measures utilized to simplify and convey complex phenomena, depicting trends and progress over time in a straightforward manner [40]. Over the past twenty years, both the scientific community and policymakers have extensively employed indicators to measure sustainability issues. The initiative to develop sustainable development indicators was initially raised as a political agenda item at the 1992 United Nations Conference on Environment and Development (UNCED) convened in Rio de Janeiro [41]. Since then, indicators have become a crucial tool for assessing various facets of sustainable development, including the promotion of sustainable transportation. Numerous international organizations have participated in crafting indicators to foster more sustainable transport practices at local, regional, and global scales. Differences in the missions and policy objectives of these organizations are mirrored in their choice of indicators. However, a common approach involves employing a three-dimensional framework of indicators that assess the economic, environmental, and social impacts of transportation activities, facilitating an impact-based analysis.

To make a transport mode ranking from the point of view of sustainability, we first must define alternatives and criteria to be implemented: entropy, FANMA, standard deviation method, and RAWEC method. Alternatives that are taken into account are Road (A_1), Air (A_2), Rail (A_3), and Water (IWW + Sea) (A_4) transport. Indicators of transport sustainability (Table 1), as outlined in the example of the European Union for the year 2020, present criteria for alternative ranking.

Table 1. Details about the indicators selected to evaluate the transport mode sustainability

Dimension	Indicator	Description	Measurement Unit	Source
Economical	CEC1	Employment of mode of transport	Number (in thousand)	Eurostat [42]
	CEC2	Turnover by mode of transport	Million euro	
	CEC3	Final energy consumption by mode of transport	Mtoe	
Environmental	CEN1	Greenhouse gas emissions from transport by mode of transport	Thousand tons of CO_2 equivalent	
Social	CSC1	Fatalities	Number	

A set of sustainable transport indicators reflecting the economic, environmental, and social dimensions is selected. These indicators cover various aspects such as employment, turnover, energy consumption, greenhouse gas emissions, and fatalities. Certainly, in analyzing the sustainable transport of European Union member states for 2020 based on sustainable transport indicators, the RAWEC method will be employed.

4 Approach Deployment and Discussion of Resultant Findings

Using the defined set of alternatives and criteria (Table 1), an initial decision matrix (Table 2) is created based on the weight coefficients of unitary criteria that affect the adopted alternatives and lead to a MCDM procedure.

Table 2. The initial decision matrix used to evaluate the transport mode sustainability

Indicator/ Transport	C_1 CEC1	C_2 CEC2	C_3 CEC3	C_4 CEN1	C_5 CSC1
Orientation	min	max	min	min	min
A_1 - Road	5075.6	454042	237.8	687.6	18836
A_2 - Air	300	59854	3	64	122
A_3 - Rail	579.9	61241	4.7	3.7	10
A_4 - Water	193	115573	3.6	137.4	20

When evaluating the sustainability of transport modes, determining the weight coefficients establishes a framework for assessing alternatives based on their performance across the selected criteria, with due consideration given to the importance of each criterion. By implementing the well-known procedures and steps for the entropy, FANMA, and standard deviation methods, the weight coefficients obtained are shown in Table 3. The goal is to assign weight coefficients to criteria in such a way that reflects their importance accurately. Typically, higher weight coefficients indicate that the corresponding criteria are considered more important in the decision-making process.

Table 3. Calculation of the weight coefficients

	C_1	C_2	C_3	C_4	C_5
Entropy	0.1740	0.0893	0.2676	0.1592	0.3099
FANMA	0.2302	0.0849	0.2317	0.2215	0.2317
Standard Deviation (SD) method	0.1367	0.1828	0.1159	0.2348	0.3298

The calculation results of weight coefficients show that entropy (0.3099) and standard deviation methods (0.3298) have the biggest values for the most important indicator C_5 (Social - Number of fatalities). The FANMA method (0.2317) shows that the most important are indicators C_3 (Final energy consumption by mode of transport) and C_5 (Social - Number of fatalities). Figure 1 presents a comparative graphical view of the calculated weight coefficients.

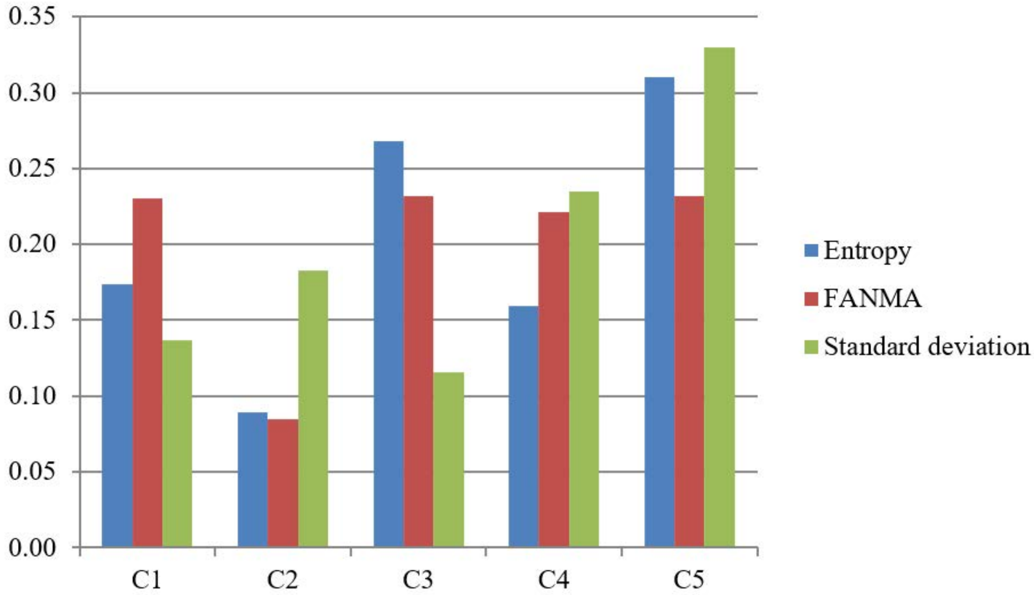

Figure 1. Graphical view of the calculated weight coefficients

Note: This figure was prepared by the authors.

