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High-Speed Rail Track Design Using GIS And Multi-Criteria Analysis

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Abstract

Infrastructure design is always a very complex task because of the many variables involved. Rail design, in particular, takes on considerable importance (together with the socioeconomic variables) among the environmental variables. The latter is a factor that contributes strongly to the definition of design choices. This paper proposes a method for optimizing the choice of the corridors/line of *"high speed rail" (HRS)*. In particular, the method is based on "multi criteria analysis" with GIS support. The method was applied to a real case in order to evaluate its economic feasibility, social and environmental impact. We considered three possible corridors (conservative, compromise and innovative) for the construction of high-speed rail lines in an area located in the south of Italy The analysis performed gave the following results:

- a conservative point of view: the better hypothesis was a corridor near the coast but more tortuous; this solution preserves the environment, but involves higher costs and greater "travel time";
- an innovative point of view and a compromised point of view: the better hypothesis was a corridor crossing the territory in the central part (central park zone of great importance for the environment).

In this case the corridor gives higher speeds and lower "travel times"; however for this solution the environmental components are jeopardized to a greater degree.

Keywords: High Speed Railway, Multicriteria, GIS.

1. Introduction And Literature Reviews

This study aimed to identify needs and to design suitable future rail corridors. The study puts social, institutional and environmental concerns on a par with economic and engineering concerns in the design and

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evaluation process. Historically, Multiple Criteria Evaluation methods developed to select the best alternative from a set of competing options. These included single criterion methods, for example cost- benefit analysis, decision tree analysis and pay-off tables, and many other methods of Multiple Criteria Decision Making (MCDM) methods. This article illustrates the application of MCDM techniques to support a HIGH-SPEED RAIL TRACK DESIGN in Italy. The various infrastructures play an important strategic role in the development of civil society. Railway networks especially, with the advent of high speed, are redefining the standard in terms of distance and journey time. Currently, with these new systems, many users have changed their habits, becoming commuters over distances which up to only a few years ago seemed Utopian. One thinks of the Rome-Milan run of around 600km, which now takes under three hours. Nevertheless, high speed often brings with it a number of environmental problems. Often, due to their fixed geometrical nature, there is no flexibility in laying out the tracks, and so it may be necessary to sacrifice some remarkable parts of the countryside. It is no wonder that where Corridor V is now under construction in Italy (Turin/ Lyon/ Lisbon), the "No TAV (No HST)" groups are protesting and making the work difficult to complete. It thus becomes very difficult to find a solution to the production of this kind of work, and it lies in a compromise between all the variables which contribute to the question. It is thus necessary to have at one's disposition instruments able to manage these complex systems, with their multiple variables, and which make a choice possible from among all those possible. There are some important texts in the literature which address these problems. A recent study *(Dell'Acqua, 2012 a)*, considered alternative alignment options combining engineering, social, environmental, and economic factors in decision-making. The research formalizes a general method useful for analyzing different case studies. The method can be used to justify highway alignment choices in environmental impact study analysis. *Sharifi et al.(2006)* describe the way spatial multiple criteria decision analysis "SMCA" has been applied to develop and evaluate an integrated plan for public transport system and land use development in the Klang Valley, in Malaysia. The SMCA was used as a framework for the design and evaluation of an alternative rail network, which, in combination with the other transportation systems, can meet the future socio-economic and environmental, requirements of people in the *Klang Valley* region. *Keshkamat, et al. (2009)* present a holistic and coherent spatial multi-criteria network analysis method for the generation of optimal routing alternatives under different policy visions, in a network of existing roads. The methodology was case-tested for the highly contested 340 km portion of the Via Baltica corridor in Poland, a part of the trans-European transport network (TEN-T) program. The methodology shows its ability to serve as a versatile effect-based decision support system for transport route planning at a strategically higher level of planning, particularly for (geographically) large-scale investment schemes. *Mateus et al. (2008),* compare alternative siting strategies, defined by the Portuguese high-speed railway authority. These strategies were put into practice in a set of location alternatives, which were evaluated according to a range of technical, economical, social and environmental criteria. This paper describes the multicriteria decision analysis (MCDA) approach by which the best alternative was identified from the given set of possible alternatives. *Macharis et al.(2010)* describe the MAMCA methodology and how it has been used in the "Flanders in Action Process". One of the objectives of this process is to turn Flanders into a top region in terms of mobility and logistics by attracting logistic activities with substantial added value, creating fluid and widely accessible mobility, a huge increase in traffic safety and a decrease in the environmental impact of transport. As there are a wide range of actors with different interests involved in this process, the MAMCA methodology was applied to evaluate a set of possible policy measures being proposed to reach this objective. With the California High-Speed Rail (HSR) Project and the Beijing–Shanghai Express Railway Project as case studies, *Xueming et al. (2010)* juxtapose HSR development processes concerning investment decisions, planning, and implementation in the United States and China and draw lessons which can be of use in strategic infrastructure investments in both countries. *Ambrasaite et al. (2011)* set out a decision support system (DSS), COSIMA, involving the combination of cost-benefit analysis and multi-criteria decision analysis (MCDA) for transport infrastructure appraisals embracing both economic and strategic impacts. Therefore, the study presents the perspective of introducing risk analysis and Monte Carlo simulation to the weighting profile in the MCDA-part. The DSS is presented through a case study concerning alternatives for the construction of the Rail Baltica railway line through the Baltic countries and Poland.

