Energy Strategy Reviews 47 (2023) 101077

Contents lists available at ScienceDirect

Energy Strategy Reviews

journal homepage: www.elsevier.com/locate/esr

Optimal routing for mass transit systems using multicriteria methodologies

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ARTICLE INFO

Keywords:
Decarbonization of public transport
Multicriteria analysis
Public bus transport
Electric buses
PROMETHEE

ABSTRACT

Transportation consumes approximately 29% of the world's energy and is responsible for approximately 25% of CO_2 emissions worldwide. In Cuenca, Ecuador, fossil fuels for transportation represent 59.9% of total energy consumption. Ecuadorian legislation has specified gradually replacing traditional public bus transport units with electric units. Because the relevant costs include those associated with replacing equipment and improving route networks, alternatives that prioritize incorporating the first units on the best routes are being sought. This work establishes a methodological process with a set of tools to prioritize the gradual migration from conventional to electric buses according to the characteristics of each route. The Preference Ranking Organization Method for Enrichment of Evaluation (PROMETHEE) multicriteria technique is used to detect the best routes according to technical, social, environmental, economic and location criteria. A final rank of routes is obtained using Visual PROMETHEE software. After the values defining each criterion and its corresponding weight were processed, the final ranking makes it possible to prioritize one route before others. Given 23 lines and 475 bus units, the method enabled us to determine that in an initial phase, 68 electric buses are required to be used on five lines to reduce fuel consumption. The factors that most influence decision making are the number of passengers served, the length of the trip and the energy required by the route.

1. Introduction

The transportation sector's dependence on fossil fuels results in the production of a series of pollutants that have impacts at the local, regional and global levels. This situation has led to efforts to promote the use of clean renewable energy and to shift to electrical alternatives [1]. Efforts are being made worldwide to replace transport units powered by fossil fuel with electrical units [2,3]. However, a gradual change typically occurs along with infrastructure changes and economic issues.

In Cuenca, Ecuador, the motorized transport sector generates 94.5% of the total carbon monoxide, 71.2% of the total nitrogen oxide, and 30.2% of the total sulfur dioxide emissions, and fossil fuels for transportation represent 59.9% of the total energy consumption. Cuenca is located 2500 m above sea level and close to the equator. As a consequence of the excellent climate conditions, the main energy requirement is for transportation, which is responsible for most of the pollution in the city, as reported by Barragan [4]. Finding ideal routes for clean public bus transport is strategic because energy savings, travel time, the preservation of transport units, reduced maintenance, and costs and emissions reduction depend on finding such routes [5].

Article 14, entitled "Eficiencia energética en el transporte" ("Energy efficiency in transport"), of the "Ley Orgánica de Eficiencia Energética" ("Organic Law of Energy Efficiency") (March 2019), states that "From the year 2025, all vehicles that are incorporated into the urban and interparish public bus transport service in continental Ecuador shall only be electric-powered" [6]. The short-term barriers to this goal are the cost and infrastructure required by these units.

The introduction of electric buses into the transportation system in the city of Cuenca has been analyzed. An electric infrastructure for electric charging stations that will initially supply 68 units belonging to the consortium (CONCUENCA) has been proposed; for a single electric charging station, the investment in the first stage will be approximately $45,000 for materials and approximately $270,000 for all necessary stations [7].

Among electric buses, the K9FE model of the BYD (Build Your Dreams) company is in the testing and operation stages in Ecuador in the cities of Loja, Cuenca and Guayaquil. Therefore, this type of vehicle is taken as a reference for this analysis [7,8]. BYD buses have a robust chassis and can accommodate up to 85 passengers. The K9FE model is

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https://doi.org/10.1016/j.esr.2023.101077
Received 14 July 2022; Received in revised form 29 January 2023; Accepted 13 March 2023
Available online 21 March 2023

List of abbreviations

AHP	Analytic hierarchy process
ANP	Analytic network process
CONCUENCA	Companies of Cuenca-Ecuador Association
DRM	Direct rating method
EW	Equal Weights
MAUT	Multiattribute utility theory
MAVT	Multiattribute value theory
MCDM	Multiple conflicting criteria in decision making
OR	Ordinal method determination
PADECO	Pilot Transportation Plan for Cuenca
SIT	Regulatory institution to modernize transport
THD	Total harmonic distortion
TOPSIS	Technique for Order Preference by Similarity to Ideal Solutions
UTA	Utility additive.

100% electric, the maximum power recorded by the wheel drive motor is 150 kW, and the maximum torque is 550 Nm, all in both traction wheels. These buses do not generate polluting emissions and produce very little noise [9,10].

The main motivation of this research is the proposal of a novel easy-to-apply methodological process to determine the adequate order for replacement of public bus transport units by characterizing existing routes and then identifying a set of criteria to determine the most favorable situation. To do so, tools for decision making are fundamental since a successful decision in a complex area that involves various criteria determines a project's success. In this work, decision making is modeled to ensure that it is easily understood and simple to implement. It is important to study the alternatives and the criteria used to evaluate the alternatives. This process of selecting based on a series of criteria is called MCDM [11–13].

In this research, the PROMETEHEE multicriteria method is used to determine the most appropriate routes to gradually replace diesel buses with electric buses. This choice guarantees that the gradual inclusion of buses incorporates technical, economic, environmental and social criteria. This proposal is applicable, especially in developing countries, because of the difficulties that could arise to acquire electric buses and its implementation in principle would consider few units, hence the attempt to obtain the greatest possible benefit through the correct selection of routes. Compared to other projects with a similar line of research, more than 5 criteria and 14 subcriteria are included, which provides greater solidity to the final decision ranking. In this way, the operation of this new fleet of buses is expected not only to optimize resources but also to guarantee the acceptance of authorities, carriers and citizens.

In the first section of this article, the problem is described, and the need to adequately incorporate the first electric bus units is shown. Then, a review of the literature is conducted, especially that in which multicriteria methods are used in the field of transportation. The methodological part describes the steps and tools used to achieve the proposed objectives. The results section describes the study area, the routes to be studied, and the criteria and subcriteria considered. Finally, the results are put in context with those obtained in other investigations.

2. Literature review

In previous research, Nassereddine & Eskandari [14] proposed six subcriteria of analysis: travel price, travel time, waiting time, accessibility, safety, and suitability. Joubert [15] then established that sloped roads are an important parameter in terms of energy consumed and emissions. Lopez-Ibarra et al. [16] proposed a methodology to manage the useful life of the batteries of an entire fleet to improve the total cost of hybrid electric buses.

Efficient transport routes represent significant strategies to reduce costs and pollutants, as well reduce traffic issues. Das M. et al. [17]. developed automatic algorithms, such as the modified genetic algorithm, with the capability to improve ship routes automatically when analyzing diverse traveling scenarios by sea to improve routed distance, travel time and fuel consumption. Bahalque et al. [18] proposed a novel methodology to resolve how to improve efficient routes for multiple vehicles to multiple nodes, considering that vehicles are typically programmed to visit each spot sequentially. Bahalque proposec a new algorithm to analyze alternatives through alternative interconnections not necessarily following the sequential rigid order but allowing several vehicles to start from different nodes fulfilled by various potential suppliers. Along with this methodological process, through stochastic processes considering random situations, Marcovic, D et al. used combinatorial optimization to reduce trips to 10% and further reduce energy requirements for municipal waste collection [19].

Yildirim and Bediroglu [20] applied sensitivity tests to datasets using the related AHP weights. The evaluation process was accelerated with the AHP and sensitivity analysis (AHP-SA) tool, thus building 120 simulations (30 trips for each criterion). Similarly, Hamurcu and Eren [21] considered only the main scenario. Grassini & Viviani [22] generated the final ranking from a combination of three scenarios: equal weights, weights from customer satisfaction surveys and weights determined through interviews with the managers of the transportation system. Finally, Nassereddine & Eskandari [14] applied seven scenarios: for the first six, all the preference functions of the PROMETHEE multicriteria methodology were considered, and for the last scenario, a combined linear and level preference function was used.

According to Hamurcu and Eren [21], the most important subcriteria are sensitive areas, soil structure, population density, capacity for expansion and development, and the cost of construction. Grassini and Viviani [22] conducted interviews with users and authorities to classify the effectiveness of the bus routes that operate in Florence. V. Yildirim and S. Bediroglu [20], the AHP multicriteria methodology integrated with geographic information system (GIS) technologies was used, and eight economic and environmental subcriteria were established: slope, geology, soil quality, rivers, protected areas, roads, land cover and lakes.

In contrast to other studies, this study proposes five criteria and 14 subcriteria, which enables us to cover the problem in an extended manner compared to previous methodologies. In short, this paper has an advantage in terms of more consolidated results compared to those obtained previously [14,20,22–24].

Using Cuenca (where this research takes place) as the background, González et al. [8] determined the energy required by an electric bus to cover a complete route for each existing route. Within this research, the best qualified line is represented by the ninth alternative. This alternative is presented as more favorable in terms of the slopes on the route, an important parameter, in accordance with [20]. Finally, Wenz et al. [25] developed a methodology to establish the priority for transitioning from buses with internal combustion engines to electric buses for Cuenca by establishing the following four criteria: the state of the charge of the batteries at the end of a day of operation, the proportion of the distance traveled by each bus line through a critical area of the city, the resulting CO_2 emissions and the number of passengers transported. The authors found that bus lines 18 (15 electric units), 19 (15 electric units) and 14 (20 electric units) obtained the highest scores and thus recommended these lines as the first lines to be fully electrically operated, resulting in the incorporation of 50 electric units in the first stage. This study extends the study by Weiz et al. [25], who focused on bus routes that cover only the Historic Center of Cuenca, while this study includes other routes and uses more criteria that strengthen the decision process. For a developing country, this analysis is essential so that the gradual entry of electric buses is implemented in such a way that decision making optimizes the use of resources and shows society the advantages of electrifying public bus transport.

