applied sciences

MDPI

Article

Evaluation and Selection of the Railroad Route between Rijeka and Zagreb

Siniša Vilke *, Ines Petrović and Frane Tadić *

Faculty of Maritime Studies, University of Rijeka, 51 000 Rijeka, Croatia; ines.ostovic@uniri.hr
* Correspondence: sinisa.vilke@uniri.hr (S.V.); frane.tadic@uniri.hr (F.T.)

Abstract: One of the biggest issues in railroad planning and design is determining the optimal railroad route. After the railroad route variants are determined, the major challenge is to identify and select the criteria which will be used for the analysis and evaluation of the variants. This paper is primarily concerned with the evaluation and selection of an optimal railroad route between Rijeka and Zagreb as part of the Mediterranean Corridor. The large number of criteria used to analyze solutions makes this decision-making complex. The objectives are usually in conflict with each other, and there are usually several groups of decision makers involved in the process. The aim of this paper was to analyze alternative railroad route variants using the optimization method of multi-criteria analysis. To achieve the research aim, a model comprising the defined criteria and sub-criteria including their weighting coefficients was set. To perform the analysis, the authors applied the defined model for evaluation and selection of a railway route between Rijeka and Zagreb using the PROMETHEE II method for multi-criteria ranking of alternatives and the computer software "Visual PROMETHEE". The value of the defined model is expressed by the presented methodology of multi-criteria optimization, which is used in railroad planning and designing.

Keywords: multi-criteria analysis; railroad planning and designing; railroad route evaluation; railway line Rijeka-Zagreb

Citation: Vilke, S.; Petrović, I.; Tadić, F. Evaluation and Selection of the Railroad Route between Rijeka and Zagreb. *Appl. Sci.* **2022**, *12*, 1306. https://doi.org/10.3390/app12031306

Academic Editor: Araliya Mosleh

Received: 30 December 2021
Accepted: 21 January 2022
Published: 26 January 2022

1. Introduction

The national railways in the territory of the Republic of Croatia are currently in a modernization phase, because a large part of the railway network in the Republic of Croatia is routes that are important for international traffic. Along these routes there is also a railway line Rijeka-Zagreb, which is of great importance for the development of the port of Rijeka. According to the geometric position, the port of Rijeka provides the most convenient natural route for the Central European countries to the Adriatic Sea, which in turn opens the way to the Mediterranean Sea, Gibraltar, the Suez Canal, and the Atlantic Ocean to the Indian Ocean.

In defining the model for evaluation of the railway infrastructure in the territory of the Republic of Croatia, a multi-criteria analysis was applied to the section Rijeka-Zagreb [1–3] in order to select the most favorable railroad route connecting the two centers. Then, using the expert survey method [4], important data was collected, which finally provided the optimal solution for the selection of a railway route using the analysis method.

The need to apply multi-criteria analysis in the decision-making process for the study and planning of a transport infrastructure [5] project is due to the characteristics of the infrastructure, which are considered a public good, in order to reduce the problems and risks associated with the development of such projects. The proposed methodology provides a complete and systematic solution to this problem. The result of the methodology represents the most appropriate path in accordance with the adopted criteria and existing restrictions.

In order to achieve a functional, safe, integrated, and high-quality urban environment, it is first necessary to plan the transportation system and develop a spatial and transportation plan that meets both the current and future requirements [6–8]. The search for a suitable railway infrastructure route is a complex process due to the different evaluation criteria resulting from the social and environmental impacts on society, but also due to the high costs and technical pressures on decision-makers. Therefore, a solution proposed by some authors is a multi-criteria approach based on a geographic information system [9–11].

The environmental impact of the route is an essential issue for both road [12] and rail transport [13], and should be carefully considered before selecting a route. Sustainability in railway infrastructure is an indispensable component in decision-making owing to the influence it enjoys in the selection of a concept for further development [14]. In addition to sustainability, some authors point out [15,16] that the importance of energy conservation is equally important in sustainable-energy decisions.

Decision-making in planning and designing transportation systems is a complex process with social, technical, and economic components [17]. Using an economic evaluation, the authors determined the optimal route for travel between Lanzhou and Beijing [18]. A similar study [19] was conducted for the purpose of economic analysis of railroad infrastructure. It evaluated the impact of methodological changes in the financial and economic evaluation of railroad construction projects in the Czech Republic.

In the paper [20], the authors used the method of multi-criteria decision-making for the selection of the most suitable solution of the railroad route, i.e., [21] for the selection of the most suitable alternative of the highway route in Serbia. A similar method for selecting the optimal solution was applied to a concrete example of a railroad project using multi-criteria analysis [22]. Various methods of multi-criteria decision-making have been shown to be appropriate as auxiliary options for the decision on the introduction of a new high-speed train on the Madrid-Valencia route [23].

It is important to consider environmental and geological sustainability criteria in the planning and design of railroad corridors, as shown by the authors [24] for the territory of Sweden.

Apart from railroad lines, it is also important to consider the impact of extreme weather conditions on overhead-line infrastructure, as explained in the papers [25–28]. In addition to infrastructure, special attention should also be paid to railroad safety related to the quality of traction of train wheels on the tracks [29,30].

New research trends [31] in rail transport are related to the interaction of pantographs and overhead routes, i.e., aerodynamics and active control of pantographs. In addition, contributions address system maintenance, life cycle costs, and reliability [32–35].

The aim of this paper was the analysis of the evaluation and selection of the optimal railroad route using the multi-criteria analysis method through defined criteria and sub-criteria.

The research problem of the paper arose from the formulation of several research questions:

- RQ1: How can the optimal selection of the Rijeka-Zagreb railway line be achieved by applying the multi-criteria analysis method?
- RQ2: Which are the relevant criteria and sub-criteria for the evaluation and selection of the railway route?
- RQ3: Is conducting surveys and interviewing experts a relevant method for determining the model for evaluating and selecting the optimal railway route?

With respect to the research problem and the defined research questions, the following scientific hypothesis was set for the evaluation and selection of an optimal railway transport route so that the multi-criteria analysis method could be applied.

For the selection of the planned railroad route, it is first necessary to define a model for evaluation comprising appropriate criteria and sub-criteria as well as their coefficient of importance Then, an analysis of these criteria has to be performed, which can be produced by a quality selection of the desired outcome using a multi-criteria approach [36,37].

In the article, the multi-criteria analysis, i.e., the PROMETHEE II method for multi-criteria ranking of alternatives was applied for the evaluation and selection of the Rijeka-Zagreb railroad route. This method was appropriate for achieving the aim of the paper as it applies the model consisting of weighted criteria and sub-criteria, enables the entry of data regarding the evaluation of each criteria and sub-criteria, and, finally, allows the complete ranking of railroad route variant solutions.

2. Multi-Criteria Analysis—A Methodological Approach

Multi-criteria decision analysis or multi-criteria decision-making (MCDA/MCDM) is a branch of operation research models and a well-known field of decision-making. According to [38], MCDA is "a general term used to describe a range of formal approaches that attempt to explicitly consider multiple criteria to help individuals or groups make important decisions."

Multi-criteria analysis can be defined as a decision model consisting of [39]:

1. A set of decision options (variants are ranked and evaluated by the decision-makers);
2. A set of criteria (containing multidimensional criteria that can only be analyzed and evaluated in different units);
3. A set of performance measures that define the scores for each decision option in relation to each criterion.

