Research Article

Electric bus preference with analytical hierarchy process and grey relational analysis combination in public transportation considering modern trend criteria: Kayseri, Türkiye case study

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ABSTRACT

Objectives such as sustainable cities and communities, accessible and clean energy, and climate action, which are among the sustainable development goals determined by the United Nations, are at the forefront of public transportation. Increasing energy efficiency, cost optimization and reducing carbon emissions are key factors in selecting bus technologies to be used in urban transportation in the future. Today, many bus technologies, such as diesel, electric, compressed natural gas, hybrid, hydrogen, and fuel cells, are used in urban transportation. The type of bus that will be preferred in the future remains a hot research topic. Public transportation companies in cities should choose environmentally friendly, economical, and efficient vehicles by considering objective and subjective criteria. Currently, multi-criteria decision-making methods are widely used in the selection of vehicles in the public transportation sector. In this study, diesel, electric, and CNG buses currently used by public transportation companies operating in Türkiye were evaluated. A comprehensive study was conducted by considering five main criteria: energy, cost, technical, social, and operational and twenty-four trend sub-criteria pertaining to the main criteria. One of the new aspects of this study is that it is based on criteria that have not been used before in the literature, and the other is the use of analytical hierarchy process and grey relational analysis methods together in urban bus selection. The weights of the criteria were calculated with analytical hierarchy process, a well-established multi-criteria decision-making method, and the most suitable bus was selected by rating with grey relational analysis. According to the findings, it was concluded that the electric bus had the highest ranking with a grey relational degree of 0.774 and offered long-term advantages in terms of operational efficiency and environmental impact. This study contributed to the literature by using innovative criteria, integrated analytical hierarchy process and grey relational analysis methods, and provided a more comprehensive and objective approach to bus selection. It also provided guidance for public transportation systems for the city targeting sustainability.

Cite this article as: İnan A, Kara H. Electric bus preference with analytical hierarchy process and grey relational analysis combination in public transportation considering modern trend criteria: Kayseri, Türkiye case study. Sigma J Eng Nat Sci 2026;44(1):439–452.

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INTRODUCTION

The Reducing the operating costs and environmental impact of fossil-fuel vehicles in urban transportation is of great importance. From a global perspective, it is clear that the transition to sustainable public transportation systems is gaining momentum and making a significant contribution to reducing atmospheric carbon emissions. Numerous green transformation projects are being launched in cities to drive a global shift towards sustainable public transport. Contributing to the sustainable development goals, 100% electric transportation is critical for reducing costs, reducing greenhouse gas emissions, and using energy efficiently. Transportation policies in cities should be made more efficient by taking more steps to develop technological opportunities.

Subways, light rail systems, and buses, which are among the vehicles providing transportation mobility to the urban public, are indispensable elements of urban life. It has become necessary to choose the most appropriate type of bus compressed natural gas (CNG), diesel, electric, fuel cell, hydrogen fueled, etc.) by examining buses that are among the public transportation arguments in terms of economic, environmental, and social perspectives in ever-growing urban life. Bus selection in urban public transportation, especially bus prices, operating costs, fuel consumption, and environmental sensitivity, is an important application area for multi-criteria decision-making methods (MCDM). This method is a discipline used to solve complex problems to maximize the benefits obtained in the decision-making process.

Organizations providing public transportation services use MCDM methods in bus selection by considering many economic, environmental, and social criteria within the sustainability framework to provide maximum benefits. MCDM commonly used in the literature include analytical hierarchy process (AHP), grey relational analysis (GRA), technique for of preference by similarity to ideal solution (TOPSIS), multi-objective optimization on the basis of ratio analysis (MOORA), and vise kriterijumska optimizacija I kompromisno resenje (VIKOR). [1].

The originality of this study lies in its inclusion of criteria for bus selection in sustainable urban transportation that have not been utilized in previous literature. Existing studies often focus on limited aspects, such as cost or performance, whereas this study introduces a comprehensive set of criteria that incorporate economic, environmental, and social dimensions. The main contribution of this research is the development of a decision-making framework that combines new and innovative criteria specifically designed for urban bus selection, which address current sustainability challenges in public transportation.

This study evaluates buses based on five main criteria—performance, energy, cost, social acceptability, and usability—and twenty-four associated sub-criteria. Notably, the inclusion of unique criteria, informed by expert opinions and tailored to the specific requirements of sustainable urban transportation, fills a research gap in the existing literature. By integrating previously unused criteria, this study provides a fresh perspective on the multi-dimensional aspects of bus selection, enhancing the applicability and relevance of the results for urban planners and policymakers.

The study was carried out in the case of Kayseri province in Turkey, taking into account local conditions and needs. This increases the originality of the study and ensures the applicability of the results to local governments.

The combination of AHP and GRA methods provides more objective and consistent results in multi-criteria decision making processes. While the AHP determines the weights of the criteria, the GRA evaluates the relationships between these criteria and determines the most appropriate bus type. Bus selection in public transportation is not only evaluated by a single criterion such as cost or performance, but also many other factors such as environmental impacts, energy efficiency, social acceptability, etc. MCDM is an effective tool for managing such multidimensional and complex decision-making processes by taking into account economic, environmental and social criteria.

In the literature review, while GRA has been applied in numerous fields, its application in public transportation bus selection is novel. This study focuses on the bus selection problem of a company providing public transportation services in the Kayseri province, Türkiye. Based on the knowledge, experience, opinions, and suggestions of experts in public transportation, many criteria that have not been used before were used in the study. Thus, this study extends the field of GRA and contributes to the literature on sustainable and environmentally sensitive public transportation.

LITERATURE REVIEW

In the literature, GRA has been used to analyze the relationship between different factors and can be applied in various sectors, such as energy, finance, manufacturing, and transportation. This method's wide range of solutions to complex, multi-criteria decision-making problems makes it a valuable tool for use in many sectors. For example, in the energy sector, GRA has been used in resource selection, power planning, and in manufacturing, it has helped with supplier selection and material selection. In the transportation sector, it has been useful in studies such as deciding on the most efficient mode of transportation, vehicle efficiency and selection.