2.1. MCDM applied to transport

To strengthen the decision-making process, multicriteria techniques are used to find the most appropriate routes to ensure that the reversal of urban mobility is efficient. According to the decision context and approach, the most commonly applied multicriteria decision-making (MCDM) methods can be classified into two large groups: methods based on the theory of value and classification methods [26].

First, methods based on the theory of value include multiattribute value theory (MAVT), which seeks to evaluate the value of alternatives globally [27]. These approaches also include multiattribute utility theory (MAUT) methodology: proceeding logically and manageably, MAUT seeks to establish trade-offs between conflicting objectives [28].

Another value theory method is the additive utilities (UTA) method, which requires solid mathematical training and involves a methodical procedure based on linear programming [29]. In contrast, measuring attractiveness by a categorical-based evaluation technique (MACBETH) is a multicriteria decision analysis approach that requires only qualitative judgments concerning differences in value [30]. The Visekriterijumska Optimizacija I Kompromisno Resenje (VIKOR) method, which, translated from Serbian, means "multicriteria optimization and compromise solution," is designed to choose among several alternative candidates; the final selection is made using complex criteria [31]. Among the most recognized value theory methodologies is the technique for order of preference by similarity to ideal solution (TOPSIS), which is presented in Ref. [32] with reference to Ref. [33]; this technique aims to provide support to decision makers when choosing among several alternatives by identifying the best and worst conditions [13,31]. Another method that has been accepted by the international scientific community as a robust and flexible tool for decision making with multiple criteria is the analytic hierarchy process (AHP) [34], which handles complex decision problems that may involve both qualitative and quantitative aspects [13]. Finally, another value theory method is the analytic network process (ANP), which improves communication, resolves conflicts, helps distribute responsibility and allows decision makers to understand the perspectives of other members [35].

The second group of MCDM methods consists of classification methods [26]. This group includes the robust ordinal regression for classification and choice problems (UTA GMS); this methodology considers the global set of compatible value functions to solve the problems of selection and classification [36]. Another MCDM method is the ELECTRE (elimination and choice expressing reality) method, based on the concepts of concordance and discordance and the democratic principle of a majority without a strong minority [37]. Finally, the preference ranking organization method for enrichment of evaluations (PROMETHEE) is notable; the method's main idea is to generate a partial or complete classification of alternatives according to the positive outranking flow, negative outranking flow and net outranking flow [38].

MCDM methods have been applied to various topics related to the transportation sector. Table 1 shows publications that have used MCDM methods in mobility studies. These projects have as a common axis the application of one or several MCDM methods that lead decision makers to select the best option in practical cases within their respective locations and refer to the subject of transport, whether the method is used to select optimal routes or address quality or planning problems [14, 20–24,39–41].

Table 1
Multicriteria techniques in articles related to transport.

No.	Objectives	Year	MCDM methods	Ref
1	Apply network analysis methods and AHPs based on geographic information systems to the Erzincan-Trabzon segment of the high-speed rail project in Turkey. Create a new hybrid route and compare the route with three existing routes.	2019	AHP	[20]
2	Select a route for the monorail transport system planned as a new system in Ankara from eight alternative monorail routes by providing the most appropriate ranking and planning.	2018	ANP TOPSIS	[21]
3	Discuss the use of MCDM methods to evaluate a series of bus routes that operate in Florence; these methods are based on a group of parameters that describe the level of service efficiency.	2005	PROMETHEE	[22]
4	Present a multiobjective approach to select an optimal network of priority public transport lanes, demonstrating the methodology with a study in Petah Tikva in Israel.	2016	AHP TOPSIS	[24]
5	Propose a preliminary study on implementing a tramway system in the city of Santander by developing a series of alternatives with different layouts and different evaluation criteria.	2020	AHP	[23]
6	Address the problem of public transport passengers in Tehran and their satisfaction levels using a satisfaction survey and integrating multicriteria methodologies for system evaluation.	2017	AHP PROMETHEE	[14]
7	Optimize the planning of charging station locations for electric vehicles by processing parameters that affect location and using the city of Istanbul as a case study.	2020	AHP VIKOR PROMETHEE	[39]
8	Propose an approach that integrates geographic information system techniques and MCDM methods to find suitable locations for charging stations for electric vehicles within Istanbul.	2020	AHP TOPSIS	[40]
9	Select batteries for hybrid electric vehicle applications using multiobjective optimization techniques. Consider several important attributes that differentiate among all the batteries.	2016	VIKOR TOPSIS	[41]

3. Materials and methods

The optimal routes are determined based on the urban routes (alternatives) of the current buses. Based on a literature review, the route characteristics (criteria and subcriteria) that facilitate the selection process are established. The methodology is specified in Fig. 1 and consists of three stages, which are described below in detail.

3.1. Recognition of existing routes

The existing routes that correspond to each bus line that provides service in the city are identified. These routes are the alternatives considered in this study. The central purpose is to classify the trajectories to determine the lines where the entry of electric units and their distribution would be optimal. Additionally, a review of the operational conditions and descriptive characteristics of electric public bus transport is conducted. For this purpose, the characteristics of the electric bus batteries are considered, and the characteristics of public bus transport routes are determined.

3.2. Multicriteria method choice

Table 1 shows that the three MCDM methods that stand out among the articles reviewed are AHP, TOPSIS and PROMETHEE. The PROMETHEE methodology has an advantage over the two other methodologies in terms of application to transportation issues. The analysis indicates that the PROMETHEE methodology stands out within the group of "classification methods"; therefore, it is better applied to

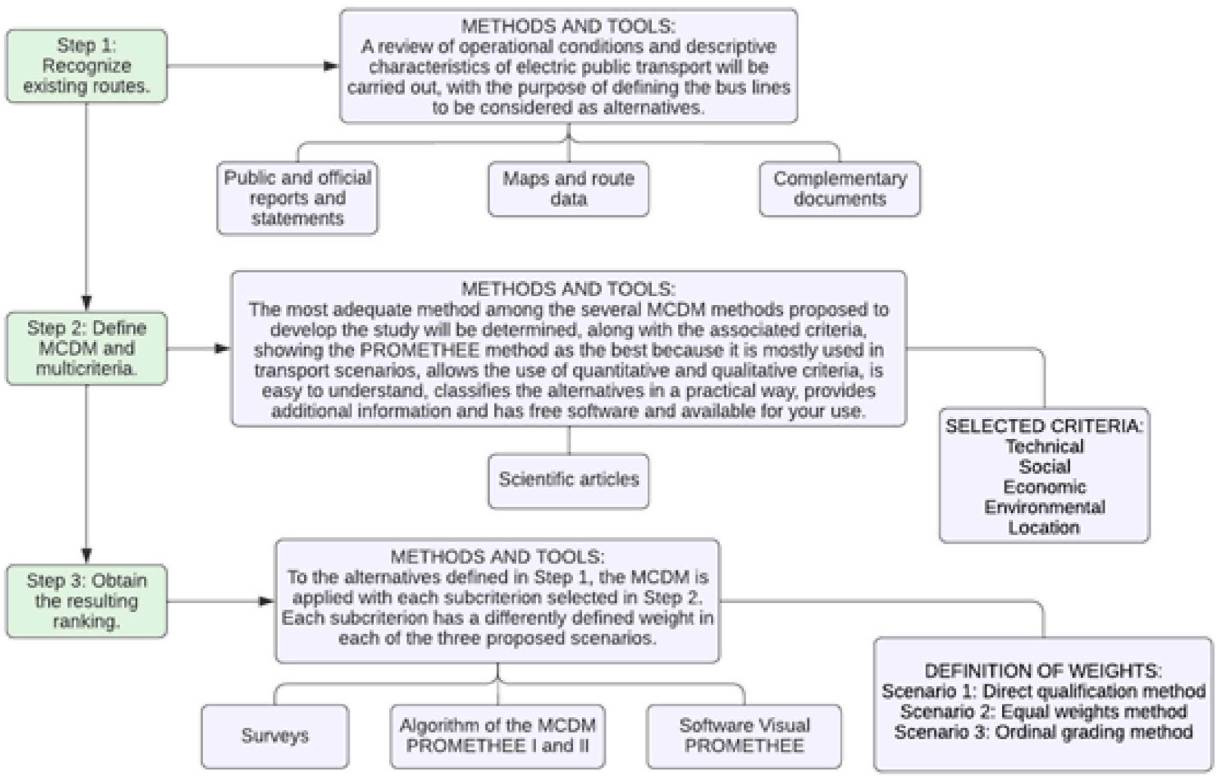


Fig. 1. Proposed methodology.

problems with many classification alternatives and different types of criteria. This fact is reflected in cases in which there are alternatives whose criteria differ. In addition, the six types of preference functions associated with this method are useful, as they facilitate adjustments according to the needs of this work.

The PROMETHEE I and II techniques are widely used in transport scenarios. These methods enable the use of qualitative and quantitative criteria and the classification of alternatives and provide useful information to decision makers regarding the final preference from a set of alternatives [42].

PROMETHEE is a superior classification methodology that selects or organizes alternatives that may conflict with each other in different fields. Its application and its versions have been previously detailed [38, 43,44]. Versions I and II permit partial and total ordering, respectively, of alternatives, and version III provides an interval order that emphasizes indifference. Version IV extends the analysis to continuous sets of possible alternatives. Version V proposes a solution for multiple selection under restrictions. Finally, version VI gives the decision maker the option to explore the space of freedom, defining the upper and lower limits of the weight values of the criteria [42].

The application of PROMETHEE I and II begins with defining the problem. In this initial stage, the most essential characteristics for starting the process and the objectives are determined. It is also necessary to define alternatives that can facilitate the optimal achievement of the objectives proposed in the first step. Subsequently, it is essential to define the criteria (technical, economic, environmental, social and location) that facilitate the structuring and modeling of the selection process [45].

Once the first three steps of the process are completed, the indicators related to the defined criteria that characterize each of the proposed alternatives are identified. Then, the preference indices that define the importance of the criteria are established. As a sixth step, the values previously entered into the evaluation matrices are analyzed (using manual or software analysis). The result is the partial classification by PROMETHEE I and the complete classification by PROMETHEE II according to the calculations of preferential flows [45].