Problems consisting of different and mostly contradictory criteria can often result in different meanings for the decision-maker. The methods by which the best solution is selected most often require information on the importance of the criteria individually. The assessment of the value of the criteria depends on the decision-maker. Likewise, the decision might be based on the recommendations of a group of experts from the relevant field [40].

Deciding on the benefits of certain alternatives usually requires the optimal search for the best alternative that would meet as many criteria as possible at once. The criteria can be distinguished according to qualitative and quantitative characteristics, for example, according to the price and quality. When assessing the impact on the environment, environmental indicators can greatly influence the final ranking of criteria, although the general task of multi-criteria decision-making is classified into individual alternatives [41].

2.1. PROMETHEE Method

Multi-criteria optimization approaches that attempt to rank variants based on the degree to which certain criteria are met include methods for multi-criteria ranking of application solutions [39].

J.P. Brans and B. Mareschal [42] developed the PROMETHEE method (preference-ranking organization approach for enrichment evaluations) for multi-criteria ranking of variations in 1983, which is one of the most important methods of multi-criteria analysis. This method is applied to a wide range of decision problems in transportation planning and design. Behzadian, M. et al. [43] present a list of PROMETHEE-related publications, research papers, applications, and debates.

The main input of the PROMETHEE method is a matrix that consists of a set of potential alternatives (actions), A, where each element of A has its own evaluation, f(a). The PROMETHEE I method allows the partial ranking of variants, where different variants can have the same rating, which allows for the utilization of certain ranks. The PROMETHEE II method enables entire ranking, where variants are precisely rated in dependence on the function of preference [44].

If the decision-maker requires a complete ranking of options, this means that two or more alternatives cannot have the same rank; each alternative must have its own rank.

For each solution $a \in A$, the net flow is:

$$\phi(a) = \phi^{+}(a) - \phi^{-}(a), \tag{1}$$

and for the solution ranking, it could be simply applied that a has a higher rank than b:

$$\left(aP^{(2)}b\right) \quad \text{if} \quad \phi(\mathrm{a}) \ > \phi(b) \tag{2}$$

a is indifferent to *b*

$$\left(aI^{(2)}b\right) \quad \text{if} \quad \phi(\mathrm{a}) \ = \phi(b) \tag{3}$$

According to [45], the PROMETHEE method can be easily understood by decision-makers and can offer reasonable ranking of all alternatives. Therefore, the method is widely adopted in energy projects, tourism competitiveness, and transport location selection.

The PROMETHEE II method is often used for traffic-planning and design purposes as it allows order determination. Based on an accurate data input, this method allows a partial or complete classification of several variants with respect to a larger number of criteria.

2.2. Methodology-Application of the Multi-Criteria Analysis Method in Traffic Planning

All multi-criteria problems consist of different and conflicting criteria that are of varying value to the decision maker, although many methods for selecting the best variant demand facts concerning the relative value of each criterion [40]. The evaluation of the importance of the criteria is in most cases made by a group of experts.

When deciding on the optimal solution for space-traffic studies, it is necessary to define the criteria and benchmarks against which the solutions are to be evaluated before deciding on the best solution. According to different studies [46], the selection of the optimal solution depends on the economic criteria in the transportation planning process or decision-making. Therefore, for the overall study of the problems of the transport system, it is necessary to have access to the simultaneous effect of the various aspects by which the possibility of valorization is determined.

A similar example is the multi-criteria optimization, which involves the selection of the optimal solution compared to the simultaneous effect of many different criteria. In transport planning, the following criteria are considered: economical, technical, planning, environmental, social, and safety.

The criteria used to decide the routing of internal transport infrastructure are very complex, so the choice of a complex decision-making task depends on the possibility of evaluation. Also, the choice of a value scale further complicates the situation by reducing the results to a common physical quantity.

Ranking individual variants and selecting the optimal solution considering the simultaneous effect of several different criteria is made possible by the method of ranking multi-criteria variants. Ranking of multi-criteria variants simplifies the decision-making and quantified representation of facts that are crucial for decision-making. Furthermore, the ranking of multi-criteria plays an important role in deciding where to select the optimal variant from a set of variants that differ according to the adopted criteria.

3. A Model for the Evaluation and Selection of the Railroad Route

Any transport solution, in addition to general criteria such as costs, environmental impact, etc., must satisfy specific criteria defined by certain physical characteristics, thus preventing the creation of a unique universal list of objectives and criteria. The decision-making methodology for the selection of a railroad route and the description of the multi -criteria optimization process for the selection and evaluation of a railroad route is illustrated in Figure 1.

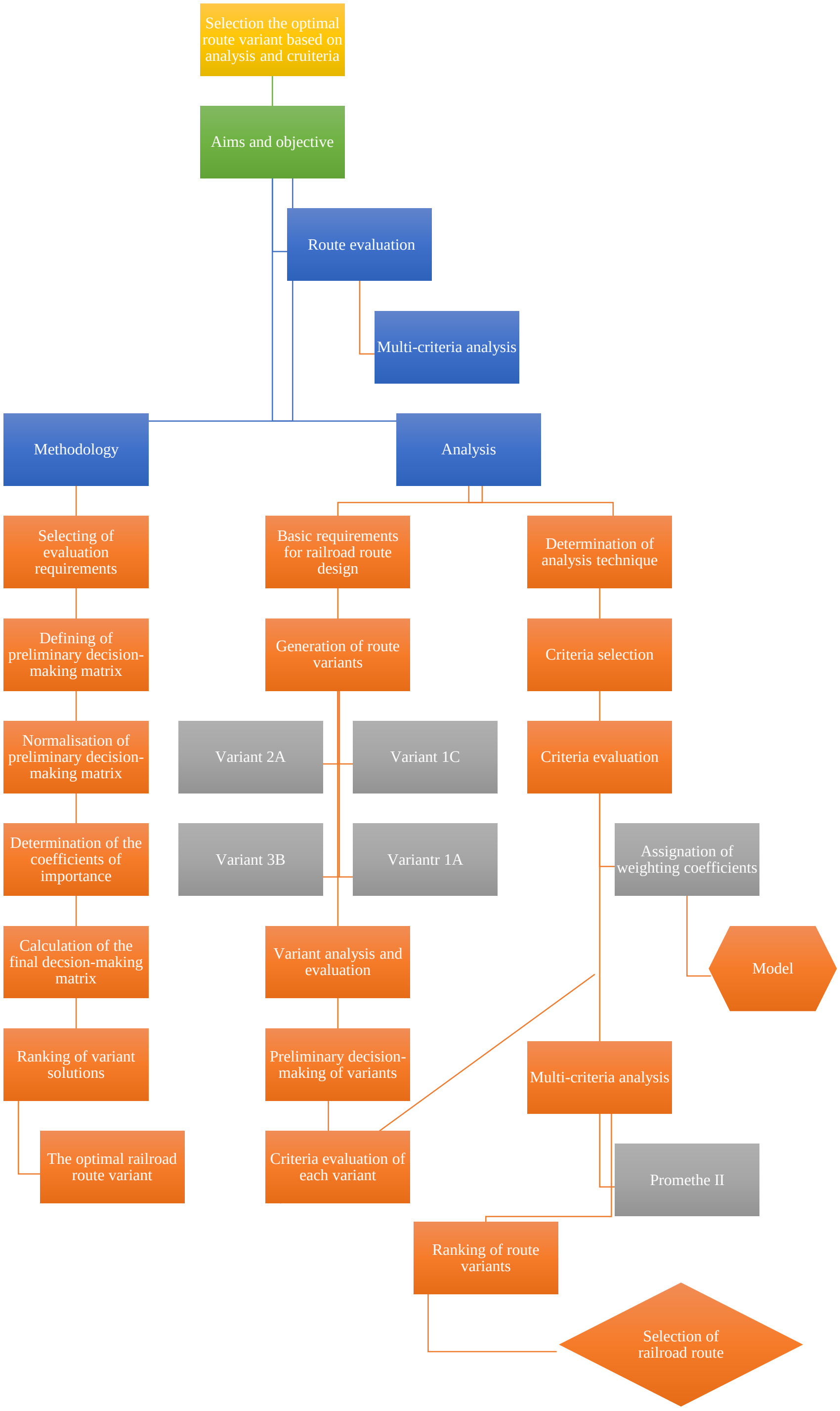

Figure 1. Scheme of decision-making methodology and multi-criteria railroad route evaluation.