In the transportation sector, GRA is applied to select a tram vehicle for a company providing urban passenger transportation services. Owing to the uncertainty of the tram vehicle selection problem, many objective and subjective criteria have been evaluated. The validity of the results obtained with GRA was tested using the MOORA method and similar results were observed [2]. In a study conducted in Madrid, the need for sustainable city transit systems

was discussed and an AHP model was proposed in which public transportation vehicles can be evaluated according to their engine type and combustion porperties. The study concluded that plug-in electric vehicles are the most economically and environmentally sustainable alternative. It is stated that the proposed model will support policy makers and companies to make strategic decisions on sustainable urban transportation policies for the future [3]. The use of the multi-criteria decision-making tools AHP and TOPSIS for selecting the most suitable electric bus alternative for public transportation in Ankara was investigated. Six electric buses were analyzed according to seven criteria, and the bus with the most superior performance was selected. Study highlighted the advantages of electric buses in reducing emissions and improving air quality for densely populated areas [1]. The study for public transportation in Argentina investigated which bus technology is more efficient in terms of energy, environmental and economic performance. The study proposes a methodology to compare the technologies of bus fleets using a single multiphysics index that measures costs, consumption and emissions. It is predicted that electric buses will be the most advantageous option in the coming years, while hydrogen-fueled buses will be the most advantageous option from 2027 onwards [4]. In Istanbul, a public transportation bus selection study was conducted with a broader perspective that includes business and strategy as well as economic factors. In the study conducted using global fuzzy AHP and classical AHP methods, it was argued that the diesel bus type stands out [5]. After presenting the advantages of electric vehicles, the decision support system for the evaluation and selection of electric bus models among themselves is comprehensively analyzed and a new approach for MCDM using an integrated fuzzy set is presented [6].

There are different topics and different sectors where AHP and GRA methods are used other than public transportation vehicle selection. A method has been developed to select the city with the best quality of life in Turkey using Grey System Theory. The criteria used in the decision analysis were determined through a survey. The weights of the criteria were assigned using the AHP, and GRA was used to reduce uncertainty in the evaluation process [7]. In a study conducted in the transportation sector, a model for selecting the best mode for sustainability in freight transportation was proposed based on GRA and fuzzy multi-objective linear programming. The analysis presented that road transportation is the most economical mode, while maritime and rail transportation are the best modes from an environmental and social perspective [8]. In a study on the resilience of transportation networks, the effectiveness of 14 indicators was evaluated by GRA in 10 public transportation networks, and the results showed that the Global Efficiency indicator had the greatest impact on the resilience of the public transportation network [9]. GRA was used to measure urban sustainability in 15 provincial cities in China. The study established a criterion system consisting of three dimensions: Economic Development,

Social Progress and Ecological Environment, and proposed a weighting method based on grey relational analysis [10]. The impacts of urbanization, population growth, GDP per capita, energy consumption, and economic development on CO_2 emissions in Asia have been analyzed using the GRA methodology [11]. The use of an integrated GRA and a multi-objective grey linear programming approach for sustainable power generation planning is discussed. It has been argued that this approach is an effective tool for optimizing complex sustainable power generation planning [12]. The problem of urban sustainability level with three main categories and 39 sub-criteria, the issue of urban sustainability level was addressed using a modified preference ranking technique (TOPSIS). For the 16 cities, GRA was used to reduce the uncertainty inherent in the sustainability assessment process. This model was validated using a case study [13]. The physical properties of fabrics in the textile industry emphasize the importance of selecting the most suitable cotton fabric for a product to meet the final requirements. GRA technique along with Fuzzy Logic has been used to solve the problem of selecting fabric made of cotton [14]. Applications in these various fields highlight the GRA method's adaptability and effectiveness in different industries.

These applications across various fields exemplify the adaptability and effectiveness of GRA when integrated with other MCDM methods. Recent studies highlight its versatility: for instance, in supply chain management within the defense industry, GRA was paired with AHP and TOPSIS to enhance supplier selection processes, showcasing its utility in complex decision-making scenarios [15]. In resource management, GRA and AHP were combined with elemination and choice translating reality english (ELECTRE I) to identify priority areas in water meter replacement, optimizing resource allocation in utility management [16]. Furthermore, GRA has been utilized in biomedical analysis by determining the most effective molecule as an active ingredient against Covid-19, integrated with AHP for prioritizing molecular preferences. Additional examples of AHP-GRA integration include optimizing the performance characteristics of alkali-activated mortars through a mix design approach, where AHP-GRA was utilized to determine ideal combinations of factors such as activator ratios and concentrations [17]. Another study applied AHP-GRA to prioritize IoT implementation challenges in India, providing a structured approach to address technological and infrastructural barriers [18]. Finally, an AHP-GRA-EMM model was developed to assess provincial energy supply security, accurately analyzing risk factors and supporting data-driven energy management [19].

CRITERIA AFFECTING BUS SELECTION IN PUBLIC TRANSPORTATION

For a public transit bus selection evaluation system to provide the most accurate results, the criteria should be multifaceted and componentized. The criteria should

be up-to-date, comprehensive, measurable, relevant, and stable to increase the performance of the analysis. In this direction, both the literature and opinions of experts working in the sector were used to determine the criteria. A face-to-face survey was conducted by experts (general manager, engineers from the bus department at Kayseri Public Transportation Inc., engineers from the planning and sustainability department, bus drivers, and representatives from the private sector) to identify all the criteria that could determine the choice of bus for public transportation. To comprehensively evaluate the bus selection problem in public transportation, social criteria such as comfort, accessibility, and safety, and availability criteria such as uninterrupted service were considered in addition to technical criteria such as range, consumption, and cost per kilometer. The five main criteria performance (P), energy (E), cost (C), social (S), and availability (A) determined for the bus selection analysis and twenty-four subcriteria of these criteria are shown in Table 1. The main criteria represent broad categories essential for assessing the suitability of buses, addressing different dimensions of bus performance and

sustainability. The subcriteria, on the other hand, provide specific, measurable factors within each category, enabling a detailed and objective evaluation that reflects real-world considerations in public transit planning.

Performance

The four sub-criteria are the main performance criteria. These sub-criteria are measured using numerical values. The range (P1), which is the maximum distance that buses can travel with a tank with fuel or battery capacity, may vary according to the route profile and driving conditions. The range of electric buses is limited compared to other buses owing to their limited battery capacity. The limited range also limits the public transportation services offered and may increase costs. The passenger capacity (P2) of buses is determined by the number of standing and seated passengers; the more passengers a bus of the same length has, the higher its performance. The passenger capacity of buses is determined by their characteristics, such as engine power, weight, location, type, and design of the energy source storage. The engine power (P3) is a criterion to be considered for the acceleration, maximum speed, and traction

Table 1. Main and sub-criteria used in bus type selection

Performance (P)	Range (P1)	km	[1,6]
	Passenger capacity (P2)	count	[1,6]
	Engine power (P3)	kW	[1,6]
	Speed (P4)	km/h	[1,6]
Energy (E)	Consumption per km (E1)	Joule	
	Consumption per passenger (E2)	Joule	
	Emission (E3)	CO_2	[3,6]
	Unit energy price (E4)	€	
	Energy source (E5)		
Cost (C)	Fuel per kilometer (C1)	€	
	Transportation cost per passenger(C2)	€	
	Purchase cost (C3)	€	[3,5,6]
	Maintenance and operation cost (C4)	km/€	[3,5,6]
	Repair costs (C5)	km/€	[3,5,6]
	Infrastructure cost (C6)	€	[5,6]
Social (S)	Suitability for a disabled vehicle (S1)		
	Route suitability (S2)		
	Comfort (S3)		
	Safety (S4)		
Availability (A)	Mean time to periodic maintenance (A1)	Minute	
	Mean time to repair (A2)	Minute	
	Refueling/recharging time (A3)	Minute	
	Economic life (A4)	Year	
	Mean distance between failure (A5)	km	

performance of vehicles. The engine power of the buses determines the type of line profile (with or without inclines) on which they can operate. Speed (P4) is a criterion for the fuel consumption and travel time of buses and influences passengers' choice of public transportation.