3.3. Description of the PROMETHEE method

Visual PROMETHEE allows one to evaluate different alternatives proposed as solution candidates for the same general problem. This classification is made according to the following mathematical algorithm corresponding to the PROMETHEE I and II methods:

1. According to the binary comparison, determine the deviation, which is the distance between two alternatives within the same criterion. The following formula is used to calculate the deviation between two alternatives:

$$d_j(a,b) = C_j(a) - C_j(b) \quad 1$$

where $d_j(a,b)$ denotes the difference between the evaluations of criterion C_j for alternatives a and b.

2. Apply the preference function previously assigned by the decision maker according to the magnitude of the deviation.

When handling criteria with maximization objectives, the preference function is

$$P_j(a,b) = F_j\left[d_j(a,b)\right] \; j = 1, \dots, k \quad 2$$

where $P_j(a,b)$ denotes the preference for alternative a over alternative b in terms of each criterion as a function of $d_j(a,b)$.

The preference function $P_j(a,b)$ adopts certain properties, depending on the magnitude of deviation $d_j(a,b)$, as follows:

$$\begin{array}{c} 0 \leq P_j \leq 1 \\ d_j(a,b) > 0 \rightarrow P_j(a,b) > 0 \\ d_j(a,b) \leq 0 \rightarrow P_j(a,b) = 0 \end{array} \quad 3$$

To build the preference matrix, it is necessary to associate a preference function with each criterion; in our case, the function is taken from the functions shown in Table 2.

3. Calculate the aggregate preference index to express the degree of preference for one alternative over another. To calculate the preference index between two alternatives, the following equation is used:

$$\forall a,b \in A, \pi(a,b) = \sum_{j=1}^{k} P_j(a,b) w_j \qquad 4$$

where w_j is the weight associated with each criterion and $\pi(a,b)$ expresses the degree of preference for alternative a over alternative b. The degree of preference takes a value between 0 and 1. π(a,b) ~ 0 indicates that the global preference of a over b is weak; π(a,b) ~ 1 indicates that the global preference of a over b is strong.

4. Calculate the overcoming or classification (PROMETHEE I partial classification) flow. Two flows are calculated. First, the positive overcoming flow is determined. The same flow that represents an alternative exceeds all the others, and the highest value of all the positive flows φ + represents the best alternative.

$$\varphi^{+}(a) = \frac{1}{n-1} \sum_{X \in A} \pi(a,x) \qquad 5$$

The negative overcoming flow represents how an alternative is overtaken by the others; thus, the best alternative is the one with the least negative flow φ – according to the following:

$$\varphi^{-}(a) = \frac{1}{n-1} \sum_{X \in A} \pi(x,a) \qquad 6$$

To obtain a partial classification through the positive and negative outperforming flows, it is also necessary to establish conditions of preference, indifference and incomparability between alternatives because alternative a may have the highest positive (negative) flow but not necessarily the best (worst) flow.

Therefore, alternative *a* will be preferred over alternative *b* if:

$$a\,P'\,b \Longleftrightarrow \begin{cases} \varphi^{+}(a) > \varphi^{+}(b) \wedge \varphi^{-}(a) < \varphi^{-}(b) \\ \varphi^{+}(a) = \varphi^{+}(b) \wedge \varphi^{-}(a) < \varphi^{-}(b) \\ \varphi^{+}(a) > \varphi^{+}(b) \wedge \varphi^{-}(a) = \varphi^{-}(b) \end{cases} \qquad 7$$

Alternative *a* will be indifferent to alternative *b* if:

$$a\,I'\,b \Longleftrightarrow \{\varphi^{+}(a) = \varphi^{+}(b) \wedge \varphi^{-}(a) = \varphi^{-}(b) \qquad 8$$

Alternatives *a* and *b* will be incomparable when:

$$a\,P'\,b \Longleftrightarrow \begin{cases} \varphi^{+}(a) > \varphi^{+}(b) \wedge \varphi^{-}(a) > \varphi^{-}(b) \\ \varphi^{+}(a) < \varphi^{+}(b) \wedge \varphi^{-}(a) < \varphi^{-}(b) \end{cases} \qquad 9$$

5 Calculate the net preference flow, i.e., the complete PROMETHEE II classification, which is the result of the difference between the positive and negative flows: $\varphi(a) = \varphi^{+}(a) - \varphi^{-}(a)$.

where φ (a) represents the net or global preference flow for each alternative. Therefore, the alternative with the highest net flow of improvement is classified as the best.

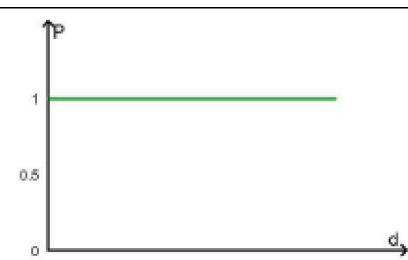
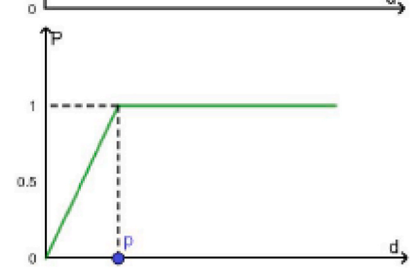
The PROMETHEE method has six preference functions that offer flexibility and adaptation according to the nature of the available data. In ascending order from functions 1 to 6, the functions are named as follows: usual, U-shape, V-shape, level, linear and Gaussian [46]. These functions are applied according to the circumstances specific to the remaining decision problem [47].

Of the six preference functions available for the PROMETHEE method, two have been adopted in this project: the usual function (function 1) and the V-form function (function 3). The graph and calculation are shown in Table 2. In each case, it may be necessary to define none, one or two of the parameters, whose meanings, following [46], are specified below:

- q is the interference limit, understood as the largest deviation that is considered nonsignificant by the decision maker.
- p is the strict preference limit, understood as the smallest deviation considered sufficient to generate a broad preference.
- s is an intermediate value between p and q; this value defines the inflection point of the preference function. It is advisable to select p and q prior to selecting s as an intermediate value.

Using the software program Visual PROMETHEE (Solvay Brussels School of Economics and Management at the Université Libre de Bruxelles) [43], the methodology is applied to determine the best option [43]. Visual PROMETHEE software began was first developed the company VP Solutions, Inc. with the corresponding review by Professor Bertrand Mareschal in 2010. The development began at the Solvay

Table 2
Preference functions used from the PROMETHEE method.

Type of Function	Form of Function	Definition	Necessary Parameters
1		$P(d)\begin{cases} 0 & d \le 0 \\ 1 & d > 0 \end{cases}$	-
3		$P(d)\begin{cases} 0 & d \le 0 \\ \frac{d}{p} & 0 < d \le p \\ 1 & d > p \end{cases}$	p

Brussels School of Economics and Management of the Université Libre de Brussels. Visual PROMETHEE is supported by the authors of the methodology: Prof. Jean-Pierre Brans and Prof. Bertrand Mareschal [38].

3.3.1. Definition of multicriteria

The criteria (economic, technological, social, environmental and location) and the most representative associated subcriteria for facilitating route selection are established. For the final selection of subcriteria, the relevant subcriteria within the topic of public transport worldwide were considered. The selected subcriteria are defined from studies where the determination of routes for public bus transport is a key goal [14,20–24] and studies where criteria related to the characteristics of transport routes are identified [15,16,48,49]. This information is summarized in Table 3.

When refining Table 3, the most cited subcriteria in the selected articles are identified. In addition, the subcriteria that most closely matched local conditions were considered. Table 4 shows the subcriteria applicable to the problem of selecting optimal routes; all these subcriteria are quantitative.

Table 4 shows that the technical criteria are the most prevalent. Of these, the network length (c1), which is a technical subcriterion, and the road slopes (c2) are used, as being a mountainous city is an influential factor. Finally, energy indicators are used. Despite not being the most commonly used subcriteria in the reviewed documents, these indicators have distinct importance in our project due to the technical weight and energy resource conservation that is proposed. From the latter, the subcriteria of energy consumed per trip (c3), energy consumed per line (c4) and required power (c5) are derived.

In the social sphere, the number of passengers attended (c6) and the number of trips completed (c7) are included. Concerning economic criteria, two subcriteria are considered based on the cost of a bus trip: the annual income generated by each bus line (c8) and the income per kilometer (c9), which considers the expenditure in kilometers traveled to generate such income.

Concerning environmental criteria, two subcriteria that differentiate between the existing routes are selected. The pollution produced per day and per transport unit (c10) and the pollution produced by the same unit in a single round trip (c11) are defined. Finally, concerning the location criteria, the number of stops (c12) and the coverage served represented by the average distance between stops (c13) are considered.

Within the group of technical criteria, the length of the network (c1) is the distance in km of each bus route. This subcriterion is to be maximized because the greater the length covered, the more profitable the replacement of the unit becomes, i.e., the replacement of diesel with an electric bus. The slope of the road uphill (c2.1) and downhill (c2.2) are subcriteria measured as the percentage of inclination and tends to be minimized because the greater the positive slope is, the greater the effort needed by the transport unit. Moreover, the energy consumed per trip (c3) represents the energy used by a bus unit to complete a route, and the energy consumed per line (c4) represents the energy consumed in a day by all the transport units that constitute a bus line. Both subcriteria are recorded in kWh and tend to be minimized because the lower the energy consumed is, the longer the journey that can be covered with a single energy charge and the lower the supply needs are. Finally, the power required per line (c5) represents the power of the fleet in kW, which is the sum of the power of each electric transport unit that forms the fleet. This subcriterion tends to be minimized because the lower the power requirements of the fleet of a bus line are, the smaller the investment needed to build the energy supply infrastructure for that line.