2. Design of Alternative High-Speed Rail Tracks

The Berlin-Palermo railway axis is Line 1 of the Trans-European Transport Networks (TEN-T),which involves the creation of a 2,200 km-long high-speed rail line between Berlin and Palermo (figure 1).The test track *Ogliastro/Cilento/Sapri* is part of the existing 400 km Naples–Reggio Calabria railway line, which will be upgraded to increase speed and capacity (European Commission, 2005). The goal of this study is to identify the best rail track integrated with land use in such a way as to meet environmental requirements. This goal can be achieved if the following objectives are met. The economic objective seeks to maximize feasible economic returns in investment from the high-speed rail track. A number of criteria were used to measure how well an alternative performs on each indicator. The engineering objective looks at three main concerns i.e. the efficiency of the rail track, construction issues, and the effective use of alignment. Three different plans were put forwards for the corridor. Figure 1 shows the three corridors loaded and managed using a GIS system. Using the GIS system (ArcGIS 9.3), it was possible to place the three different track projects on the territory and evaluate their respective limits in terms of countryside, geometrical features and other information, as set out in table 1. This research was funded in part by the Transportation Office of the Salerno Provincial Administration. The projected High-Speed Rail Tracks should minimize intrusion and damage to the environment. This will be accomplished through a reduction in energy consumption, minimal intrusion into environmentally sensitive areas, and minimal noise impact to sensitive land use. Bearing in mind the set goal, objectives, related criteria and indicators, three alternative competitive High-Speed Rail Tracks with three different design approaches were developed. Designing the tracks was an iterative process, guided by the set criteria structure. It took a number of iterations to come up with the three distinct tracks that are potentially good alignments, each, with its own pros and cons. The three rail tracks are presented in Figure 1.To further support the design and evaluation of the high-speed rail tracks, the objectives had to be broken down further into criteria and their corresponding indicators. The indicators were further used to measure the performance of each alternative rail track on each objective. Then, using the GIS system, it was possible to organize the data following the logic illustrated in table 1. The impact on the territory was assessed as a percentage for each environmental indicator (shown in table 1), with the exception of category D1 for which the number of interferences is stated explicitly. For the “geometric-functional” indicators, the values of the last three lines of table 1 were used. The selected value-focused MCDM approach was implemented using a top down method to define the goal, objectives, and the relative indicators of the required HIGH-SPEED RAIL TRACK. After several rounds of discussions involving the consulting team, Technical Committee members and local authority officials, a criteria structure as presented in Table 1 was accepted and used as the basis for the development and evaluation of the rail-network.