Energy

There are five sub-criteria for the main criterion, energy. Four sub-criteria were measured numerically, and one sub-criterion was measured with verbal values. Consumption per km (E1) is calculated by dividing the amount of fuel consumed by buses according to their fuel technology by the number of kilometers traveled on that fuel and is a criterion that should be considered in terms of fuel efficiency in bus selection. The consumption per passenger (E2) was calculated by dividing the amount of fuel consumed by buses for the same kilometer by their passenger capacity. Emission (E3) is a measurement criterion representing the amount of emissions per kilometer that buses emit while traveling. The contribution of zero- and low-emission buses with energy-efficient technologies to sustainable environmental and energy goals is important for urban life. Electric buses have zero tailpipe emission. Other buses produce emissions, such as nitrogen oxides, particulate matter, and carbon dioxide. The unit energy price (E4) is the criterion used to compare the unit price of the energy source used by the buses. Energy is the most important input in the transportation sector. The unit energy price should also be evaluated to reflect the cost of the powering buses. The energy source (E5) indicates the type of source that generates the energy that powers buses. The type of energy source determines the efficiency of the system, as each source has its own advantages and disadvantages.

Cost

The cost sub-criterion has seven sub-criteria that are measured numerically. According to fuel technologies, the financial equivalent of the amount of fuel per kilometer (C1) consumed by the bus is expressed as cost per kilometer. We can say that the cost per kilometer has a large share in the overall cost efficiency of a public transport system, including personnel and other operating costs. It also imposes a serious burden on businesses because of constantly rising prices. This criterion is used in bus selection to determine a sustainable bus-type option with an appropriate operating cost. Transportation cost per passenger (C2) is a benchmark that considers the passenger capacity, technology, and energy resources of buses. Transport cost per passenger is a financial performance indicator that should be considered in municipalities' macro plans. The purchase cost (C3) represents the initial purchase cost of the buses. This cost is a primary determining criterion and has a significant impact on the efficiency of enterprises' investment and budgets. Maintenance and operation (M&O) cost (C4) is the criterion that shows the sum of the costs such as periodic maintenance, labor, spare parts supply, vehicle insurance, and withholding tax, which are necessary for buses to provide uninterrupted and long-term service. M&O costs vary considerably according to bus technologies and have an impact on total costs over the service period. The repair costs (C5) represent the costs of buses according to the number and size of breakdowns during the passenger transportation service. The financial aspects of breakdowns vary according to the type of bus and are evaluated in terms of other operating costs. The infrastructure cost (C6) is the criterion that defines the cost of the area to be allocated and the facility to be established so that the buses can supply their fuel and meet their other needs.

Social

The main social criterion has four sub-criteria that are measured verbally. The suitability for a disabled vehicle (S1) is the criterion for the suitability of bus types in terms of accessibility. This criterion is important for socially evaluating disabled citizens' ability to benefit from public transportation vehicles and contribute to a barrier-free life. Route suitability (S2) is the criterion used to assess the ability of buses to operate on all route profiles within a city without disrupting services. For example, electric buses may cause problems with existing bumps owing to the proximity of their bases to the ground, have low reverse maneuverability because their battery systems are usually located near the tail of the buses, and have difficulties in areas with high road gradients. Comfort (S3) defines the characteristics of buses, such as seating arrangement, aesthetics, flexibility, spatial width, noise level, and vibration, to provide a comfortable travel experience for passengers and drivers. Safety (S4) is a criterion that is evaluated depending on vehicle features so that passengers can travel without worrying about the safety of life and property in public transportation. In light of historical knowledge and experience, depending on the fuel technology of the buses, incidents such as battery combustion, fuel tank ignition, and natural gas tank explosion can be seen in the event of an accident. Safety and security in public transportation operations are of critical importance as they relate to the lives of passengers. Although public transportation vehicles are manufactured in accordance with legal safety regulations, risks may increase or decrease depending on the design of the buses.

Availability

The continuity of service is an important issue in public transportation, and there are five sub-criteria under the main criterion of availability. The mean time to periodic maintenance (A1) is the time spent on maintenance by the bus type. While maintenance helps reduce the risk of breakdowns and prolong the life of buses, longer maintenance times can lead to service disruption and reduced quality. The mean time to repair (A2) is the time required to eliminate vehicle malfunctions according to their technology. Troubleshooting time is an important maintenance time for service continuity and quality. The refueling/recharging

time (A3) affects the uptime of public transport vehicles and their availability to the passengers. For example, long refueling times for electric buses can disrupt services and increase the operating costs. Economic life (A4) defines how long buses can provide the best function and service for the investment. The mean distance between failures (MDBF) (A5) is a measure of the average distance (kilometers) traveled by a bus before preventive or restorative maintenance is required. A high MDBF value means that the service is not interrupted by failure and that the equipment and service are reliable.

METHODOLOGY

In this section, detailed information regarding the method used in bus-type selection is provided. In this study, a multi-criteria strategic decision-making methodology was proposed by integrating AHP, one of the most frequently utilized MCDM methods, and the GRA method, which allows the use of subjective criteria. In the first scenario, the weights of the criteria were computed using AHP, then the grey relational degrees were calculated using GRA, and in the last stage, bus type options were listed. In the second scenario, bus-type selection was analyzed using only the AHP method. The scenario results of the two methods were compared.

AHP (Analytic Hierarchy Process)

AHP is typically used in the process of choosing among many alternatives when there are many decision makers and criteria. AHP, developed by Saaty in the late 1970s, is a mathematical method for prioritizing alternatives in a logical and consistent manner using qualitative and quantitative factors. The hierarchical structure of this method is illustrated in Figure 1. The basic steps of the method were developed by Saaty are given below [15,16,20-22].

Step 1: In the hierarchical structure of AHP, the decision-making problem is posed in the first step and the objective is determined. A list of criteria and alternatives was prepared based on expert opinions.