In terms of the social criteria, the number of passengers served (c6) represents the number of people who used a bus line during a year. It is a subcriterion that is maximized since the greater the number of passengers served by the bus line is, the greater the social benefit that is generated. Finally, the number of trips performed (c7) represents the number of weekly trips made by each bus line. This subcriterion is maximized because the number of trips scheduled by the authorities of each transport company is directly linked to the service demand, which must be covered precisely for the social benefit.

Among the economic criteria, the income per year per line (c8) is

Table 4
Subcriteria for the optimal route selection problem.

Criteria	Subcriteria		Unit
Technical	c1	Network length	km
	c2.1 and c2.2	Road slopes	% (+, -)
	c3	Energy consumed per trip	kWh
	c4	Energy consumed per line	kWh
	c5	Power required per line	kW
Social	c6	Number of passengers served	users
	c7	Number of trips completed	trips
Economic	c8	Income per year per line	USD
	c9	Income per kilometer	USD/km
Environmental	c10	Pollution produced per day	kg of CO_2
	c11	Pollution by route	kg of CO_2
Location	c12	No. of stops	stops
	c13	Distance between stops	meters $\overline{X}$

Table 3
Subcriteria related to bus routing.

Reference:	[20]	[21]	[22]	[24]	[23]	[14]	[48]	[15]	[16]	[49]
TECHNICAL SUBCRITERIA										
Network length			X				X	X		X
Road slopes	X						X	X		
Pavement quality	X									
Bus speed			X						X	X
Total travel time		X		X		X				
Consumed energy									X	X
SOCIAL SUBCRITERIA										
Number of passengers served		X	X							
Information at stops			X							
Number of trips completed			X							
Visual and aesthetic impact		X			X					
ECONOMIC SUBCRITERIA										
Construction costs		X		X	X					
Cost of the bus trip						X				
ENVIRONMENTAL SUBCRITERIA										
Contamination			X		X					
Impact on protected areas	X	X								
LOCATION SUBCRITERIA										
Coverage served	X	X	X	X	X					X
No. of stops/accessibility		X	X		X	X				

recorded; this criterion is measured in USD and represents the annual profits recorded by a bus line. Additionally, these criteria include income per kilometer (c9); this criterion represents the annual income generated by a bus line. In relation to the route distance in km for that line, the subcriterion is measured in USD/km.

Among the environmental criteria, the first subcriterion is the pollution produced per day (c10); measured in kg of CO_2, this subcriterion represents the pollution produced on a normal day by all transport units on a single bus line when covering the corresponding route. Finally, the pollution produced by a route (c11) represents, in kg, the amount of CO_2 expelled by a single diesel transport unit. This subcriterion is maximized because the objective is to eliminate the environmental pollution generated by the current diesel transport units.

Finally, the location criteria consist of two subcriteria. The number of stops (c12) represents the number of stops located on each route and is maximized because the existence of a greater number of stops along the trajectory of a bus line means more accessibility for the final consumer. The distance between stops (c13) represents the average distance in meters between two stops on each route, and the subcriterion is minimized because the lower the average distance between stops is, the greater the coverage for the final consumer.

Function 1 is the only one of the six preference functions of the PROMETHEE method that does not require thresholds for its application. Only one of the proposed sub-criteria can define thresholds that limit physical conditions. In sub-criterion (c3) concerning the energy consumed, a limiting threshold is considered due to the capacity characteristics of the battery (324 kWh according to data from the BYD vehicle used in previous research) [7,9,10]. Therefore, the V-shape preference function is used, as the energy consumed is limited between 0 kWh and 324 kWh. All other criteria are considered with respect to the usual preference function among the six functions described in Ref. [46].

3.3.2. Definition of weights for each subcriterion

Assigning the same weight to all subcriteria is the simplest approach (equal weights (EW)). However, the criteria and subcriteria affect the candidate alternatives differently, hence the importance of assigning different weights to indicate the alternatives' relative importance [50].

Three methods for assigning weights are applied. The first scenario uses the direct rating method (DRM). The assessments are defined using a questionnaire delivered to a group of experts. The items are evaluated on a Likert scale [51,52]. Then, the valuations are normalized by dividing each value by the sum of all values. The second and third scenarios are compared with the main scenario. In the second scenario, equal weights are directly assigned to the subcriteria. In the third scenario, the weights are obtained using the ordinal ranking (OR) method.

The analysis is based on the definition of the weight vector shown in Equation (10), where k is the number of subcriteria. The condition specified by Equation (11) must also be met, ensuring the weights sum to 100% [52].

$$\omega_j = \{\omega_1, \omega_2, \ldots, \omega_k\} \tag{10}$$

$$\sum_{j=1}^{k} \omega_j = 1 \tag{11}$$

- ***Direct qualification method***

In this method, the importance of each criterion is indicated using a scale that can be 1-m, where m can be 5, 7 or 10 (for our project, m = 5). The weight of each of the k subcriteria ω_j is established by Equation (12) [52].

$$\omega_j = \frac{\sum_{i=1}^{m} \left(P_{j,i} * R_{j,i}\right)}{\sum_{j=1}^{k} \sum_{i=1}^{m} \left(P_{j,i} * R_{j,i}\right)} \tag{12}$$

where.

- ω_j is the weight of subcriterion j
- k is the number of subcriteria
- $P_{j,i}$ is the number of Likert scale points i assigned by the participants for each subcriterion j
- $R_{j,i}$ is the fraction of the sum of each score (Pi) of the sum of all scores for each criterion

- ***Equal weights method***

This method is the simplest; all subcriteria are assigned equal weights. Equation (13) establishes the corresponding weight value.

$$\omega_j = \frac{1}{k} \tag{13}$$

- ***Ordinal grading method***

To use this method, the criteria must be ordered by importance. Then, the expected value method is applied [53]. If there are k criteria, the expected values, which are assigned weights, are determined by Equation (14), thus representing the third scenario in this paper [54].

$$\omega_1 = \frac{1}{k^2} \; \omega_2 = \frac{1}{k^2} + \frac{1}{k*(k-1)} \omega_{k-1} = \frac{1}{k^2} + \frac{1}{k*(k-1)} + \ldots + \frac{1}{k*2} \omega_k = \frac{1}{k^2} + \frac{1}{k*(k-1)} + \ldots + \frac{1}{k*2} + \frac{1}{k*1} \tag{14}$$

4. Results

4.1. Application to the cuenca case study

The Cuenca canton in Ecuador has 505,585 inhabitants, according to the latest census by the National Institute of Statistics and Census (Instituto Nacional de Estadísticas y Censo - INEC) in 2010, with an estimated population increase of approximately 2.1% per year [55]. Together with Quito, the capital, Cuenca, was one of the first cities in the country to begin transportation planning. The process began in 1999 with the creation of the Pilot Plan of Transportation for Cuenca (Plan Piloto de Transporte para Cuenca - PADECO); this plan was sponsored by the Inter-American Development Bank (IDB). The project allowed for the characterization of transport problems in the city and considered problems in public transport and buses and the misuse of sidewalks and streets. Over time, management was transferred from the central government to the local government. In 2012, a change in the management of mobility, road safety, transit and transportation occurred, constituting the final change that is managed to date, as mentioned in Ref. [56].

Currently, Cuenca's urban transportation system consists of 29 bus lines, operating 14% in a trunk model with transfer terminals and forming part of the Integrated Transportation System (Sistema Integrado de Transporte - SIT). The remaining units cover isolated conventional routes distributed throughout the city [56]. The 29 public bus transport lines that operate within the limits of the city of Cuenca are described in Table 5. The lines are listed as alternatives within the multicriteria selection method in ascending order according to the number with which the lines operate within the city. Twenty-three alternatives that make up the routes within the city are considered, except trunk and feeder lines [56].

Table 5
Public transport bus lines in the city of Cuenca and assignment of alternative numbers.

Alternative	Bus line	Description
1	2	Totoracocha - Feria Libre
2	3	Sayausí - Eucaliptos
3	5	Totoracocha - Control Sur
4	6	Mayancela - Nueve de Octubre
5	7	Trigales - Feria Libre
6	8	Trigales - San Joaquín
7	10	Ochoa León - Feria Libre
8	12	Baños - Quinta Chica
9	13	Monay - Mall del Río
10	14	El Valle - Feria Libre
11	15	Monay - Feria Libre
12	16	San Pedro - Monay
13	17	Feria Libre - Diez de Agosto
14	18	Zhucay - Técnico
15	19	Católica - San Joaquín
16	20	San Pedro - Cdla. Kennedy
17	22	Salesianos - Gapal
18	24	Cochapamba - Miraflores
19	25	Jaime Roldós - Sta. María Vergel
20	26	Checa - Mercado 27 de Febrero
21	27	Sinincay - Huizhil
22	28	Chaullabamba - Feria Libre - Llacao
23	50	Monay IESS - Balzay
N/A	100	North Trunk: Ricaurte
N/A	100	South trunk: Baños
N/A	101	Feeder: Yanaturo - Terrestrial Terminal
N/A	102	Feeder: Eucalyptus
N/A	201	Feeder: Sayausí
N/A	203	Feeder: Monay - Tejar

4.1.1. Determination of values for each subcriterion

In Table 6, following the previous calculations for each subcriterion, the values of each alternative are shown according to the unit of measurement for each subcriterion proposed (see Table 4). To apply the method, the necessary parameters are subsequently entered into Visual PROMETHEE.

Regarding the values, (c1) is obtained directly from information from previous studies [8,56]. For (c2), the percentage of elevation is calculated for both uphill and downhill slopes along a round trip based on the height above sea level of the points on the route [8,56]. For this purpose, the height difference at two adjacent time instants is calculated and compared with the last recorded height to determine the change. For (c3), the calculation is performed by multiplying the known length from criterion (c1) and the efficiency of the transport unit battery, with a value of 1.26 kWh/km, as supported by previous studies [7,9,10]. Subcriterion (c4) is obtained directly based on projects previously developed in the city of Cuenca, Ecuador, as reported in Ref. [8]. However, subcriterion (c5) is calculated by multiplying the 300 kW of power of each machine according to the technical specifications defined by Refs. [9,10] by the number of buses needed to supply each of the already established lines [8].