The specifics of the analyzed approach can be expressed more directly by assigning the respective importance of the criteria or the "weight" of the criteria. The activities in traffic study include decisions based on a formalized matrix of the weight of criteria. This matrix of the importance of criteria is the result of a thought process that presents a limited range depending on the innovative skills of the planner to analyze all the relevant aspects of the problem. Traffic study variant solutions are achieved through decisions in which the public and the broadest socio-political structure are directly involved. Therefore, it is necessary to examine the position in the hierarchy of criteria and objectives, while at the same time clearly defining the social advantage of the importance of the defined criteria.

Since the effectiveness of the chosen criteria determines the quality of the implemented selection method for the optimal version of the railroad route and the accuracy of the final choice, it is crucial that the criteria and measurements for performing the optimization are well defined. Experts should be involved in the definition of the criteria to ensure that the weighting coefficient, i.e., the relevance of the criteria, is not subject to a subjective approach [47].

The procedures for the assessment of the criteria for the evaluation and selection of the railroad route distinguish two categories of criteria:

- A group of criteria that are evaluated based on concrete, exact, and quantitatively expressed data,
- A group of criteria that are evaluated based on the subjective opinions of researchers who are assumed and required to have sufficient knowledge of the problems and criteria they will evaluate.

In order to create a model for the evaluation and selection of the railroad route, the criteria and sub-criteria were defined, and their evaluation was made by assigning weighting coefficients. The selection of the criteria and sub-criteria and the weighting of their importance was based on interviews with numerous experts and professionals in the field of transport planning and design. The method of multi-criteria analysis was applied to make the selection of the optimal choice of the desired route as high-quality as possible.

The criteria for the assessment and selection of railway routes were divided into five groups, which in turn were subdivided into less complex components or sub-criteria for the evaluation and selection of railway routes. By breaking down the criteria into simpler components, a better process of ranking variants according to several criteria is achieved. In addition, it is possible to analyze the results and draw conclusions about the evaluation of specific routes. Table 1 shows a model for the selection of the railroad route, which contains criteria and sub-criteria for the evaluation with the weighting coefficients assigned to them, which were necessary for further evaluation.

Table 1. Criteria and sub-criteria for evaluation and selection of a railroad route.

Criteria (%)		Sub-Criteria	
		Full Name	**Value**
Economic	21%	Costs of route construction	26%
		Costs of maintenance	13%
		Costs of management	17%
		Influence of the land depreciation of the local population	16%
		Development of tourism in the zone of influence	11%
		Development of economic activities in the region	17%
Transport	27%	Integration into the city railway system	6%
		Integration into the intermodal traffic system	9%
		Proximity of passenger aprons with regard to other traffic terminals	6%
		Route position at the facilities	7%
		Route length	13%
		Capacity of railway line	16%
		Train-journey duration	13%
		Transport reliability and speed	11%
		Transport safety	19%
Constructional-technical	12%	Technical–technological complexity of the construction of the route	35%
		Terrain geology and seismology	17%
		Passing of the route through common infrastructure corridors (yes/no)	27%
		Availability of land or free space	21%

Table 1. *Cont.*

Criteria (%)		Sub-Criteria	
		Full Name	**Value**
Urban planning	18%	Visual landscape impact	22%
		Damage to the relief and possibilities of recovery	10%
		Attracting other activities that endanger the geomorphological features of the area	9%
		Impact on the development of the potential in urban planning	14%
		Deviation of the route from the aviation line	6%
		Space limitations	15%
		Spatial units' preservation and land taking	13%
		The layout occupancy of the land area of variant solutions	11%
Ecological-sociological	22%	Environmental impact	15%
		Spatial impact	8%
		Noise impact	7%
		Vibration impact	5%
		Influence of meteorological conditions	4%
		Impact of the route on the water and soil pollution	7%
		Conservation restrictions	6%
		Impact on the wider community	7%
		Protected parts of nature and cultural heritage	9%
		Protected areas and habitat (ecological network)	11%
		Influence on the population	9%
		Distance from tourism zones	6%
		Distance from populated areas	6%

The importance of the sub-criteria were compared, and the weighting coefficients were normalized so that their sum was 100%. In addition, the weighting coefficients of the sub-criteria within a thematic group of criteria were normalized so that the sum within each group of criteria was 100%.

The defined model for the evaluation and selection of the railroad route was applied to create a ranking list of railroad variants for the construction of the Rijeka-Zagreb railroad route.

4. Application of the PROMETHEE Multi-Criteria Method for the Evaluation and Selection of the Railroad Route Rijeka-Zagreb as Part of the Mediterranean Corridor

For the connection of central Croatia, Gorski Kotar, and the northern littoral, the main railway line, i.e., the national railway line Rijeka-Zagreb-Botovo, plays a significant role, which was also perceived by the European Commission as this route was categorized as a part of the priority Axis 3 of the TEN-T transport network. This route connects the port of Rijeka with central and eastern Europe including the southern section of the Baltic-Adriatic Route and has been evaluated as part of the former transversal Vb corridor.

A multi-criteria ranking of variants as well as the method PROMETHEE II and the computer software "Visual PROMETHEE" for multi-criteria optimization were used for the selection of the railroad route that would connect the stations of Rijeka, Zagreb, and Botovo on the border between Croatia and Hungary.

Analysis of the application of the multi-criteria method for the evaluation and selection of the railway route was carried out in several stages, which proceeded in the following order:

- Identification of variant solutions for the railway route;
- Evaluation of individual variants according to the established criteria and sub-criteria;
- Estimation and ranking of variants;
- Selection of the optimal variant.

For the analysis of potential route corridors of the railway route Rijeka-Zagreb, several variants stood out among the route corridors. By identification alternative routes of the railway line, four solutions were selected for the ranking of variants by multi-criteria analysis. Technical parameters and elements were defined according to the Feasibility Study Modernization and Construction of State Border-Botovo-Zagreb-Rijeka Railway Transport Corridor and Transport Technical Designing Project Vb Corridor-State Border-Botovo-Zagreb-Hrvatski Leskovac-Krasica-Rijeka [48].

Each variant selected for multi-criteria analysis was described by the criteria, sub-criteria, and weighting coefficient. Applying the computer software, an optimal railroad route between Rijeka and Zagreb was selected. As input data the importance sets of the criteria and sub-criteria determined by surveys and the values of the parameters of the corresponding sub-criteria for the four selected variants were used.