Step 2: Using Saaty's table of importance levels given in Table 2 [15], the importance levels of the criteria are determined, pairwise comparison matrices are created, and the importance weights of the criteria are computed [15,20].

Step 3: Because numerical quantities in pairwise comparisons involve subjective judgments, the consistency index (CI) in Equation 1 and consistency ratio (CR) in Equation 2 were calculated to measure the acceptability of the comparison matrices.

The CI was calculated using the eigenvalue of the matrix (λ) and number of criteria (n). The ratio of CI to the value (RI) obtained from the random index table (Table 3) developed by Saaty determines the CR.

$$CI = \frac{\lambda - n}{n - 1} \qquad (1)$$

$$CI = \frac{CI}{RI} \qquad (2)$$

If the CR value is 0,1 or lower, the comparison matrix is considered acceptable and consistent. However, If the CR exceeds 0.1, the comparison matrix is inconsistent. This means that the inconsistent comparison matrix should be re-evaluated until the CR achieves the desired value.

GRA (Grey Relational Analysis)

The GRA is an important part of the Grey system theory and was developed by Deng Julong in 1982. The grey
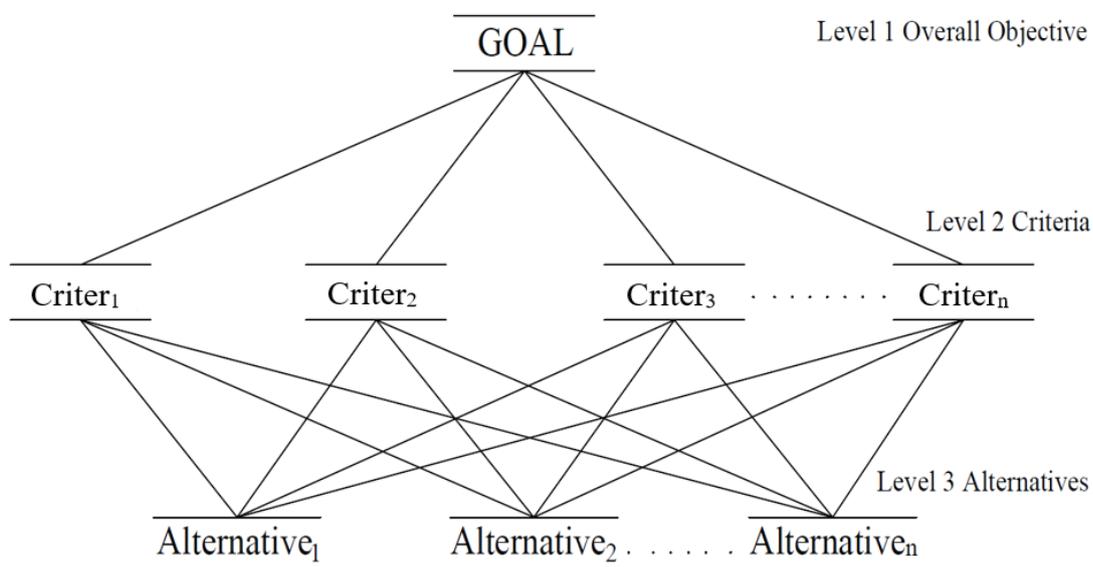

Figure 1. AHP hierarchical structure.

Table 2. Importance degree scale

Importance Degree	Conceptual correspondence	Explanation
1	Equal importance	Two activities contribute equally to the objective
3	Moderate importance of one over another	Experience and judgement strongly favor one activity over another
5	Essential or strong importance	Experience and judgement strongly favor one activity over another
7	Very strong importance	An activity is strongly favored and its dominance demonstrated in practice
9	Extreme importance	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between the two adjacent judgments	When compromise is needed

Table 3. Random index values (RI)

n	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
RI	0	0	0.58	0.9	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.58

system theory is a method that produces useful information in the mathematical analysis of problems with insufficient data and where uncertainties are defined by interval values [17,23]. In the grey system theory, known systems are expressed as white, unknown systems as black, and partially known systems as grey [2]. The GRA is a rating, classification, and decision-making technique that allows the best decision to be made according to the proximity of each criterion determined for the problem to the determined reference value.

As the GRA method is the main focus of this study, it is explained in detail in the following five steps:

Step 1: A decision matrix X_i with m alternatives and n criteria is created as shown below:

$$X_i = \begin{bmatrix} x_1(1) & x_1(2) & \cdots & x_1(n) \\ x_2(1) & x_2(2) & \cdots & x_2(n) \\ \vdots & \vdots & \cdots & \vdots \\ x_n(1) & x_n(2) & \cdots & x_n(n) \end{bmatrix} \begin{array}{l} i = 1, 2 \ldots, m \ and \\ j = 1, 2 \ldots, n \end{array} \quad (3)$$

where $x_i(j)$ is the value of alternative i for criterion j.

Step 2: The decision matrix is normalized to allow comparison of criteria with different units, resulting in the normalized matrix (Z) shown below. Normalization is performed using the following formula when a larger value is better:

$$z_i(j) = \frac{x_i(j) - min_j(x_i(j))}{max_j(x_i(j)) - min_j(x_i(j))} \quad (4)$$

When a smaller value is better, normalization is performed using this formula:

$$z_i(j) = \frac{max_j(x_i(j)) - x_i(j)}{max_j(x_i(j)) - min_j(x_i(j))} \quad (5)$$

where;

$min_j(x_i(j))$: minimum value for criterion jth
$max_j(x_i(j))$: maximum value for criterion jth

$$Z = \begin{bmatrix} z_1(1) & z_1(2) & \cdots & z_1(n) \\ z_2(1) & z_2(2) & \cdots & z_2(n) \\ \vdots & \vdots & \cdots & \vdots \\ z_n(1) & z_n(2) & \cdots & z_n(n) \end{bmatrix} \quad (6)$$

Step 3: The absolute value matrix is derived by subtracting the values of the normalized matrix, scaled between "0" and "1," from the reference series value. For each criterion, the reference series takes on a value of "1" for the highest value and "0" for the lowest value. The expression $\Delta_{0j}(j)$, which quantifies the distance and proximity to the reference series, is calculated using the following formula:

$$\Delta_{0j}(j) = |z_0(j) - z_i(j)| \quad (7)$$

Subsequently, the absolute value matrix (Δ_{ij}) is constructed based on the calculated distances for each criterion, as represented here:

$$\Delta_{ij} = \begin{bmatrix} \Delta_{01}(1) & \Delta_{01}(2) & \cdots & \Delta_{01}(n) \\ \Delta_{02}(1) & \Delta_{02}(2) & \cdots & \Delta_{02}(n) \\ \vdots & \vdots & \cdots & \vdots \\ \Delta_{0n}(1) & \Delta_{0n}(2) & \cdots & \Delta_{0n}(n) \end{bmatrix} \quad (8)$$

Step 4: The grey relational coefficients ($\delta_{0i}(j)$) used to determine the closeness of the absolute value matrix to the reference series are calculated as shown below. Δ_{min} and Δ_{max} are the minimum and maximum values, respectively, in the absolute value matrix.

$$\delta_{0i}(j) = \frac{\Delta_{min} + \rho\Delta_{max}}{\Delta_{0i}(j) + \rho\Delta_{max}} \quad (9)$$

where ρ is the distinguishing coefficient used to expand and compress the range of the grey relational coefficients. In the literature, ρ can be set as a value in the range [0,1], and is usually taken as 0.5.