The values for (c6) are given in Ref. [56]. In contrast, subcriterion (c7) is determined from the number of expeditions that are normally performed on each bus route on a common working day [56,57]. For subcriterion (c8), the result is obtained by multiplying the percentage of the rate previously defined in Ref. [56] and the number of passengers (c6). Subcriterion (c9) results from dividing the value of the profit for an entire year in dollars (c8) by the length of each route according to the values defined in (c1). Subcriterion (c10) is calculated by multiplying the constant 0.069 kg of CO_2 for each [km] per passenger justified in Ref. [58] by the three remaining multipliers, whose values appear in (c1), (c7), and finally, the unit constant, since the number of passengers is 1 in all cases because the driver is considered the only occupant of the bus. Similarly, to calculate the values in (c11), the number of trips recorded in the previous environmental subcriterion are not considered. Thus, this subcriterion is established under the same conditions and parameters as subcriterion (c10); however, (c11) depends on only the independent variable (c1). Subcriterion (c12) is determined based on the local conditions [56,57]. Finally, (c13) is calculated by dividing the values recorded in (c1) and the total minus one of each value recorded in (c12), which is obtained from the number of stops recorded along each trajectory in both directions for each alternative.

4.1.2. Weights for each subcriterion

To define the weights of the subcriteria by applying the direct rating method and subsequently the ordinal rating method, a survey was

Table 6
Value for each alternative according to the corresponding criterion.

Alternative	c1	c2.1	c2.2	c3	c4	c5	c6	c7	c8	c9	c10	c11	c12	c13
1	28.23	0.0078	0.0068	35.82	1682.51	3000	3264925	112	710121.22	25154.84	218.16	1.95	116	245.5
2	33.46	0.0089	0.0075	42.46	5541.61	6000	7367160	328	1631089.25	48747.44	757.27	2.31	112	301.4
3	27.17	0.0093	0.0074	34.48	5456.24	5700	6171420	320	1318215.26	48517.31	599.91	1.87	101	271.7
4	20.15	0.0106	0.0091	25.57	1892.31	1800	2580915	114	544573.13	27025.96	158.50	1.39	66	310.0
5	38.54	0.0074	0.0065	48.91	6851.40	7500	6837545	392	1576054.09	40893.98	1042.43	2.66	151	256.9
6	33.75	0.0080	0.0073	42.83	4974.89	5700	6513790	250	1425217.20	42228.66	582.19	2.33	104	327.7
7	42.99	0.0095	0.0086	54.55	3042.99	2700	1647975	84	349865.06	8138.29	249.17	2.97	88	494.1
8	35.60	0.0099	0.0078	45.18	6801.19	6000	6329465	320	1368430.32	38439.05	786.05	2.46	151	237.3
9	32.84	0.0078	0.0067	41.67	1754.83	3300	7479580	250	1675425.92	51017.84	566.49	2.27	131	252.6
10	26.31	0.0112	0.0122	33.39	4085.44	6000	6814185	324	1446651.43	54984.85	588.19	1.82	92	289.1
11	33.35	0.0102	0.0092	42.32	3554.94	3900	3343765	326	731615.73	21937.50	750.17	2.30	131	256.5
12	42.12	0.0085	0.0082	53.45	6315.39	5400	10374760	240	2310459.00	54854.20	697.51	2.91	148	286.5
13	31.18	0.0081	0.0084	39.57	1417.04	2400	653715	112	137083.99	4396.54	240.96	2.15	75	421.4
14	29.48	0.0080	0.0067	37.41	2601.51	4500	5010720	322	1115887.37	37852.35	654.99	2.03	107	278.1
15	30.35	0.0085	0.0074	38.51	2959.22	4500	3526630	166	780795.83	25726.39	347.63	2.09	91	337.2
16	34.74	0.0106	0.0089	44.09	5280.29	5400	5043205	180	1096897.12	31574.47	431.47	2.40	114	307.4
17	29.21	0.0087	0.0069	37.07	8639.09	8700	1962240	400	442092.62	15134.98	806.20	2.02	110	268.0
18	39.60	0.0147	0.0159	50.25	7135.49	6000	7967950	248	1650162.51	41670.77	677.64	2.73	134	297.7
19	32.27	0.0086	0.0071	40.95	1912.05	2700	1185520	104	248603.57	7703.86	231.57	2.23	110	296.1
20	36.16	0.0098	0.0096	45.89	2168.16	2700	2761955	112	611496.85	16910.86	279.44	2.50	140	260.1
21	43.59	0.0128	0.0148	55.32	6211.87	5100	11292005	166	2514729.52	57690.51	499.28	3.01	161	272.4
22	40.00	0.0131	0.0110	50.76	2784.51	2700	8477855	398	1766784.93	44169.62	1098.48	2.76	75	540.5
23	26.39	0.0086	0.0072	33.49	2355.01	3600	3164915	132	713055.33	27019.91	240.36	1.82	89	299.9

c1:network length (km); c2 and c3: road slopes + or – (%); c3: energy consumed per trip (kWh); c4: energy consumed per line (kWh); c5: peak power required per line (kW); c6: number of passengers served (users); c7: number of trips completed (trips); c8: income per year per line (USD); c9: income per kilometer (USD/km); c10: pollution produced per day (kg of CO_2); c10: pollution by route (kg of CO_2); c12: number of stops (stops by each route); c13: distance between stops (meters $\overline{X}$).

distributed to 25 energy professionals familiar with the local conditions of the city of Cuenca in terms of public transport. 60% de los encuestados pertenecen están relacionados con la academia e investigación, 5% trabajan en empresas públicas, 12% en empresas privadas y 8% en organismos municipales de planeamiento. A Likert scale (scale 1 to 5) was used to assess the importance of each subcriterion, with 1 indicating unimportant and 5 indicating very important.

Table 7 shows the survey results for each of the subcriteria described in Table 4. The 25 experts surveyed (local experts who know public transportation) defined the weight for each proposed subcriterion; an inconvenience was initially present due to the lack of documentation coinciding with the simultaneous use of all the subcriteria proposed in this project. Table 8 shows the weights obtained, where the values of the second column were calculated according to Equation (3), those of the third column were calculated according to Equation (4), and those of the fourth column were calculated according to Equation (5).

4.2. Analysis of results

With Visual PROMETHEE, each resulting ranking is obtained according to the final preference flow for each alternative. Table 9 compares the rankings obtained in each of the three scenarios proposed in this project, with the first column being the number of places the scenarios occupy according to the ranking and the other three columns identifying the number of each alternative in the corresponding scenario. Table 10 shows the PROMETHEE flows for each alternative in the analyzed scenarios.

Spearman's correlation coefficient (rho) between scenario 1 and scenario 2, scenario 1 and scenario 3 and scenarios 2 and 3 indicated strong correlation (0.99, 0.90 and 0.88, respectively). Additionally, the hypothesis test showed that rho is different from zero. Therefore, the ranking of the chosen routes does not have substantial variation in the described scenarios, giving robustness to decision making.

Comparison of the first two scenarios (see Table 9) reveals similarity in the final positions of each alternative. The final positions for the alternatives of the second scenario, in the worst case, are positioned higher or lower than the same alternatives in the ranking of the main scenario; these alternatives are positioned in the same place for both scenarios in most cases. The particularity described above results mainly because the weights set in the first scenario are not far from the average value (0.071), as the professionals surveyed rarely considered any of the proposed subcriteria to be only slightly important (see Table 7).

Comparison of the first and third scenarios demonstrates how the position of each alternative changes in the last scenario with respect to the classification for the same alternatives in the main scenario. This change results because the weights described in Table 8 for the third scenario are distributed with greater separation from the average value (0.071) with respect to the main scenario. In this case, when attributing greater importance to the most substantial subcriteria and less importance to the less relevant subcriteria in the third scenario, some alternatives clearly benefit at the expense of others that fall several places in the final ranking.

Table 7
Survey results.

Subcriterion	Not important	Slightly important	Moderately important	Important	Very important
c1	0	0	0	12	13
c2.1	0	0	5	10	10
c2.2	0	0	5	10	10
c3	0	0	3	7	15
c4	0	1	3	5	16
c5	0	1	3	6	15
c6	0	0	2	5	18
c7	0	0	5	9	11
c8	0	0	3	12	10
c9	0	0	5	11	9
c10	0	1	2	8	14
c11	0	2	1	10	12
c12	0	0	10	11	4
c13	0	1	15	6	3

Table 8
Weights for each scenario according to the calculation method.

Subcriterion	Weight under scenario 1 (DRM)	Weight under scenario 2 (EW)	Weight under scenario 3 (OR)
c1	0.076	0.071	0.161
c2.1	0.071	0.071	0.023
c2.2	0.071	0.071	0.030
c3	0.075	0.071	0.125
c4	0.075	0.071	0.101
c5	0.074	0.071	0.069
c6	0.078	0.071	0.232
c7	0.071	0.071	0.038
c8	0.072	0.071	0.047
c9	0.070	0.071	0.017
c10	0.074	0.071	0.083
c11	0.072	0.071	0.057
c12	0.063	0.071	0.011
c13	0.058	0.071	0.005

Table 9
Comparison of the final ranking for the three proposed scenarios.

Position	Rank under scenario 1 (DRM)	Rank under scenario 2 (EW)	Rank under scenario 3 (OR)
1	a9	a9	a22
2	a5	a5	a12
3	a12	a12	a21
4	a22	a21	a9
5	a21	a22	a5
6	a2	a8	a18
7	a8	a2	a2
8	a14	a14	a6
9	a6	a6	a8
10	a11	a11	a14
11	a18	a18	a11
12	a1	a1	a20
13	a20	a20	a16
14	a3	a3	a7
15	a16	a16	a15
16	a10	a10	a10
17	a15	a17	a3
18	a17	a15	a1
19	a19	a19	a13
20	a7	a23	a19
21	a23	a7	a23
22	a13	a13	a17
23	a4	a4	a4

In the first stage of incorporating buses in the city, 68 electric units are considered. In this manner, the number of electric units that cover the lines can be established according to the ranking of the main scenario (see Table 9). Thus, the ranking begins with "line 13" represented in "a9" (first place in the main ranking) and continues until all the electric units are assigned. Not considered in the analysis is the fact that sometimes the same diesel bus is used for different routes on different days, depending on internal decisions within each transport company.