4.1. Analysis of Alternative Railroad Route Variants—Optimization Model and Evaluation

According to the Feasibility Study Modernization and Construction of State Border-Botovo-Zagreb-Rijeka Railway Transport Corridor, several variants of the railway route Zagreb (Hrvatski Leskovac)-Rijeka (Krasica) were considered [49]. The route was divided into three sections:

- Section 1: Hrvatski Leskovac station-Belaj station;
- Section 2: Belaj station-Skradnik station;
- Section 3: Skradnik station-Krasica station.

From Hrvatski Leskovac to Skradnik, four variants were analyzed, i.e., three basic and one transitional variant (Figure 2): variant 1, variant 2, variant 3, and variant 4, as a transitional variant (representing the transition from variant 3 to variant 1).

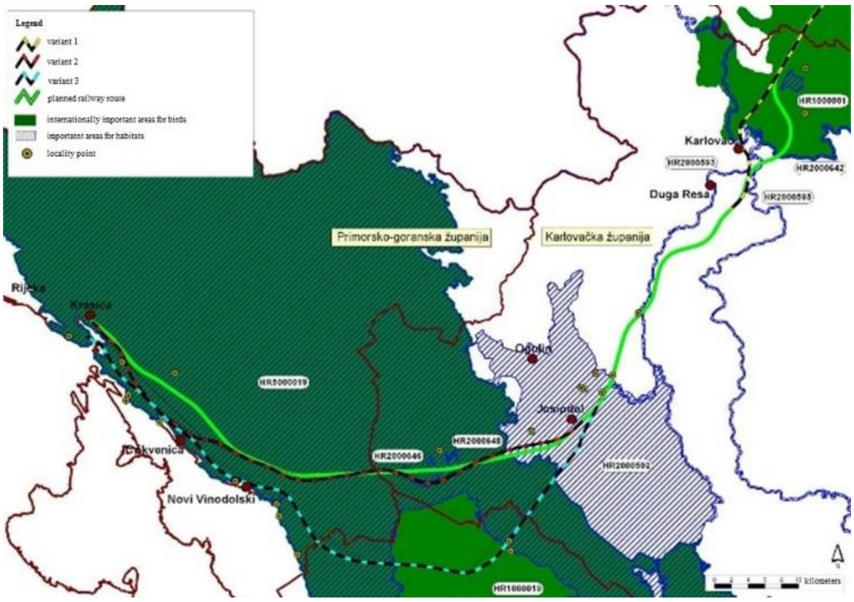

Figure 2. A clear overview of the analyzed railroad route variants [49].

The railway route from Hrvatski Leskovac (120.3 m above sea level) to Skradnik (143.6 m above sea level) is slightly ascending with long sections that are horizontal, with the largest inclinations of the track axis of 8 mm/m (on the shorter part in the length of 1575 m in the inclination of 10.7 mm/m). The relevant resistance is up to 12.5 daN/t. In the opposite direction, from Skradnik to Hrvatski Leskovac, the railway line is descending, with a smaller ascent of 8 mm/m on shorter sections (2180–2400 m). The corresponding resistance in the opposite direction is up to 10 daN/t. A shorter ascent can be overcome by train travel and inertia, i.e., by reducing the travel speed on these sections.

From Skradnik to Krasica, three basic variants were elaborated: Variant A, Variant B, and Variant C. This area is an extremely challenging one in terms of ecology, relief, and geology, and in terms of other segments. Therefore, in terms of transport infrastructure, this area is, at the same time, a strategic area of the state, which ensures the passage of large infrastructures between northern, central, and southern Croatia. From Skradnik to Krasica station, the railway is very demanding in terms of construction and exploitation, as the facilities contain 51,292 m and 76.56% of the route.

The railway route from Skradnik to Drežnica has an ascent of 8 mm/m (on a shorter section of 972 m a gradient of 11.7 mm/m). In this part there are two tunnels, one (Veljun) 2860 m and the other (Kapela 1) 9300 m long. The line is mostly stretched with a curve of 6500 m in radius. Considering the resistance of the train due to the passage through the tunnel, the relevant resistance of the line is up to 14 daN/t. From Drežnica (470 m above sea level) to Krasica (183 m above sea level) the line has a continuous gradient of 8 mm/m (except for the station area where it is horizontal or has a decline of 1 mm/m).

Combining all the above variants, ten variants for the construction of the railway route from Rijeka (Krasica) to Zagreb (Hrvatski Leskovac) are obtained. The following variants were selected for the multi-criteria ranking of variants: 1A, 1C, 2A, and 3B.

The length of the railway route according to Variant 1A is 151.6 km (section: Hrvatski Leskovac-Skradnik 81.9 km, Skradnik-Krasica 69.7 km). For Section A of the railway route (Skradnik-Krasica) the construction of a double-track railway is envisaged along the line descending nearest to the sea. On some sections of the planned corridor of the Variant 1A it is not possible to provide the necessary technical elements of the route for high speeds because of the ground plan and elevation elements, so it is necessary to deviate from the planned corridors. Moreover, at some sections of the route high technical and economical requirements are envisaged. From a transportation point of view, variant 1A on the route from Skradnik to Krasica is the most acceptable option, as it runs nearest to the sea. From this route, the shortest branch of the future railroad leads to the island of Krk, where the construction of a new container terminal is planned.

Figure 3 shows that Variant 1C differs from variant 1A on the part of the route from the Drežnica station to the Krasica station and at the junction of the new railway line with the island of Krk. In variant 1C it is necessary to build a new railway line from Krasica to Krk, and in variant 1A, the railway line to Krk is separated from the route of the new railway between the stations of Jadranovo and Krasica. The length of the route according to variant 1C is 150.1 km (section: Hrvatski Leskovac-Skradnik, 81.9 km; Skradnik-Krasica, 68.2 km).

Variant 2A involves the construction of a second track along the existing line from Horvati to the connection with the new route in the Belaj area (the route is double-tracked through Karlovac to the connection with a new line of the Belaj-Skradnik double-tracked railway route). From Belaj, the route is identical to the route of the railway in variant 1A. The length of the railway according to variant 2A is 152.5 km (section: Hrvatski Leskovac-Skradnik, 81.9 km; Skradnik-Krasica, 68.2 km).

The length of the route according to variant 3B is 149.1 km (section: Hrvatski Leskovac-Skradnik 80.7 km; Skradnik-Krasica 68.4 km). Variant 3B meets the required technical elements, but during the review of technical and geological characteristics of the terrain, very unfavorable technical and geological areas were found in the area of the northern slopes of the Vinodol Valley. It is an area comprising many landslides, and unstable for building. In addition, the influences from the point of view of environmental protection (demolition of some old houses, blacksmiths, difficulties with noise protection, etc.) are also unfavorable.