Step 5: The grey relational degrees (γ_{0i}) of the alternatives are calculated by multiplying the importance weight of each criterion by the grey relational coefficient.

$$\gamma_{0i} = \sum_{j=1}^{n}[W_i(j)\delta_{0i}(j)] \quad (10)$$

where W_i is the importance weight of the jth criterion for the ith alternative calculated using the AHP method. [17] [23].

APPLICATION

The effectiveness of the bus selection model was demonstrated by the public transportation service in the city of Kayseri, Turkey, which transports approximately 350,000 passengers per day. The company, which provides services on 400 different routes with 645 buses and 8200 daily average trips, needs to make strategic decisions, as it aims to provide efficient, innovative, and state-of-the-art public transportation services. This study aims to evaluate alternatives in the bus fleet to be sensitive to the environment, reduce emissions, increase the share of renewable energy sources in energy use, and reduce costs in public transportation.

For public transportation services, three types of buses (Diesel, CNG, Electric) of 18 m are currently used in passenger transportation. These three types of buses were analyzed using the AHP and GRA methods according to five main criteria and twenty-four sub-criteria shown in Table 1. The quantitative and qualitative values of the features of the alternative buses are shown in Table 4, according to the

Table 4. Quantitative and qualitative values of the criteria

			Diesel	CNG	Electric
Performance (P)	Range (P1)	km	410	450	400
	Passenger capacity (P2)	count	141	141	144
	Engine power (P3)	kW	265	235	450
	Speed (P4)	km/h	80	80	80
Energy (E)	Consumption per km (E1)	joule	18773524	24606720	5040000
	Consumption per passenger (E2)	joule	39920305	52354214	7419600
	Emission (E3)	CO_2	1.41	1.46	0.63
	Unit energy price (E4)	€	0.648*	0.739**	0.136***
	Energy source (E5)		Poor	Poor	Excellent
Cost (C)	Fuel per kilometer (C1)	€	0.323	0.525	0.190
	Transportation cost per passenger (C2)	€	0.248	0.192	0.182
	Purchase cost (C3)	€	4950000	5450000	9600000
	Maintenance and operation cost (C4)	km/€	1.45	2.29	0.55
	Repair costs (C5)	km/€	Excellent	Good	Fair
	Infrastructure cost (C6)	€	200000	166666.67	181800
Social (S)	Suitability for a disabled vehicle (S1)		Excellent	Excellent	Excellent
	Route suitability (S2)		Fair	Fair	Good
	Comfort (S3)		Good	Good	Excellent
	Safety (S4)		Excellent	Good	Good
Availability (A)	Mean time to periodic maintenance (A1)	min	120	120	40
	Mean time to repair (A2)	min	Excellent	Fair	Good
	Refueling/recharging time (A3)	min	10	12	240
	Economic life (A4)	year	15	15	15
	Mean distance between failure (A5)	Km	783	2880	676

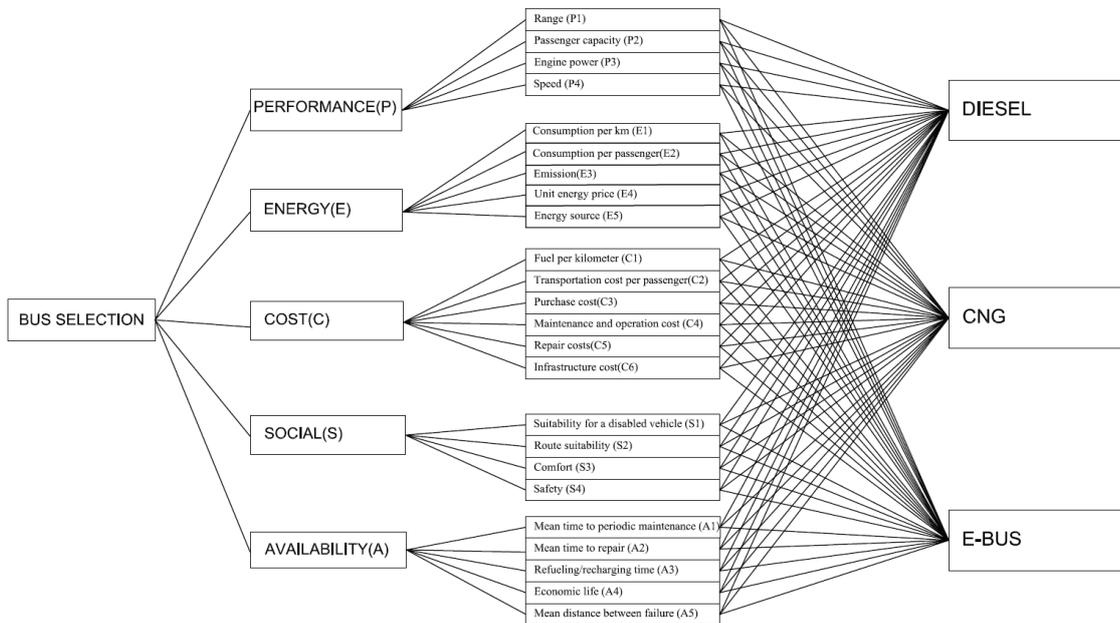*Note*: *€/lt; ** € /m³; ***€/kWh; min: Minute

Figure 2. Hierarchical structure of bus type selection.

criteria determined in line with the experience, opinions, and suggestions of the experts.

The experts are managers, engineers and consultants with at least 10 years of experience in planning, operation and maintenance in public transportation companies.

The hierarchical structure according to the bus type and selection criteria is shown in Figure 2.

To measure the effectiveness of the main criteria and sub-criteria in bus selection, the importance weights were computed using the AHP method. The importance weights of the main criteria are listed in Table 5. Among the main criteria, cost (0.423) and energy (0.309) have higher importance weights than the others and have a high impact on bus selection. The weights of the sub-criteria and the consistency ratios of the comparison matrices calculated according to Equation 9-10 are given in Tables 6-10. Because all the consistency ratios given at the bottom of these tables

are less than 0.1, it can be said that all pairwise comparison matrices are consistent.