With reference to the information provided by the different public transport entities [8,56,57], it is possible to identify how many of the existing 475 units are necessary to cover each bus line per day according to the schedule, the time necessary to cover the journey and the frequency of service. Table 10 shows the minimum number of units necessary to cover the operation of the five best-rated lines until completing the quota of 68 buses in the first stage. In this sense, it would be possible to cover the entire number of units of the first four bus lines (shown in Table 11). Additionally, for this case, it would be possible to cover the bus line located in fifth place with five electric units, thus reaching the aforementioned total.

Table 10
Results of the PROMETHEE flows in the scenarios.

Alternatives	Scenario 1	Scenario 2	Scenario 3
a1	−0.02	0.00	−0.18
a2	0.15	0.14	0.17
a3	−0.07	−0.06	−0.16
a4	−0.41	−0.42	−0.39
a5	0.39	0.40	0.27
a6	0.08	0.07	0.10
a7	−0.23	−0.25	−0.10
a8	0.14	0.16	0.09
a9	0.43	0.44	0.33
a10	−0.16	−0.16	−0.15
a11	0.02	0.03	−0.02
a12	0.35	0.35	0.41
a13	−0.29	−0.31	−0.28
a14	0.12	0.12	0.00
a15	−0.17	−0.18	−0.15
a16	−0.13	−0.13	−0.04
a17	−0.18	−0.16	−0.37
a18	0.00	0.00	0.18
a19	−0.21	−0.20	−0.28
a20	−0.05	−0.04	−0.04
a21	0.24	0.24	0.39
a22	0.24	0.21	0.53
a23	−0.24	−0.24	−0.31

Table 11
Units needed to cover the five best-rated lines.

Alternative	Bus line	Required units
9	13	11
5	7	25
12	16	18
22	28	9
21	27	5

In addition, Fig. 2 shows the balance between the criteria that benefited and harmed each alternative in the main scenario (DRM). For example, except for the network length subcriterion (c1) and both environmental subcriteria (c10 and c11), all the subcriteria benefit the first alternative (a9) more than they harm it. In the case of the alternative in second place (a5), the energy subcriteria of both power and energy (c3, c4 and c5) subtract points in favor. Finally, in the case of the alternative in third place (a12), in addition to being harmed by the same subcriteria (c3, c4 and c5) that weigh against the alternative in second place, the subcriteria associated with the slope of the descent on the road (c2.2) and the number of runs made (c7) are added.

In contrast, only three subcriteria had a positive influence on the worst-rated alternative (a4) in this scenario (DRM): the energy subcriteria of both power and energy (c3, c4 and c5). However, all other subcriteria had a negative influence.

5. Discussion

In previous research using the PROMETHEE classification method [22], nine subcriteria were included: network length/number of stops, number of bus shelters/number of stops, number of stops with information on schedules/number of stops, number of trips produced/number of planned trips, speed, number of municipalities served/number of municipalities in the network, pollution limitations, importance for tourism and number of passengers. None of these subcriteria is economic. However, in Ref. [24], only three criteria are generally established without associated subcriteria: travel time, construction costs and connectivity between lanes and terminals. In Torre et al. [23], four criteria are included: functional, economic, environmental and territorial, not considering technical criteria within the selection process. In contrast, in this research project, it was considered essential to include six subcriteria associated with the technical criterion, thus ensuring the robustness of the results. Likewise, Nassereddine & Eskandari [14] consider only economic and social subcriteria and omit technical, environmental and location subcriteria from their study. As Joubert suggested [15], the degree of inclination of roads is an important parameter in terms of the energy consumed. In the case of Andean areas, this fact is more evident due to the existence of steep slopes. In concordance with Lopez-Ibarra et al. [16], related subcriteria are included since the slope of the route and the power and energy requirements are assumed to be limiting factors. This consideration translates into economic and environmental savings since the greater the conservation of the batteries is, the lower the investment necessary for their maintenance. Analogously, the pollution generated will be lower since the energy required for the load decreases.

As Yildirim and Bediroglu [20], Grassini & Viviani [22] and Nassereddine & Eskandari [14] found, the greater the number of scenarios proposed, the more solid the resulting solution. In view of this finding, this study concludes that the generation of the three scenarios shows reliability but that this approach could be improved by increasing the number and types of scenarios because more scenarios generates more possibilities for comparison and offers greater support for experimental results.

To assign weights to the subcriteria, surveys were conducted, as in other studies [14,20–22]. In this study, the criteria were assessed by 25 professionals. Yildirim and Bediroglu [20] surveyed 35 professionals on route planning. No statistical method was used to process the interview data because the mean values satisfied the need for calculations using the AHP methodology. Hamurcu and Eren [21] established the weights on the basis of a decision-making committee consisting of six transportation system experts who assigned qualitative ratings using the Saaty scale to evaluate the alternatives and criteria. Likewise, Grassini and Viviani [22] propose three types of subcriteria weights: equal weights, weights from customer satisfaction surveys and weights obtained from interviews with the managers of the transportation system. Nassereddine and Eskandari [14] calculated the weights of the criteria using the AHP method. The experts performed evaluations using the Saaty scale to determine the values of the components of the pairwise comparison matrices.

In concordance with Hamurcu and Eren [21], the most important subcriteria correspond to sensitive areas, soil structure, population density, capacity for expansion and development, and the cost of construction. Hence, the line selected in first place is the longest route and has a large population. In our project, the following are defined as the most important subcriteria: the number of passengers served, the length of the route and the energy consumed. In general, terms, these subcriteria correspond to the most relevant feature that led to the line in Ref. [21] being ranked first. Similarly, in both projects, the social importance is evident based on the subcriteria analyzed, although the nature of both are not identical. As in Grassini and Viviani [22], among the social criteria, the number of passengers is the best parameter. To obtain these results [22], conducted interviews with users and authorities to classify the effectiveness of bus routes that operate in Florence. In contrast to their study, this work includes technical parameters that seek to highlight the problem of identifying optimal routes for the entry into operation of new electric units beyond the objective of determining the performance and efficiency of the original service.

Similar to González et al. [8], who determined the energy required by an electric bus, this value was also estimated by numerical calculation, as shown in Section 3.1. For most bus lines, the values are similar. However, there are cases where the experimental and calculated values are distant, probably because in practice, parameters that influence the distortion are included; these parameters include traffic, road slopes, applied speed, time of day, and stops. In addition, the following are included within these parameters that imply better aptitude: the energy consumed per line, the number of passengers attended, the income generated and the distance between stops. After studying the behavior of an electric bus in relation to its battery system within commercial routes

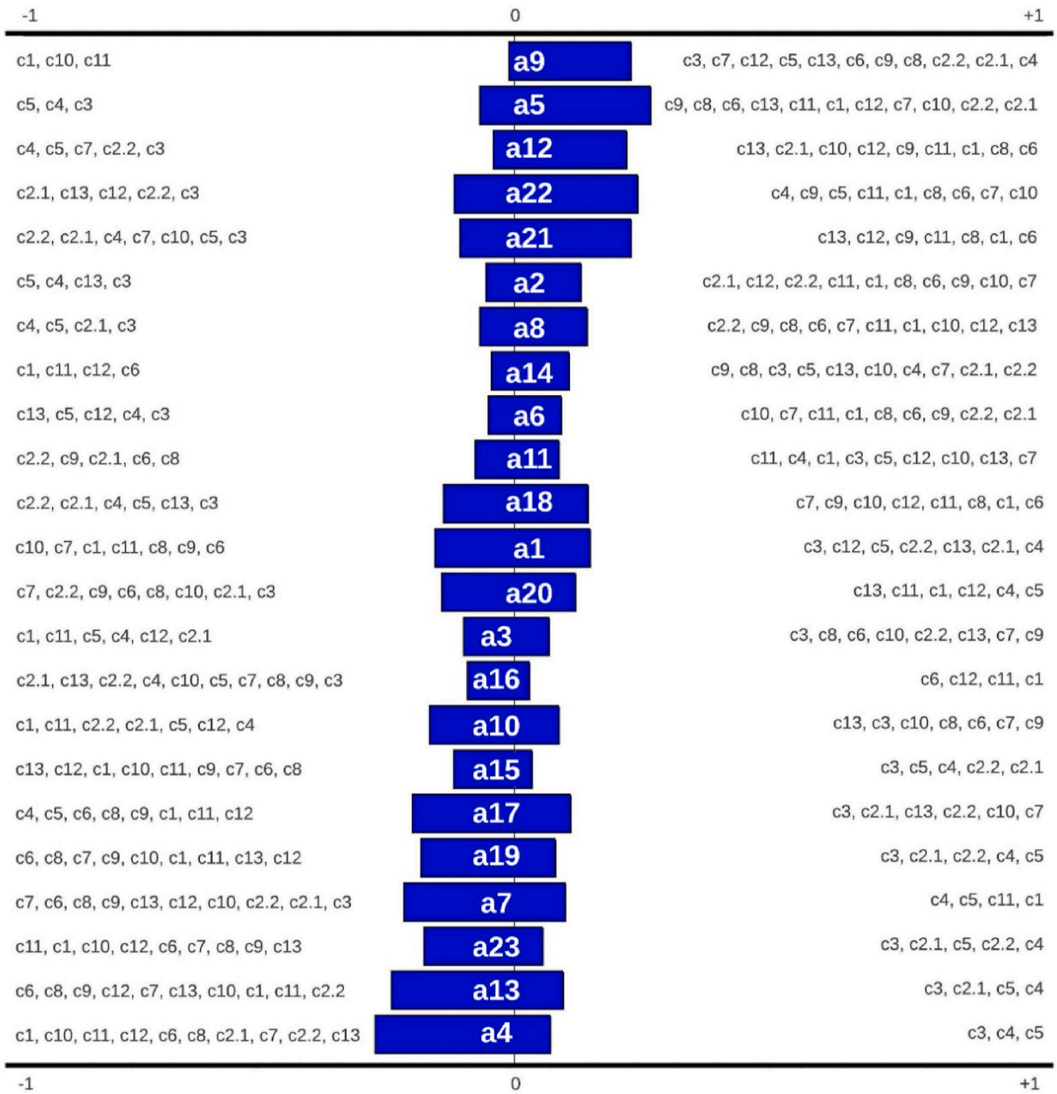


Fig. 2. Positive or negative impact of each criterion on each alternative obtained from Visual PROMETHEE for the main scenario.