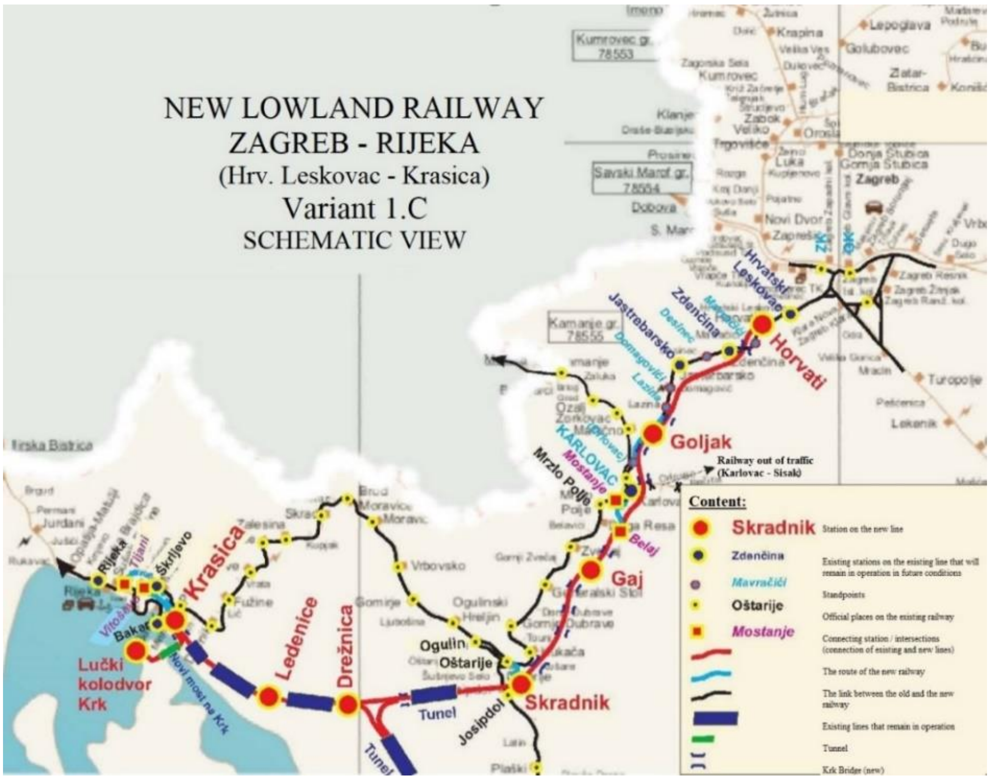

Figure 3. An overview of variant 1C [50].

The critical section of the existing railroad line route is located between Moravice and Rijeka, on the part of the railroad route in the mountains, where it features very unfavorable elements (slope of the route 25–28 mm/m, curves 250–300 m). The problem is to be solved by building a lowland railway from Horvati to Krasica. The part of the new route from Skradnik to Krasica currently solves the problem of crossing the mountain range located between the Adriatic Sea and the interior of the country. The part of the route from Horvati to Skradnik significantly improves the route elements in comparison with the existing routes and at the same time enables the improvement, in the future, of the railroad connection to Lika and Central Dalmatia (Split, Šibenik, Zadar, and Ploče). The construction of a new route according to variant 1C solves the problem of penetration of the mountain range to the sea. All the three variants considered are suitable for this purpose, yet the variant C seems to be the most favorable one.

As presented in Table 2 the economic criteria C1, C2, and C3 as well as the transport criteria C11 are expressed quantitatively [48–50]. For criteria C5, C6, C7, C8, and C18, the units of the yes/no criteria were applied, while for the eco-sociological criteria C28, C33, C36, and C37, the input parameters were from GIS (Geographic Information System), which was developed specifically for this multi-criteria analysis. Other criteria were assigned their respective parameters according to the rating scale from 0 to 10. A corresponding object function, i.e., its minimum and maximum, was also assigned to each criterion.

Table 2. Criteria evaluation for variant solutions.

CRITERIA (%)		SUB-CRITERIA Mark	Unit/ Object Function	Variant 1A	1C	2A	3B
Economic	21%	C1	Mil EUR Min	4756	4732	4766	4796
		C2	000 EUR Min	20,586	20,185	20,697	20,901
		C3	000 EUR Min	7073	7056	7080	7097
		C4	Grade Min	6	5	6	5
		C5	Yes/No Max	N	N	N	N
Transport	27%	C6	Yes/No Max	Y	Y	Y	Y
		C7	Yes/No Max	Y	Y	Y	Y
		C8	Yes/No Max	Y	Y	Y	Y
		C9	Rating Min	7	4	7	5
		C10	Rating Min	7	4	7	6
		C11	Km Min	151.6	150.1	152.5	149.1
		C12	Grade Min	5	5	5	5
		C13	Grade Min	3	6	5	6
		C14	Grade Min	3	6	5	6
		C15	Grade Min	6	5	6	5
Constructional-technical	12%	C16	Rating Min	7	6	7	8
		C17	Grade Min	7	6	8	7
		C18	Yes/No Max	Y	N	Y	N
		C19	Rating Min	6	4	5	7
Urban planning	18%	C20	Rating Min	5	7	5	6
		C21	Grade Min	5	8	5	5
		C22	Rating Min	6	5	6	7
		C23	Grade Min	4	6	4	5
		C24	Grade Min	5	5	5	5
		C25	Rating Min	5	8	5	4
		C26	Grade Min	4	7	5	6
		C27	Rating Min	6	6	7	7

Table 2. *Cont.*

CRITERIA (%)		SUB-CRITERIA	Unit/ Object Function	Variant			
		Mark		1A	1C	2A	3B
Ecological-sociological	22%	C28	m min	15,676	12,333	16,043	17,342
		C29	Grade Min	6	3	7	6
		C30	Rating Min	4	5	6	4
		C31	Rating Min	4	5	4	3
		C32	Grade Min	4	5	4	6
		C33	m min	16,387	11,378	17,111	17,645
		C34	Rating Min	7	3	7	7
		C35	Rating Min	7	313	8	7
		C36	m min	13,797	9788	13,544	14,878
		C37	Grade Min	12,494	10,467	13,138	11,979
		C38	Rating Min	6	4	7	7
		C39	Grade Min	5	4	5	5
		C40	Rating Min	7	4	6	6

The economic criteria C1, C2, and C3 were used in accordance with the estimated financial resources [48]. Regarding railway infrastructure, the most cost-effective option is variant 1C because it requires the construction of the fewest structures. The most expensive option for the construction of the rail infrastructure and future costs of maintenance and management is the Variant 3B.

Regarding criteria C21 and C22, it should be noted that variants 1A and 2A mostly pass through agricultural and forest areas. Variant 1C has the advantage for connecting the railway line Rijeka-Zagreb to the system of Croatian railroads, i.e., the railway line towards the Dalmatia region. Variants 1A, 2A, and 3B are technically and technologically highly complex with a large number of structures, viaducts and tunnels. The extremely difficult technical requirements for the connection to an open rail route would lead to higher capital expenditures, which increases the values of the economic criteria and thus disadvantages variant 3B compared to the other variants. Furthermore, according to the study evaluation, it has been accepted that variants 1A, 2A and 3B are unacceptable from an environmental point of view.

4.2. Results—Selection of an Optimal Railroad Route

For the evaluation and selection of the optimal railroad connection between Rijeka and Zagreb from the four proposed variants, the values of the criteria defined in the earlier chapter were imported into the computer program “Visual PROMETHEE” for multi-criteria optimization. The values for the importance of criteria and sub-criteria analyzed and appraised by experts were also entered into the software.

Two different scenarios for multi-criteria ranking of variants were developed. For the first scenario, the weighting coefficients of the criteria defined in the model presented in Chapter 3 were used, while the second scenario gave more importance to the planning criteria. Therefore, for the second scenario, higher weight coefficients were assigned to the urban planning criteria, so that their weight coefficient was 30%. In addition, for economic criteria an importance of 19% was assigned; for transportation criteria, an importance of 25%; for constructional-technical criteria, a weight of 10%; and for environmental-sociological criteria, a weight of 16%.