Because there were five main criteria and 24 sub-criteria in the study, the importance weights of the main criteria were calculated first, and then the importance weights of

Table 6. The pairwise comparison matrix of the performance sub-criteria, the weights of the criteria and the consistency ratio of the matrix

Criteria	P1	P2	P3	P4	(Wi)
P1	1	3	6	5	0.528
P2	0.33	1	6	5	0.315
P3	0.167	0.167	1	0.5	0.062
P4	0.2	0.2	2	1	0.096

Note: λ=4.189; CI=0.063; RI=0.9; CR=0.07

Table 5. The pairwise comparison matrix of the main criteria, the weights of the criteria and the consistency ratio of the matrix

Criteria	P	E	C	S	A	(Wi)
P	1	0.25	0.2	0.5	0.33	0.060
E	4	1	0.5	5	4	0.309
C	5	2	1	5	4	0.423
S	2	0.2	0,2	1	0.5	0.081
A	3	0.25	0.25	2	1	0.127

Note: λ=5.205; CI=0.051; RI=1.12; CR=0.046.

Table 7. The pairwise comparison matrix of the energy sub-criteria, the weights of the criteria and the consistency ratio of the matrix

Criteria	E1	E2	E3	E4	E5	(Wi)
E1	1	3	6	4	5	0.453
E2	0.333	1	5	4	4	0.274
E3	0.167	0.2	1	0.25	2	0.070
E4	0.25	0.25	4	1	3	0.146
E5	0.2	0.25	0.5	0.333	1	0.058

Note: λ=5.410, CI=0.103, RI=1.12, CR=0.092

Table 8. The pairwise comparison matrix of the cost sub-criteria, the weights of the criteria and the consistency ratio of the matrix.

Criteria	C1	C2	C3	C4	C5	C6	(Wi)
C1	1	3	2	4	4	5	0.354
C2	0.333	1	0.5	2	3	4	0.160
C3	0.5	2	1	4	5	3	0.254
C4	0.25	0.5	0.25	1	0.5	3	0.082
C5	0.25	0.333	0.2	2	1	4	0.103
C6	0.2	0.25	0.333	0.333	0.25	1	0.048

Note: λ=6,466; CI=0.093; RI=1.24; CR=0.075.

Table 9. The pairwise comparison matrix of the social sub-criteria, the weights of the criteria and the consistency ratio of the matrix.

Criteria	S1	S2	S3	S4	(Wi)
S1	1	4	5	1	0.401
S2	0.25	1	3	0.333	0.136
S3	0.2	0.333	1	0.143	0.060
S4	1	3	7	1	0.402

Note: λ=4.065; CI=0.022; RI=0.9; CR=0.024.

Table 10. The pairwise comparison matrix of the availibility sub-criteria, the weights of the criteria and the consistency ratio of the matrix

Criteria	A1	A2	A3	A4	A5	(Wi)
A1	0.333	0.25	1	0.333	0.25	0.061
A2	0.5	0.333	3	1	0.333	0.117
A3	4	4	4	3	1	0.447
A4	1	0.5	3	2	0.25	0.149
A5	2	1	4	3	0.25	0.226

Note: λ=5.354; CI=0.089; RI=1.12; CR=0.079.

the sub-criteria of each main criterion were calculated. The final weights, calculated by multiplying the weight of each sub-criterion by the weight of the relevant main criterion, are listed in Table 11. According to the final weights, the three most important sub-criteria are consumption per kilometer, cost per kilometer, and purchase cost, which have values of 0.140, 0.128, and 0.096, respectively.

After the final weights of the criteria are calculated, the GRA method is used to determine the preference ranking of the alternatives. Table 12 presents the decision matrix obtained after entering the quantitative equivalents of the qualitative values in the dataset given in Table 4. To evaluate

Table 11. Final importance weights of the criteria

Main criteria	Main criteria weight	Sub criteria	Sub criteria weight	Final weight
P	0.059	P1	0.528	0.031
		P2	0.315	0.019
		P3	0.062	0.004
		P4	0.096	0.006
E	0.309	E1	0.453	0.140
		E2	0.274	0.085
		E3	0.070	0.022
		E4	0.146	0.045
		E5	0.058	0.018
C	0.423	C1	0.354	0.150
		C2	0.160	0.068
		C3	0.254	0.107
		C4	0.082	0.035
		C5	0.103	0.044
		C6	0.048	0.020
S	0.081	S1	0.401	0.033
		S2	0.136	0.011
		S3	0.060	0.005
		S4	0.402	0.033
A	0.126	A1	0.447	0.057
		A2	0.149	0.019
		A3	0.226	0.029
		A4	0.061	0.008
		A5	0.117	0.015

the criteria with different units on the same scale, the decision matrix was normalized using the cost-benefit method from Equations 4 and 5. For example, the range sub-criterion, which concerns performance and is desired to be high, is normalized using the benefit method, or the purchase cost criterion, which concerns cost and is desired to be low, is normalized using the cost method. The normalization matrix was scaled in the range [0-1] as shown in Table 13.

After the calculation of the normalization matrix, the absolute value matrix, which is determined using Equations 7-8 and expresses the distance of the alternative series to the reference series, is presented in Table 14. The grey relational coefficients express the similarity between the reference series and the normalized series and are used to calculate the grey relational degrees. These coefficients were obtained by using Equation 9 and are listed in Table 15.

The grey relational coefficients obtained are also shown in the radar graph in Figure 3. The radar plot is surrounded by these criteria. According to the grey relational coefficients of the alternatives for each criterion, the option that

Table 12. Decision matrix

Sub criteria	Diesel	CNG	Electric
P1	410	450	400
P2	141	141	144
P3	265	235	450
P4	80	80	80
E1	18773524	24606720	5040000
E2	39920305	52354214	7419600
E3	1.41	1.46	0.63
E4	0.648	0.739	0.136
E5	0.3	0.3	0.9
C1	0.323	0.525	0.190
C2	0.248	0.192	0.182
C3	4950000	5450000	9600000
C4	1.45	2.29	0.55
C5	0,9	0.7	0.5
C6	200000	166666.67	181800
S1	0.9	0.9	0.9
S2	0.5	0.5	0.7
S3	0.7	0.7	0.9
S4	0.9	0.7	0.7
A1	120	120	40
A2	0.9	0.5	0.7
A3	10	12	240
A4	15	15	15
A5	783	2880	676