in the city of Cuenca, Gonzales et al. [8] determined the technical feasibility of replacing the entire fleet of buses in the city. This determination was made after considering certain electric variables in the battery charging process, obtaining total harmonic distortion (THD) with current distortions lower than 4%, therefore complying with national and international standards. Thus, it is estimated that the maximum demand during charging can reach 33.92 MW if the fleet is charged at 80 kW per battery and 19.96 MW if the load is 40 kW, while the charging time can range from 4 h to 9 h. The daily energy required to power the fleet is 115 MWh, which represents approximately 4% of the daily energy demand in the city of Cuenca. The energy efficiency of the electric transport unit under analysis presents values in the range of 0.67 and 0.94 km/kWh, depending on the conditions of the route. The results of the study are also supported by user satisfaction surveys, where the preference is to replace existing transport units with electric units, due mainly to the environmental benefit and the reduction in urban noise. In this sense, this study supports the feasibility of replacing fossil fuel bus units with electric units and recommends gradual replacement based on the results of the multicriteria analysis (see Tables 9 and 10).

Wenz et al. [25] performed another route selection method for the city of Cuenca. In accordance with the analysis, after considering more subcriteria within this study and applying a different methodology, the results suggest the operation of 11 electric units for line 13, 25 electric units for line 7, 18 electric units for line 16, nine electric units for line 28, and five electric units for line 27. If these changes were to be implemented, in the first stage, 68 electric buses would be needed, in contrast to the 50 units suggested by Wenz and others. While Wenz et al. [25] present a case study in the historic center of the model city, this project expands its scope by working with the coverage of routes for the entire city. Thus, the influence of the remaining coverage zones modifies the final results with respect to those obtained when analyzing a smaller area. For its part, the multicycle methodology used in Ref. [25] is developed for that particular case and considers only some of the criteria that condition the choice of alternatives: technical characteristics of the electric and combustion buses and operational details of the existing routes. and the number of passengers per route. This project uses a decision-making methodology widely tested in various scientific fields and includes other additional analysis factors that give more solidity to decision making.

Several qualitative criteria were used in this research. Qualifications were made from experts in the area of transportation. Although this study has sought to limit subjectivity, it will be present due to the influence of human perception. The study could be strengthened by conducting quantitative assessments or by using fuzzy logic. The use of three scenarios made it possible to define the 5 most suitable routes for the incorporation of the initial fleet of electric buses. In this case, all the alternatives coincide even when they change position. In this sense, a sensitivity analysis per alternative could be used to establish which subcriteria are most influential.

6. Conclusions

In this research, a multicriteria methodology incorporating technical, social, economic, environmental and location aspects was established for optimal routing, applicable to the conversion of transport technologies. The methodology can be used for different environments and is undoubtedly useful for prioritizing investments in the current scenario where more sustainable transport is sought. The proposed methodological process could be applied to any other mid-sized city, especially one where buses prevail as the main transport system.

The MCDM processes show utility and applicability in the transport sector, specifically when optimizing route selection for transitioning to the operation of electric buses. The greater the diversity of the criteria considered for decision making is, the more robust the results. Therefore, we considered five types of criteria, which define the electric unit of public bus transport and the specifications of urban routes.

When considering the influence on the results according to each set of the five criteria considered, the group of technical subcriteria accounts for 44.2% of the impact on the choice of the final ranking within the main scenario; thus, these subcriteria are considered the most important. In this same sense, in descending order, the social subcriteria contribute 14.9%, the environmental subcriteria contribute 14.6%, the economic subcriteria contribute 14.2%, and finally, the location subcriteria contribute 12.1%. In terms of individual subcriteria, the five criteria that most influence the results, in descending order, are the number of passengers served (c6) with 7.8% influence, the length of the network (c1) with 7.6% influence, the energy consumed per stroke (c3) and the energy consumed per line (c4), each with an individual contribution of 7.5%, and finally, the power required per line (c5) and the daily pollution produced (c10), both with a 7.4% influence on the calculation of the global preference flow for each proposed alternative. However, the subcriterion with the least influence is the distance between stops (c13), with a 5.8% contribution.

After calculating the flow of overcoming $\varphi\hat{}+$ and $\varphi\hat{}-$ using PROMETHEE I and subsequently calculating the net or global preference flow φ using PROMETHEE II, for the main scenario, alternative (a9) is the best qualified, with an overall flow of 0.4267 compared to an overall flow of 0.3901 for the second-place alternative (a5). Third, alternative (a12) obtained an overall flow of 0.3484, fourth-place alternative (a22) obtained an overall flow of 0.2410, and fifth-place alternative (a21) obtained an overall flow of 0.2374. Finally, within the same main scenario, the worst-rated alternative is alternative (a4), with an overall flow of −0.4052.

This approach can determine the real consumption according to variables such as traffic, road slope, speed, and time of day. Using the city of Cuenca in Ecuador as a case study, this study has satisfactorily identified the operational conditions and main characteristics of mass transit to detail the preestablished routes as alternatives.

Credit author statement

Conceptualization, E.A.B.-E. and V.M.-M.; methodology, V.M.-M.; software, V.M.-M.; validation, E.A.B.-E and X.S.-G.; investigation, E.A.B.-E. and V.M.-M.; resources, E.Z.-L. and V.M.-M.; data curation, E.A.B.-E.; writing—original draft preparation, E.A.B.-E. and V.M.-M.; writing—review and editing, E.A.B.-E. and E.Z.-L.; visualization, E.A.B.-E.; project administration, E.A.B.-E.; funding acquisition, E.A.B.-E and X.S.-G. All authors have read and agreed to the published version of the manuscript.

Declaration of competing interest

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

Data availability

Data will be made available on request.

Acknowledgments

The authors wish to express their most sincere acknowledgment of and gratitude to Salesian Polytechnic University (Universidad Politécnica Salesiana – UPS), particularly the Energy Research Group, for their guidance and for funding this research. This research was also supported by the Virtualtech research group of the Vicerrectorado de Investigación de la Universidad de Cuenca.

References

[1] G.H. Tzeng, C.W. Lin, S. Opricovic, Multi-criteria analysis of alternative-fuel buses for public transportation, Energy Pol. 33 (11) (2005) 1373–1383, https://doi.org/10.1016/j.enpol.2003.12.014.
[2] J. Mújica, Recomendaciones para la introducción progresiva de la tecnología de propulsión eléctrica en el transporte público de Santiago de Chile, 2014.
[3] A. Rodríguez Álvarez, M.B. Folgueras Díaz, J. Izquierdo López, Estudio de la descarbonización parcial del parque automovilístico español mediante la sustitución de éste por vehículos eléctricos y de gas natural, 2016.
[4] A. Barragán Escandon, El autoabastecimiento energético en los países en vías de desarrollo en el marco del metabolismo urbano: caso Cuenca, Ecuador, Universidad de Jaén, 2018.
[5] EMOV, Informe Calidad Aire Cuenca 2017, 2017.
[6] Asamblea Nacional República del Ecuador, Ley orgánica de eficiencia energética, 2019.
[7] W. Alvear, J. Espinoza, L. González, Diseño del sistema eléctrico en baja tensión para estaciones de carga de autobuses eléctricos, Universidad de Cuenca, 2019.
[8] L.G. González, D. Cordero-Moreno, J.L. Espinoza, Public transportation with electric traction: experiences and challenges in an Andean city, Renew. Sustain. Energy Rev. 141 (August 2020) 2021, https://doi.org/10.1016/j.rser.2021.110768.
[9] BYD, Build Your Dreams, 2018.
[10] M.-A. Molina, Características Técnicas De Buses Eléctricos BYD Modelo K9FE, UNIVERSIDAD TECNICA FEDERICO SANTA MARIA, 2018.
[11] C.N. Wang, V.T. Nguyen, H.T.N. Thai, D.H. Duong, Multi-criteria decision making (MCDM) approaches for solar power plant location selection in Viet Nam, Energies 11 (2018) 6, https://doi.org/10.3390/en11061504.
[12] J.M. Sánchez-lozano, M.S. García-cascales, M.T. Lamata, Evaluation of Suitable Locations for the Installation of Solar Thermoelectric Power Plants, vol. 87, 2015, pp. 343–355, https://doi.org/10.1016/j.cie.2015.05.028.
[13] J.M. Sánchez-Lozano, J. Teruel-Solano, P.L. Soto-Elvira, M. Socorro García-Cascales, Geographical Information Systems (GIS) and Multi-Criteria Decision Making (MCDM) methods for the evaluation of solar farms locations: case study in south-eastern Spain, Renew. Sustain. Energy Rev. 24 (2013) 544–556, https://doi.org/10.1016/j.rser.2013.03.019.
[14] M. Nassereddine, H. Eskandari, An integrated MCDM approach to evaluate public transportation systems in Tehran, Transp. Res. Part A Policy Pract. 106 (August) (2017) 427–439, https://doi.org/10.1016/j.tra.2017.10.013.
[15] J.W. Joubert, Multi-agent model of route choice when vehicles are sensitive to road grade, Procedia Comput. Sci. 109 (2017) 869–874, https://doi.org/10.1016/j.procs.2017.05.402.
[16] J.A. Lopez-Ibarra, A. Milo, H. Gaztanaga, V.I. Herrera, H. Camblong, Bus-to-route and route-to-bus approaches in hybrid electric buses fleet for battery lifetime extension, 2019 14th Int. Conf. Ecol. Veh. Renew. Energies, EVER (2019) 8–15, https://doi.org/10.1109/EVER.2019.8813543, 2019.
[17] M. Das, A. Roy, S. Maity, S. Kar, S. Sengupta, Solving fuzzy dynamic ship routing and scheduling problem through modified genetic algorithm, Decis. Mak. Appl. Manag. Eng. 5 (2) (2022) 329–361, https://doi.org/10.31181/dmame181221030d.
[18] U. Bahalke, N. Hamta, A.R. Shojaeifard, M. Alimoradi, S. Rabiee, A new heuristic algorithm for multi vehicle routing problem with and/or-Type precedence constraints and hard time windows, Oper. Res. Eng. Sci. Theory Appl. 5 (2) (2022) 28–60, https://doi.org/10.31181/oresta300622015b.
[19] D. Marković, G. Petrović, Ž. Ćojbašić, A. Stanković, The vehicle routing problem with stochastic demands in an Urban area – a case study, Facta Univ. – Ser. Mech. Eng. 18 (1) (2020) 107–120, https://doi.org/10.22190/FUME190318021M.
[20] V. Yildirim, S. Bediroglu, A geographic information system-based model for economical and eco-friendly high-speed railway route determination using analytic hierarchy process and least-cost-path analysis, Expet Syst. 36 (3) (2019) 1–14, https://doi.org/10.1111/exsy.12376.