The PROMETHEE I method for multi-criteria analysis brings the calculated Phi values, i.e., input (−) and output (+) flows or correlation of supremacy of particular pairs of actions. In addition, the optimization method of PROMETHEE II provides the final ranking of variants based on the calculation of the net value of Phi.

Figure 4 shows the resulting values for each variant and its positive and negative value of Phi. The studied variants are arranged in order:

PROMETHEE Flow Table

Rank	action		Phi	Phi+	Phi-
1	Variant 1C		0,0920	0,4335	0,3415
2	Variant 2A		0,0491	0,3541	0,3050
3	Variant 1A		-0,0439	0,3076	0,3515
4	Variant 3B		-0,0971	0,2806	0,3778

Figure 4. An overview of the result of Scenario 1 of the multi-criteria analysis of the evaluation of the Rijeka-Zagreb railroad route section.

- Variant 1C, with the value of net flow of 0.0920 is the optimal selection;
- Variant 2A, with the value of net flow of 0.0491 is the second-ranked alternative;
- Variants 1A and 3B have a decidedly negative net flux.
- Variants 1C and 2A should be given priority consideration when choosing a railroad route. However, the final option will be determined by the decision-makers and the goals set.

The best outcome of variant 1C results from the better values of the ecological-sociological and economic criteria. In terms of some urban-planning criteria, Variant 2A is the best choice, but it has a significant negative influence on eco-sociological criteria. Variant 1A is technically more complex and less suitable for the selection, having many shortcomings-great technical complexity of construction, challenging terrain geology and seismology, and a significant total length of tunnels and viaducts.

Variant 3B is also unacceptable for environmental and financial reasons, as it has the highest projected capital and operating costs and is, in fact, the least suitable for selection. Indeed, this variant was intended to avoid critical situations in the planning corridor, which would mean moving the route further north between Ledenice and Krasica. However, this would take the route into a very unfavorable geological area or into a protected area of the cultural heritage of the Vinodol Valley.

Figure 5 illustrates a clear interpretation of multi-criteria analysis in the GAIA (“Geometrical Analysis for Interactive Aid”) “u, v” plane, which includes both variants and criteria. The grouping of criteria or variants indicates the similarity of their numerical values, while the dispersion indicates their diversity.

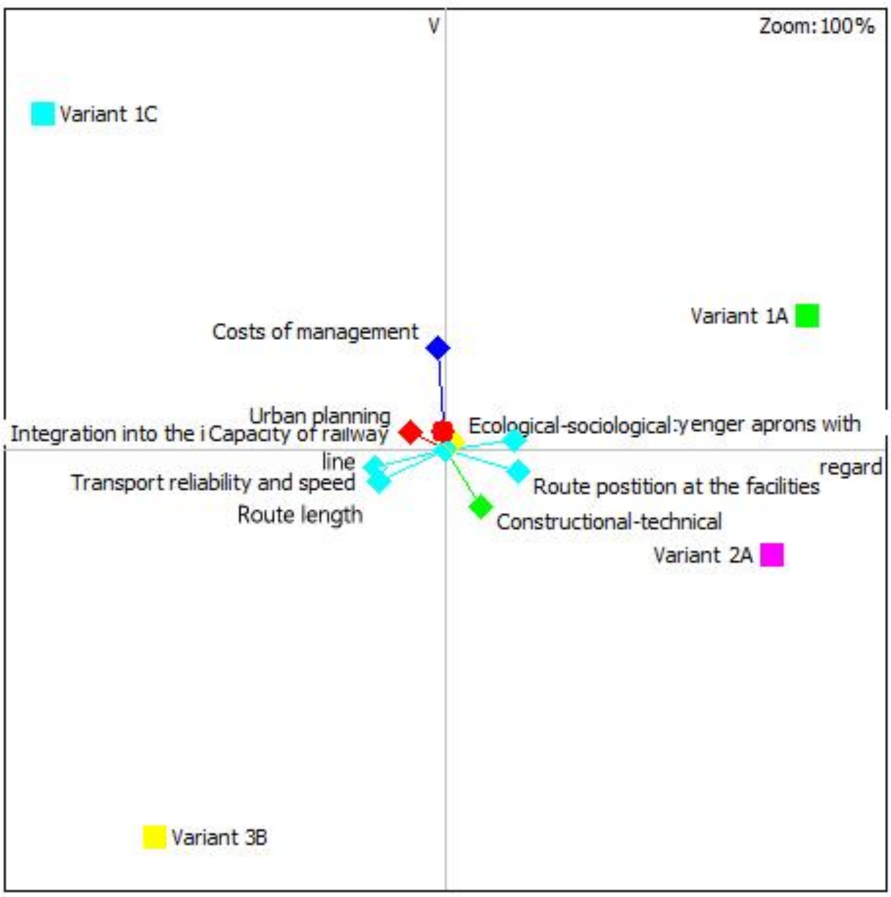

Figure 5. An overview of the result of the Scenario 1 of the multi-criteria analysis in the GAIA plane.

Figure 6 shows the results of the numerical values for each variant used to rank Scenario 2 and illustrates the importance of the urban-planning criteria. The values of the net flows for the first two variants, Variant 1C and Variant 2A, result in the same order as when Scenario 1 was processed. The results show that variant 1C has indeed increased its dominance over the other variants. The obtained results show that Variant 1A has decreased its value and that the value of Variant 3B is nearly equal to the result of its net flow in Scenario 1.

PROMETHEE Flow Table

Rank	action		Phi	Phi+	Phi-
1	Variant 1C		0,2125	0,4914	0,2789
2	Variant 2A		-0,0048	0,3169	0,3217
3	Variant 3B		-0,1027	0,2732	0,3758
4	Variant 1A		-0,1050	0,2696	0,3746

Figure 6. An overview of the result of scenario 2 of the multi-criteria analysis of the evaluation of the Rijeka—Zagreb route section.

Although Scenario 2 has no impact on the ranking of the alternatives, Figure 7 illustrates how the ranking shifts as the value of the constructional-technical criteria varies. The sensitivity analysis shows the lowest limit (or range) within which the weighting of the criterion may be modified without altering the criteria's established ranking. The weight stability period (WSI), or the weighing interval in which the ranking does not vary, is between 0 and 24%.

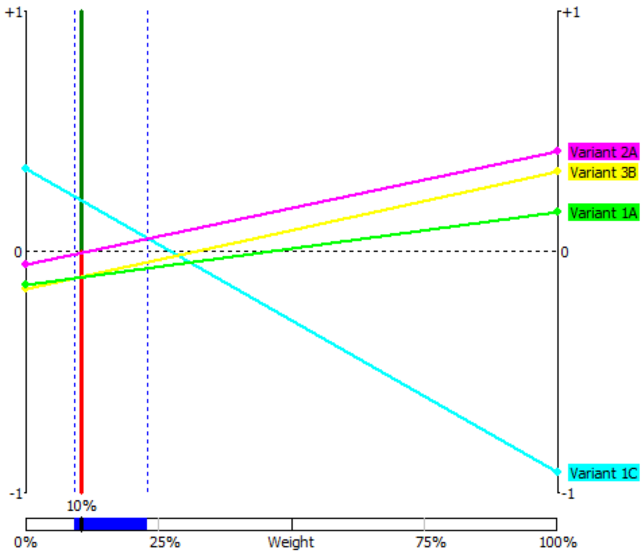

Figure 7. Sensitivity analysis of the constructional-technical criteria.