Table 13. Normalization matrix

Sub criteria	Diesel	CNG	Electric
P1	0.200	1.000	0.000
P2	0.000	0.979	1.000
P3	0.140	0.522	1.000
P4	0.000	0.000	0.000
E1	0.298	0.000	1.000
E2	0.277	0.000	1.000
E3	0.060	0.000	1.000
E4	0.151	0.000	1.000
E5	0.000	0.000	1.000
C1	0.604	0.000	1.000
C2	0.000	0.855	1.000
C3	1.000	0.892	0.000
C4	0.483	0.000	1.000
C5	0.000	0.500	1.000
C6	0.000	1.000	0.546
S1	0.000	0.000	0.000
S2	0.000	0.000	1.000
S3	0.000	0.000	1.000
S4	1.000	0.000	0.000
A1	0.000	0.000	1.000
A2	0.000	1.000	0.500
A3	1.000	0.991	0.000
A4	0.000	0.000	0.000
A5	0.049	1.000	0.000

scans the most area in the radar graph and is closest to the reference value is the electric bus.

The grey relational coefficients of the criteria and the importance weights of each criterion are multiplied according to Equation 10 to determine the grey relational degrees of the alternatives. The grey relational degrees of the alternatives, according to the determined criteria, are listed in Table 16. Because the option with the highest grey relational degree should be prioritized, the electric bus, which has a value of 0.767 according to the grey relational degrees, is the best option among the alternatives.

Many methods can be used to create and analyze problems. In order to test the accuracy of the results, the electric bus selection problem was analyzed and ranked according to both AHP and TOPSIS methods (Table 17). It was seen that the rankings made with these methods and the GRA method rankings were the same and the GRA method solution was supported.

RESULTS AND DISCUSSION

Multi-criteria decision-making methods are mechanisms that include the opinions, suggestions, and judgments of experts in line with their knowledge, experience, and evaluation. In this context, satisfactory results could be obtained by using the functional and comprehensive approach of the AHP and GRA methods, which are multi-criteria decision-making methods.

This paper presents an effective approach for solving the problem of bus type selection for urban transportation with multiple criteria and alternatives by integrating the AHP method, which can bring objectivity and consistency, and the GRA, which can quantify the uncertainties in qualitative judgments. The combination of the two methods simplifies complex relationships and increases the reliability of the results, thus empowering the decision maker to make an informed choice.

The selection of buses for the public transportation service of Kayseri Municipality, which works on a sustainable economy, environment, and energy, has been an issue directly related to increasing energy efficiency, reducing costs, and eliminating greenhouse gas emissions. Therefore, bus selection is evaluated in light of the integrated advantages of the AHP and GRA methods by including criteria not previously used in the literature under rapidly changing technological developments.

Table 14. Absolute value matrix

Sub Criteria	Diesel	CNG	Electric
P1	0.800	0.000	1.000
P2	1.000	0.021	0.000
P3	0.860	0.478	0.000
P4	1.000	1.000	1.000
E1	0.702	1.000	0.000
E2	0.723	1.000	0.000
E3	0.940	1.000	0.000
E4	0.849	1.000	0.000
E5	1.000	1.000	0.000
C1	0.396	1.000	0.000
C2	1.000	0.145	0.000
C3	0.000	0.108	1.000
C4	0.517	1.000	0.000
C5	1.000	0.500	0.000
C6	1.000	0.000	0.454
S1	1.000	1.000	1.000
S2	1.000	1.000	0.000
S3	1.000	1.000	0.000
S4	0.000	1.000	1.000
A1	1.000	1.000	0.000
A2	1.000	0.000	0.500
A3	0.000	0.009	1.000
A4	1.000	1.000	1.000
A5	0.951	0.000	1.000

Table 15. Grey relational coefficients

Sub criteria	Diesel	CNG	Electric
P1	0.385	1.000	0.333
P2	0.333	0.960	1.000
P3	0.368	0.511	1.000
P4	0.333	0.333	0.333
E1	0.416	0.333	1.000
E2	0.409	0.333	1.000
E3	0.347	0.333	1.000
E4	0.371	0.333	1.000
E5	0.333	0.333	1.000
C1	0.558	0.333	1.000
C2	0.333	0.775	1.000
C3	1.000	0.823	0.333
C4	0.492	0.333	1.000
C5	0.333	0.500	1.000
C6	0.333	1.000	0.524
S1	0.333	0.333	0.333
S2	0.333	0.333	1.000
S3	0.333	0.333	1.000
S4	1.000	0.333	0.333
A1	0.333	0.333	1.000
A2	0.333	1.000	0.500
A3	1.000	0.983	0.333
A4	0.333	0.333	0.333
A5	0.344	1.000	0.333
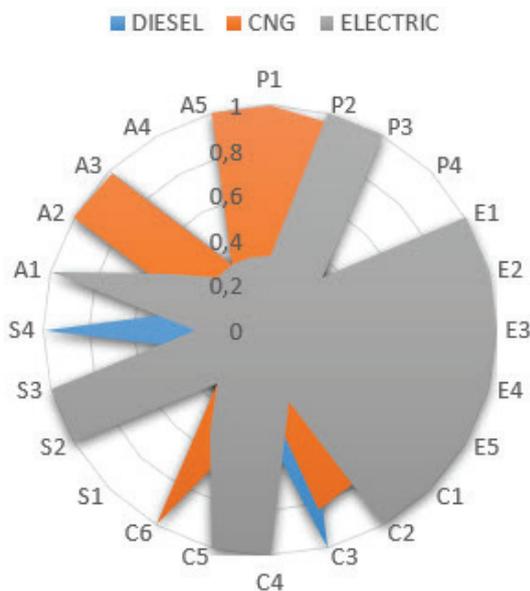
Figure 3. Grey relational coefficients radar plot.

Tablo 16. Grey relational degrees and ranking of alternatives

	Grey relational degrees	Rank
Diesel	0.525	3
CNG	0.535	2
Electric	0.774	1

In this study, three bus types (Diesel, CNG, Electric) were ranked according to their grey relational ranking using five main criteria (performance, energy, cost, comfort, and availability), and twenty-four sub-criteria in total.

- In the analysis, the electric bus received the highest ranking for consumption per km, cost per km, maintenance and repair costs, and emission criteria, and the lowest ranking for procurement and infrastructure installation costs.
- According to the application outputs, the electric bus has a higher rating than the diesel and CNG buses in 14 of the twenty-four sub-criteria. This shows that the electric bus is a superior option compared to other alternatives.