[21] M. Hamurcu, T. Eren, An application of multicriteria decision-making for the evaluation of alternative monorail routes, Mathematics 7 (2018) 1, https://doi.org/10.3390/math7010016.
[22] L. Grassini, A. Viviani, A multicriteria decision method to evaluate local transport service, in: Conferences, telecom-bretagne, 2005, pp. 1173–1180.
[23] B. Torre, R. Sañudo, L. Dell'Olio, Estudio y valoración de alternativas para la construcción de un tranvía en la ciudad de Santander, Universidad de Cantabria, 2020.
[24] Y. Hadas, O.E. Nahum, Urban bus network of priority lanes: a combined multi-objective, multi-criteria and group decision-making approach, Transport Pol. 52 (2016) 186–196, https://doi.org/10.1016/j.tranpol.2016.08.006.
[25] K.P. Wenz, X. Serrano-Guerrero, A. Barragán-Escandón, L.G. González, J. M. Clairand, Route a study of case in anoute prioritization of urban public transportation from conventional to electric buses: a new methodology a intermediate city of Ecuador, Renew. Sustain. Energy Rev. 148 (December 2020) 2021, https://doi.org/10.1016/j.rser.2021.111215.
[26] B. Roy, R. Słowin, Questions Guiding the Choice of a Multicriteria Decision Aiding Method, 2013, pp. 69–97, https://doi.org/10.1007/s40070-013-0004-7.
[27] R.L. Keeney, H. Raiffa, Decisions with Multiple Objectives : Preferences and Value Trade-Offs, 1976, https://doi.org/10.1109/TSMC.1979.4310245.
[28] J.S. Dyer, MAUT – multiattribute utility theory, in: J.R. Figueira, S. Greco, M. Ehrgott (Eds.), *Multiple Criteria Decision Analysis: State of the Art Surveys*, N, Springer, Nueva York, 2005, pp. 265–292.
[29] J. Siskos, I. France, Assessing a set of additive utility functions for multicriteria decision-making, the UTA method 10 (1982) 151–164, https://doi.org/10.1016/0377-2217(82)90155-2.
[30] C.A. Bana, J.-M. De Corte, J.-C. Vansnick, On the mathematical foundations of MACBETH, in: J.R. Figueira, S. Greco, M. Ehrgott (Eds.), *Multiple Criteria Decision Analysis: State of the Art Surveys*, N, Springer, New York, 2005, pp. 409–442.
[31] S. Opricovic, G.-H. Tzeng, Compromise Solution by MCDM Methods : A Comparative Analysis of VIKOR and TOPSIS, vol. 156, 2004, pp. 445–455, https://doi.org/10.1016/S0377-2217(03)00020-1.
[32] C.L. Chen, S.J. Hwang, Fuzzy Multiple Attribute Decision Making: Methods and Applications, Springer-Verlag, Berlin, Heidelberg, 1992.
[33] K. Hwang, C.L. Yoon, Multiple Attribute Decision Making— Methods and Applications, Springer, New York, 1981.
[34] T.L. Saaty, GROUP decision making and the AHP, Springer 53 (9) (1989) 59–67, https://doi.org/10.1017/CBO9781107415324.004.
[35] T.L. Saaty, M.S. Ozdemir, Why the magic number seven plus or minus two, Math. Comput. Model. 38 (2003) 233–244, https://doi.org/10.1016/S0895-7177(03)90083-5, 3–4.
[36] S. Greco, V. Mousseau, R. Słowinski, Ordinal Regression Revisited : Multiple Criteria Ranking Using a Set of Additive Value Functions, vol. 191, 2008, pp. 416–436, https://doi.org/10.1016/j.ejor.2007.08.013.
[37] J.R. Figueira, V. Mousseau, B. Roy, ELECTRE methods, in: S. Greco, et al. (Eds.), Multiple Criteria Decision Analysis, vol. 233, N. Springer, Nueva York, 2006, pp. 155–185, 2016.
[38] J.-P. Brans, B. Mareschal, PROMETHEE methods, in: J.R. Figueira, S. Greco, M. Ehrgott (Eds.), *Multiple Criteria Decision Analysis: State of the Art Surveys*, N, Springer, Nueva York, 2005, pp. 163–195.
[39] Ö. Kaya, A. Tortum, K.D. Alemdar, M.Y. Çodur, Site selection for EVCS in Istanbul by GIS and multi-criteria decision-making, Transport. Res. Transport Environ. 80 (2020), 102271, https://doi.org/10.1016/j.trd.2020.102271. February.
[40] D. Guler, T. Yomralioglu, Suitable location selection for the electric vehicle fast charging station with AHP and fuzzy AHP methods using GIS, Ann. GIS 26 (2) (2020) 169–189, https://doi.org/10.1080/19475683.2020.1737226.
[41] A. Panday, H.O. Bansal, Multi-Objective optimization in battery selection for hybrid electric vehicle applications, J. Electr. Syst. 12 (2) (2016) 325–343.
[42] E.A. Barragán, J. Terrados, E. Zalamea, P. Arias, Electricity production using renewable resources in urban centres, Proc. Inst. Civ. Eng. 171 (1) (2018) 12–25, https://doi.org/10.1680/jener.17.00003.
[43] B. Mareschal, Visual PROMETHEE Manual, VPSolutions, Brussels, Belgium, 2013, pp. 1–192.
[44] M. Behzadian, R.B. Kazemzadeh, A. Albadvi, M. Aghdasi, PROMETHEE: a comprehensive literature review on methodologies and applications, Eur. J. Oper. Res. 200 (1) (2010) 198–215, https://doi.org/10.1016/j.ejor.2009.01.021.
[45] L.S. García, V. Magar, Energía eólica y desarrollo sostenible en la región de la Rumorosa, municipio de Tecate, Colegio de la Frontera Norte, 2016.
[46] J.-P. Brans, B. Mareschal, PROMÉTHÉE-GAIA Une méthodologie dàide à la decision en presence de critères multiples, 2002.
[47] L. Abdullah, W. Chan, A. Afshari, Application of PROMETHEE method for green supplier selection: a comparative result based on preference functions, J. Ind. Eng. Int. 15 (2) (2019) 271–285, https://doi.org/10.1007/s40092-018-0289-z.
[48] M.S. Rahaman, Y. Mei, M. Hamilton, F.D. Salim, CAPRA: a contour-based accessible path routing algorithm, Inf. Sci. (Ny) 385 (386) (2017) 157–173, https://doi.org/10.1016/j.ins.2016.12.041.
[49] K. Kivekas, J. Vepsalainen, K. Tammi, Stochastic driving cycle synthesis for analyzing the energy consumption of a battery electric bus, IEEE Access 6 (2018) 55586–55598, https://doi.org/10.1109/ACCESS.2018.2871574.
[50] J.J. Wang, Y.Y. Jing, C.F. Zhang, J.H. Zhao, Review on multi-criteria decision analysis aid in sustainable energy decision-making, Renew. Sustain. Energy Rev. 13 (9) (2009) 2263–2278, https://doi.org/10.1016/j.rser.2009.06.021.
[51] R. Likert, A Technique for the Measurement of Attitudes, 1932. New York.
[52] E.A. Barragán, El autoabastecimiento energético en los países en vías de desarrollo en el marco del metabolismo urbano: caso Cuenca, 2018, pp. 1–373. Ecuador.
[53] S.A. Hajkowicz, G.T. McDonald, P.N. Smith, An evaluation of multiple objective decision support weighting techniques in natural resource management, J. Environ. Plann. Manag. 43 (4) (2000) 505–518, https://doi.org/10.1080/713676575.
[54] S. Ghafghazi, T. Sowlati, S. Sokhansanj, S. Melin, A multicriteria approach to evaluate district heating system options, Appl. Energy 87 (4) (2010) 1134–1140, https://doi.org/10.1016/j.apenergy.2009.06.021.
[55] Instituto Nacional de Estadísticas y Censos, Fascículo Provincial Azuay, 2010.
[56] Ilustre Municipalidad de Cuenca, Plan de movilidad de Cuenca 2015-2025, Cuenca, 2015.
[57] Moovit Inc, MOOVIT (2023).
[58] DEFRA, Guidelines to Defra's GHG Conversion Factors: Methodology Paper for Transport Emission Factors, 2008, 2008.