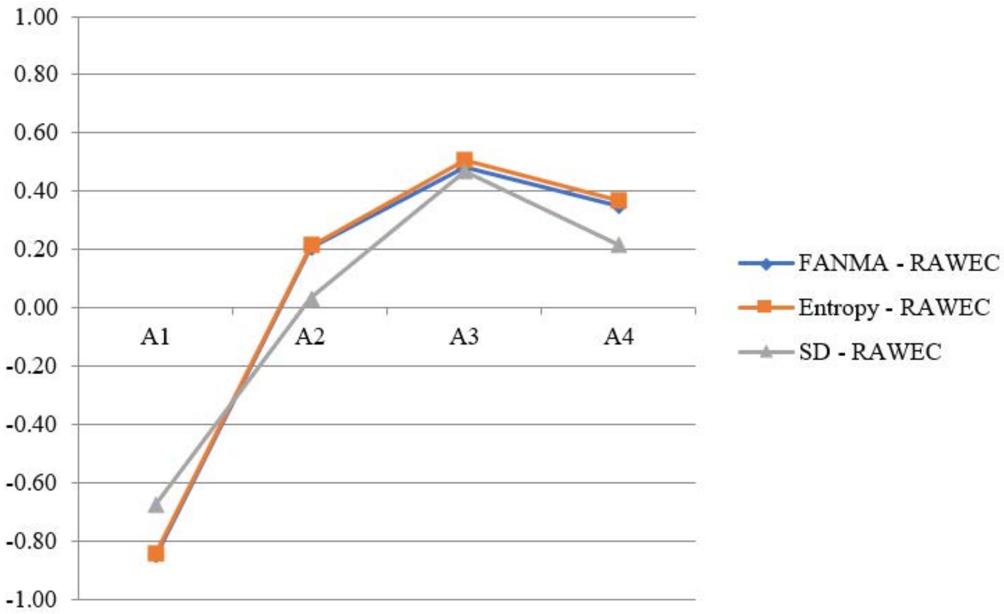

Figure 2. Graphical view of the ranking alternatives

Note: This figure was prepared by the authors.

In Table 2 and the initial decision matrix, values of criteria C_2 should be maximized (benefit), while other values of criteria C_1, C_3, C_4, and C_5 should be minimized (cost). After the determination of weight coefficients using the created initial matrix, the next step of the RAWEC method is the utilization of double normalization by Eqs. (1) and (2), i.e., a unique kind of normalization is applied, whereby every criterion is transformed into benefit criteria, then into cost criteria, and vice versa. In the third step, using Eqs. (3) and (4), the weighted normalized decision matrix with the calculation of deviation from the weight of the criteria is integrated. In the last (fourth) step, the values of the RAWEC method (Q_i) are calculated by applying Eq. (5) and are shown in Table 4.

Table 4. The transport modes sustainability ranking

	FANMA - RAWEC		**Entropy - RAWEC**		**SD - RAWEC**	
	(Q_i)	Rank	(Q_i)	Rank	(Q_i)	Rank
A_1	-0.84898	4	-0.84132	4	-0.67206	4
A_2	0.20585	3	0.21052	3	0.03446	3
A_3	0.48012	1	0.50685	1	0.46717	1
A_4	0.34966	2	0.36782	2	0.21581	2

Based on the adopted indicators, the results revealed that Rail transport (A_3) presents the best sustainable transport mode, while Road transport (A_1) presents the worst sustainable transport mode in the EU for 2020. In all cases, when using the FANMA, entropy, and standard deviation methods for the calculation of weight coefficients, the ranking by using the RAWEC method is not changed (Figure 2).

5 Conclusions

Transportation faces a significant challenge today due to its negative impact on the environment and human health, along with the imperative for sustainable development. Despite substantial efforts by the European Union, particularly its developed nations, to devise and implement transport development strategies aimed at enhancing mobility and environmental conditions, this paper indicates that rail transport demonstrates the highest level of sustainability, while road transport lags. Embracing alternative energy sources could curb the consumption of traditional fuels and mitigate greenhouse gas emissions. Therefore, there is a growing need to explore and adopt various technological and economic measures to elevate the sustainability of transportation in the European Union's developed countries.

MCDM is a complex process extensively utilized across various domains of human endeavor. Based on the above, it is evident that multi-criteria analysis can effectively rank transport modes in terms of their sustainability. In the example provided, solved through the RAWEC method, road, air, rail, and water transport were ranked based on the sustainability of their development using indicators of sustainable transport. The findings revealed that rail transport consistently secured the top position across all ranking lists, demonstrating the highest level of sustainability compared to other transport modes. Changing the weight coefficients obtained by the FANMA, entropy, and standard deviation methods did not affect the final ranking of alternatives with the RAWEC method.

Applying the RAWEC method allows for a comprehensive evaluation of sustainable transport modes in the European Union for 2020. It's important to highlight those criteria, and their relative importance can be adjusted as needed.

Furthermore, other alternative methods of multi-criteria analysis can be employed when assessing and ranking modes of transport based on their sustainability development.

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Data Availability

The data used to support the research findings are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no conflict of interest.

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