The most relevant variant from an environmental point of view is Variant 1C. Although this variant is the most demanding concerning urban planning criteria and has also very high technical requirements, it has the least negative impact on the environment and is therefore the most optimistic solution for implementation. The railway route from Skradnik to Krasica runs through the mountainous area of Velika and Mala Kapela. In order to meet the specified parameters, one smaller and four larger tunnels will have to be built, as well as a few viaducts, bridges, etc., which will have a significant impact on the increase in investment costs.

Variant 1A is not acceptable for several reasons. Firstly, it does not meet the required technical elements, as it requires extremely large and technologically very complex construction facilities and, secondly, the corridor has a negative impact on the environment.

5. Conclusions

The research problem discussed in this paper is elaborated using the multi-criteria analysis as an optimization method which involves the application of many criteria and solutions to obtain more reliable results in the decision-making process.

The model for the evaluation and selection of the railroad route consisting of the defined criteria and sub-criteria and their weighting coefficients, respectively, has been developed. Many specialists, planners, and designers in the field of railroad transportation planning have analyzed and reviewed the criteria and sub-criteria, assigning the corresponding weighting coefficients. The evaluation and selection of the railroad route between Rijeka and Zagreb was carried out by applying the multi-criteria optimization ranking of variants, more precisely using the method PROMETHEE II, which confirms the hypothesis set in the introduction of this article.

The need for the use of multi-criteria analysis was demonstrated by the successful test of the defined model. The results support the importance of using the multi-criteria analysis method in decision-making for space-traffic studies, as it clarifies the research problem and leads to appropriate answers to the research questions posed.

Further research will aim to improve the model by including more relevant criteria that will increase the accuracy of the result. In addition, a more detailed survey for a defined model will be performed as part of the evaluation of criteria and sub-criteria, including a larger number of respondents than the conducted survey. The update of the model will increase the quality of the multi-criteria analysis, i.e., it will provide a more accurate result in evaluating and selecting the optimal solution for the tested railroad route.

Author Contributions: Conceptualization, S.V.; methodology, S.V.; software, S.V.; validation, S.V.; formal analysis, I.P. and F.T.; investigation, I.P. and F.T.; resources, I.P. and F.T.; data curation, I.P. and F.T; writing—original draft preparation, S.V.; writing—review and editing, I.P. and F.T.; visualization, S.V., I.P. and F.T; supervision, S.V.; project administration, S.V.; funding acquisition, S.V. All authors have read and agreed to the published version of the manuscript.

Funding: University of Rijeka, Faculty of Maritime Studies.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Hamurcu, M.; Eren, T. An Application of multicriteria decision-making for the evaluation of alternative monorail routes. *Mathematics* **2018**, *7*, 16. [CrossRef]
2. Nedevska, I.Z.; Krakutovski, Z.M.; Zafirovski, Z.S. Application of different methods of multicriteria analysis for railway route selection. *Tehnika* **2017**, *72*, 797–805. [CrossRef]
3. Wu, Z.; Abdul-Nour, G. Comparison of multi-criteria group decision-making methods for urban sewer network plan selection. *CivilEng* **2020**, *1*, 26–48. [CrossRef]
4. Kurwi, S.; Demian, P.; Blay, K.; Hassan, T. Collaboration through Integrated BIM and GIS for the Design Process in Rail Pro-jects: Formalising the Requirements. *Infrastructures* **2021**, *6*, 52. [CrossRef]
5. Bruen, M. Uptake and dissemination of multi-criteria decision support methods in civil engineering—lessons from the literature. *Appl. Sci.* **2021**, *11*, 2940. [CrossRef]
6. Petrović, M.; Mlinarić, T.J.; Šemanjski, I. Location planning approach for intermodal terminals in urban and suburban rail transport. *Promet Traffic Transp.* **2019**, *31*, 101–111. [CrossRef]
7. Otković, I.I.; Karleuša, B.; Deluka-Tibljaš, A.; Šurdonja, S.; Marušić, M. Combining traffic microsimulation modeling and Multi-criteria analysis for sustainable spatial-traffic planning. *Land* **2021**, *10*, 666. [CrossRef]
8. Brustad, T.F.; Dalmo, R. Railway Transition Curves: A Review of the State-of-the-Art and Future Research. *Infrastructures* **2020**, *5*, 43. [CrossRef]
9. Özceylan, E.; Erbaş, M.; Çetinkaya, C.; Kabak, M. Analysis of Potential High-Speed Rail Routes: A Case of GIS-Based Multicriteria Evaluation in Turkey. *J. Urban Plan. Dev.* **2021**, *147*, 04021012. [CrossRef]
10. Farooq, A.; Xie, M.; Stoilova, S.; Ahmad, F. Multicriteria evaluation of transport plan for high-speed rail: An application to Beijing-Xiongan. *Math. Probl. Eng.* **2019**, 1–23. [CrossRef]
11. Malczewski, J.; Jankowski, P. Emerging trends and research frontiers in spatial multicriteria analysis. *Int. J. Geogr. Inf. Sci.* **2020**, *34*, 1257–1282. [CrossRef]
12. Broniewicz, E.; Ogrodnik, K. Multi-criteria analysis of transport infrastructure projects. *Transp. Res. Part D: Transp. Environ.* **2020**, *83*, 102351. [CrossRef]
13. Jurković, Ž.; Hadzima-Nyarko, M.; Lovoković, D. Railway corridors in Croatian cities as factors of sustainable spatial and cultural development. *Sustainability* **2021**, *13*, 6928. [CrossRef]
14. Økland, A.; Olsson, N.; Venstad, M. Sustainability in railway investments, a study of early-phase analyses and perceptions. *Sustainability* **2021**, *13*, 790. [CrossRef]
15. Kokkinos, K.; Karayannis, V. Supportiveness of Low-Carbon Energy Technology Policy Using Fuzzy Multicriteria Decision-Making Methodologies. *Mathematics* **2020**, *8*, 1178. [CrossRef]
16. Morfoulaki, M.; Papathanasiou, J. Use of the sustainable mobility efficiency index (SMEI) for enhancing the sustainable urban mobility in Greek cities. *Sustainability* **2021**, *13*, 1709. [CrossRef]
17. Cascetta, E.; Cartenì, A.; Pagliara, F.; Montanino, M. A new look at planning and designing transportation systems: A decision-making model based on cognitive rationality, stakeholder engagement and quantitative methods. *Transp. Policy* **2015**, *38*, 27–39. [CrossRef]
18. Tian, Z.; Sun, G.; Chen, D.; Qiu, Z.; Ma, Y. Method for determining the valid travel route of railways based on generalised cost under the syncretic railway network. *J. Adv. Transp.* **2020**, 1–12. [CrossRef]
19. Yoon, J.I.; Son, C.H.; Moon, C.G.; Funk, T.; Hromadka, V.; Korytarova, J. New methodology for railway infrastructure evaluation and its impact. *IOP Conf. Series: Mater. Sci. Eng.* **2019**, *471*, 022028. [CrossRef]
20. Ivić, M.; Marković, M.; Belošević, I.; Kosijer, M. Multicriteria decision-making in railway route planning and design. *J. Croat. Assoc. Civ. Eng.* **2012**, *64*, 195–205.
21. Marković, L.; Marković, L.M.; Mitrović, S.; Stanarević, S. The evaluation of alternative solutions for the highway route E-763 Belgrade-South Adriatic: A case study of Serbia. *Tehnički Vjesnik* **2017**, *24*, 1951–1958. [CrossRef]
22. Yücel, N.; Taşabat, S.E. The Selection of Railway System Projects with Multi Creteria Decision Making Methods: A Case Study for Istanbul. *Procedia Comput. Sci.* **2019**, *158*, 382–393. [CrossRef]
23. Anton, J.M.; Grau, J.B. Madrid-Valencia high-speed rail line: A route selection. In Proceedings of the Institution of Civil Engineers-Transport; Thomas Telford Ltd.: London, UK, 2004; Volume 157, pp. 153–161. [CrossRef]
24. Karlson, M.; Karlsson, C.S.J.; Mörtberg, U.; Olofsson, B.; Balfors, B. Design and evaluation of railway corridors based on spatial ecological and geological criteria. *Transp. Res. Part D Transp. Environ.* **2016**, *46*, 207–228. [CrossRef]