Tablo 17. Importance degrees and ranking of alternatives

	AHP importance degrees	Rank	TOPSIS relative closeness value	Rank
Diesel	0.152	3	0.320	3
CNG	0.385	2	0.429	2
Electric	0.463	1	0.769	1

- Consequently, despite the disadvantages of electric buses, such as high purchase costs, short range, and long charging times, it has been shown that it is a preferable vehicle when other advantageous criteria are considered.
- As a result of the analysis, it was found that the electric bus is superior in environmental and economic criteria such as energy consumption, cost per kilometer, and emissions, while the diesel bus has advantages such as lower purchasing costs and longer range. The CNG bus, on the other hand, offers a good option in terms of infrastructure costs and emission rates. These results indicate that the electric bus is generally the best option. However, other bus types can also be evaluated according to urban transportation needs, where they may be more suitable under certain operational and economic conditions.
- The fact that electric buses are the most suitable bus type for urban public transportation according to the criteria determined by experts is also consistent with similar studies in the existing literature. Other studies in the literature have also revealed that electric buses have advantages over other bus types, especially in terms of sustainability and energy efficiency.

Overall, the integration of AHP and GRA methods provided a robust framework for evaluating bus options in urban transport. The findings show that electric buses offer significant advantages, especially in terms of environmental impact and long-term operational efficiency.

CONCLUSION

This study, which resulted in the selection of electric buses with the highest scores according to the determined criteria, will guide urban public transport service providers towards environmentally, economically and socially sustainable transportation in the future. This study is limited to the local context of Kayseri and the determined criteria. The study can be applied to other regions by considering the methodology developed here, new technologies, region-specific criteria and operational needs. Future research can focus on integrating additional criteria such as policy, battery technologies, incentives, which can further support the adoption of electric buses.

AUTHORSHIP CONTRIBUTIONS

Authors contributed equally to this work.

CONFLICT OF INTEREST

There are no potential conflicts of interest regarding the research and publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

STATEMENT ON THE USE OF ARTIFICIAL INTELLIGENCE

Artificial intelligence was not used in the preparation of the article.

REFERENCES

[1] Hamurcu M, Tamer E. Electric bus selection with multicriteria decision analysis for green transportation. Sustainability 2020;12:2777. [CrossRef]

[2] Canbulut G, Köse E, Arik OA. Public transportation vehicle selection by the grey relational analysis method. Public Transport 2022;14:367–384. [CrossRef]

[3] Rivero Gutiérrez L, De Vicente Oliva MA, Romero-Ania A. Managing sustainable urban public transport systems: An AHP multicriteria decision model. Sustainability 2021;13:4614. [CrossRef]

[4] Munoz P, Franceschini EA, Levitan D, Rodriguez CR, Humana T, Perelmuter GC. Comparative analysis of cost, emissions and fuel consumption of diesel, natural gas, electric and hydrogen urban buses. Energy Convers Manag 2022;257:115412. [CrossRef]

[5] Buran B, Erçek M. Bus type selection with fuzzy approach for public transportation. Syst Soft Comput 2023;5:200055. [CrossRef]

[6] Alamodi AH, Albahri OS, Deveci M, Albahri AS, Yussof S, Dinçer H, Yüksel S, Sharaf IM. Selection of electric bus models using 2-tuple linguistic T-spherical fuzzy-based decision-making model. Exp Syst Appl 2024;249:123498. [CrossRef]

[7] Kose E, Vural D, Canbulut G. The most livable city selection in Turkey with the grey relational analysis. Grey Syst Theory Appl 2020;10:529–544. [CrossRef]

[8] Fulzele V, Shankar R, Choudhary D. A model for the selection of transportation modes in the context of sustainable freight transportation. Ind Manag Data Syst 2019;119:1764–1784. [CrossRef]

[9] Hu M, Bhouri N. Evaluation of resilience indicators for public transportation networks by the grey relational analysis. IEEE International Conference on Intelligent Transportation Systems (ITSC) 2020. [CrossRef]

[10] Yi P, Dong O, Li W, Wang L. Measurement of city sustainability based on the grey relational analysis: The case of 15 sub-provincial cities in China. Sustain Citi Soc 2021;73:103143. [CrossRef]

[11] Rehman E, Rehman S. Modeling the nexus between carbon emissions, urbanization, population growth, energy consumption, and economic development in Asia: Evidence from grey relational analysis. Energy Rep 2022;8:5430–5442. [CrossRef]

[12] Malekpoor H, Chalvatzis K, Mishra N. Integrated grey relational analysis and multi objective grey linear programming for sustainable electricity generation planning. Ann Oper Res 2018;269:475–503. [CrossRef]

[13] Tang J, Zhu HL, Liu Z, Jia F, Zheng XX. Urban sustainability evaluation under the modified TOPSIS based on grey relational analysis. Int J Environ Res Public Health 2019;16:256. [CrossRef]

[14] Chakraborty S, Chatterjee P, Das PP. Cotton fabric selection using a grey fuzzy relational analysis approach. J Inst Eng (India) Ser E 2019;100:21–36. [CrossRef]

[15] Efe Evcioglu H, Kabak M. Supplier selection in supply chain network using MCDM methods. Sigma J Eng Nat Sci 2023;41:1–16. [CrossRef]

[16] Yilmaz S, Firat M, Bozkurt C, Özdemir Ö. Identification of the priority regions in the customer water meters replacement using the AHP and ELECTRE methods. Sigma J Eng Nat Sci 2021;39:331-342. [CrossRef]

[17] Mishra A, Lahoti M, Khare S, Yang E. Recycling electric arc furnace slag through tailoring of ambient-cured alkali-activated mortar mix using hybrid AHP-GRA and TOPSIS. J Clean Prod 2024;452:142216. [CrossRef]

[18] Teli TA, Masoodi FS. IoT implementation in India: A complex decision process using GRA/AHP. 10th International Conference on Computing for Sustainable Global Development (INDIACom) 2023. p. 773–778.

[19] Gong X, Huang Y, Yun X, Zhang T, Li Y, Peng B. Provincial energy supply and demand risk assessment based on GRA-AHP-EWM method. Proceedings of the 3rd International Conference on Big Data, Artificial Intelligence and Risk Management (ICBAR) 2023. p. 699–704. [CrossRef]

[20] Saaty TL. How to make a decision: The analytic hierarchy process. Eur J Oper Res 1990;48:9–26. [CrossRef]

[21] Saaty TL. Decision making with the analytic hierarchy process. Int J Serv Sci 2008;1:83. [CrossRef]

[22] İnan A, Kara H. Urban railway system route selection in Turkey based on socio-economic and technical criteria using the analytical hierarchy process. Transp Res Record 2022;2676:633–644. [CrossRef]

[23] Liu S, Yang Y, Xie N, Forrest J. New progress of grey system theory in the new millennium. Grey Syst Theory Appl 2016;6:2–31. [CrossRef]