25. Song, Y.; Zhang, M.; Øiseth, O.; Rønnquist, A. Wind deflection analysis of railway catenary under crosswind based on nonlinear finite element model and wind tunnel test *Mech. Mach. Theory* **2021**, *168*, 104608. [CrossRef]
26. Song, Y.; Liu, Z.; Wang, H.; Lu, X.; Zhang, J. Nonlinear analysis of wind-induced vibration of high-speed railway catenary and its influence on pantograph-catenary interaction. *Veh. Syst. Dyn.* **2016**, *54*, 723–747. [CrossRef]
27. Song, Y.Z.; Liu, H.; Wang, J.; Zhang, X.L.; Duan, F. Analysis of the galloping behaviour of an electrified railway overhead contact line using the non-linear finite element method. *Proc. Inst. Mech. Eng. Part F J. Rail Rapid Transit* **2018**, *232*, 2339–2352. [CrossRef]
28. Xie, Q.; Zhi, X. Wind tunnel test of an aeroelastic model of a catenary system for a high-speed railway in China. *J. Wind. Eng. Ind. Aerodyn.* **2019**, *184*, 23–33. [CrossRef]
29. Urda, P.; Aceituno, J.F.; Muñoz, S.; Escalona, J.L. Artificial neural networks applied to the measurement of lateral wheel-rail contact force: A comparison with a harmonic cancellation method. *Mech. Mach. Theory* **2020**, *153*, 103968. [CrossRef]
30. Marques, F.; Magalhães, H.; Pombo, J.; Ambrósio, J.; Flores, P. A three-dimensional approach for contact detection between realistic wheel and rail surfaces for improved railway dynamic analysis. *Mech. Mach. Theory* **2020**, *149*, 103825. [CrossRef]
31. Bruni, S.; Bucca, G.; Carnevale, M.; Collina, A.; Facchinetti, A. Pantograph-catenary interaction: Recent achievements and future research challenges. *Int. J. Rail Transp.* **2017**, *6*, 57–82. [CrossRef]
32. Facchinetti, A.; Bruni, S. Special issue on the pantograph-catenary interaction benchmark. *Veh. Syst. Dyn.* **2015**, *53*, 303–304. [CrossRef]
33. Ambrosio, J.; Pombo, J.; Pereira, M.; Antunes, P.; Mosca, A. A computational procedure for the dynamic analysis of the catenary-pantograph interaction in high-speed trains-web of science core collection. *J. Theor. Appl. Mech.* **2012**, *50*, 681–699.
34. Wu, T.X.; Brennan, M.J. Dynamic stiffness of a railway overhead wire system and its effect on pantograph-catenary system dynamics. *J. Sound Vib.* **1999**, *219*, 483–502. [CrossRef]
35. Nåvik, P.; Rønnquist, A.; Stichel, S. Identification of system damping in railway catenary wire systems from full-scale measurements. *Eng. Struct.* **2016**, *113*, 71–78. [CrossRef]
36. Krpan, L.; Vilke, S.; Milković, M. A model of the selection of an optimal railroad route by applying the multiple-criteria analysis. *Tehnički Vjesnik* **2017**, *24*, 1155–1164. [CrossRef]
37. Longo, G.; Medeossi, G.; Padonao, E.; Using simulation to assess infrastructure performance in multicriteria evaluation of railway projects. Road and Rail Infrastructure I I, Proceedings of the Conference CETRA. 2012, pp. 105–111. Available online: https://www.researchgate.net/profile/Elio_Padoano/publication/257413718_Using_simulation_to_assess_infrastructure_performance_in_multicriteria_evaluation_of_railway_projects/links/0c9605253c9bfb1d00000000.pdf. (accessed on 29 December 2021).
38. Belton, V.; Stewart, T.J. *Multiple Criteria Decision Analysis*; Springer: Boston, MA, USA, 2002. [CrossRef]
39. Hajkowicz, S.; Collins, K. A Review of Multiple Criteria Analysis for Water Resource Planning and Management. *Water Resour. Manag.* **2007**, *21*, 1553–1566. [CrossRef]
40. Roubens, M. Preference relations on actions and criteria in multicriteria decision making. *Eur. J. Oper. Res.* **1982**, *10*, 51–55. [CrossRef]
41. David, A.; Mako, P.; Lizbetin, J.; Bohm, P. The impact of an environmental way of customer's thinking on a range of choice from transport routes in maritime transport. *Sustainability* **2021**, *13*, 1230. [CrossRef]
42. Mareschal, B.; Brans, J.P.; Vincke, P. Prométhée: A new family of outranking methods in multicriteria analysis. *Oper. Res.* **1984**, *3*, 477–490.
43. Behzadian, M.; Kazemzadeh, R.B.; Albadvi, A.; Aghdasi, M. Prométhée: A comprehensive literature review on methodologies and applications. *Eur. J. Oper. Res.* **2010**, *200*, 198–215. [CrossRef]
44. Brans, J.-P.; Mareschal, B. Promethee Methods. *Int. Ser. Oper. Res. Manag. Sci.* **2005**, *78*, 163–186. [CrossRef]
45. Yu, X.; Chen, H.; Ji, Z. Combination of probabilistic linguistic term sets and PROMETHEE to evaluate meteorological disaster risk: Case study of Southeastern China. *Sustainability* **2019**, *11*, 1405. [CrossRef]
46. Karleuša, B.; Dragičević, N.; Deluka-Tibljaš, A. Review of multicriteria-analysis methods application in decision making about transport infrastructure. *Građevinar* **2013**, *65*, 619–631.
47. Vilke, S.; Baričević, H.; Maglić, L. Criteria for the evaluation in land transport track. *Mod. Traffic* **2013**, *33*, 422–427.
48. Kralj, S. (Institut IGH plc.; Željezničko Projektno Društvo plc., Hrvatska, Zagreb, Croatia). Feasibility Study, High Perfomance Railway State Border–Botovo–Zagreb–Rijeka, Modernization and Construction of State Border—Botovo-Zagreb-Rijeka Railway Transport Corridor. Unpublished work; 2011.
49. Kralj, S. (Željezničko Projektno Društvo plc, University of Zagreb, Faculty of Transport and Traffic Scineces, Zagreb, Croatia). Technical Designinig Project. Book T2: Transport-Technological Designing Project.V. b. Corridor-State Border—Botovo-Zagreb-Hrvatski Leskovac-Krasica-Rijeka. Unpublished work. 2008.
50. HŽ Infra-Struktura (Institut IGH plc., Zagreb, Croatia). Environmental Impact Study and Main Assessment: Hrvatski Leskovac (Zagreb)-Drežnica. Unpublished work. 2008.