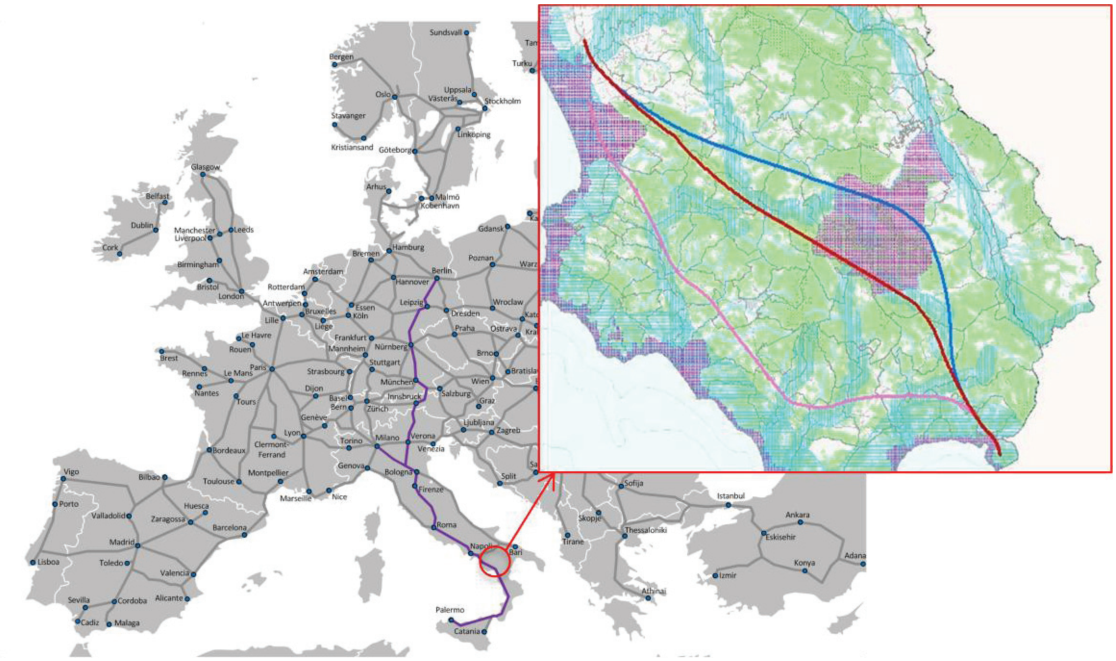

Fig. 1. "*Berlin-Palermo*" railway axis 1 and corridors loaded and managed using a GIS system

Table 1. Environmental Components

Category	Factor	Indicator
Land stability	A Geological	A1- Landslide risk A2-Seismic risk and Volcanic risk A3-GeolithologicComposition.
	B Hydraulic	B1-Interference with a stream (course of water) B2- Hydraulic risk
Biological and natural impact	C Natural resources	C1- Percentage of internal park area (area of high environmental value) C2-Zoning of Park C3- Visual impact C4- Landscape values C5- Degree of naturalness C6- Degree of biodiversity
Social and Economical components	D Land use E Future land use	D1-General Interference D2-Specific Interference with roads D3-Specific interference with urban areas E1- Characteristics of the areas crossed (urban, agricultural, etc.)
Geometric and functional factors	H	H1-Average speed of track H2- Length of the track H3- Possibility of inserting intermediate stop

3. Data Analysis

The following analysis method was applied to the collected data.

3.1. Multi-criteria Analysis

The existing methods in the multi-criteria analysis *(Dell'Acqua et al 2012 b)* involve both simple methods like cost-benefit analysis *(Salling et alt. 2009),* and more complex methods like Multi Criteria Analysis (MCDM) or multi-dimensional analysis *(Belton 2002)*. For many years now, several algorithms have been developed on this topic to solve these mathematical procedures. Concordance analysis, like multi-criteria analysis, begins with the clarification of the main objective and then goes on to define all the alternatives and criteria.

Subsequently, weights are assigned to the criteria by producing the weights vector w = (w_1, w_2,…,w_n). This vector is generally made using one of the numerous methods available in the scientific literature and, of course, taking the nature of the problem into account. When different points of view exist, a weights-matrix with n rows and v columns is constructed. After establishing a point of view, a subset C (i, j), defined within the space of n criteria, or concordance set is defined, involving all the criteria for which the i^{th} alternative is no worse than the j^{th} alternative, as follows:

$$p(i,k) \geq p(j,k) \quad (1)$$

The *discordance set* is defined as the complementary subset of the previous one, i.e., the subset consisting of n criteria for which the ith alternative is no better than the jth alternative, as follows:

$$p(i,k) < p(j,k) \quad (2)$$

If we use the *concordance – discordance method*, two matrices must be created by comparing the alternatives in pairs to define the system of final preferences. The basic starting information, obtained by comparing the alternatives in pairs, is quantified as ***c*** (i, j) and ***d*** (i, j) elements of the concordance *C* and discordance *D* matrices respectively, with *m* rows and *m* columns. The elements c_{ij} of the concordance matrix are defined thus:

Table 2. Objectives and Weight

	Indicator	Conservative (Track 1)	Compromise (Track 2)	Innovative (Track 3)	Weight Point of view Conservative (Track 1)	Weight Point of view Compromise (Track 2)	Weight Point of view Innovative (Track 3)
1	A	0.6111	0.2778	0.1111	3	2	1
2	A2	0.6111	0.2778	0.1111	3	2	1
3	A3	2.41	2.27	1.45	3	2	1
4	B1	0.1111	0.2778	0.6111	1	2	3
5	B2	0.1111	0.2778	0.6111	1	2	3
6	C1	0.75	0.70	0.29	3	2	1
7	C2	0.4633	0.3166	0.11	3	2	1
8	C3	0.131	0.126	0.15	3	2	1
9	C4	0.1111	0.2778	0.6111	3	2	1
10	C5	0.8667	0.87	0.7167	3	2	1
11	C6	0.80	0.9167	0.8833	3	2	1
12	D1	18 interference	21 interference	39 interference	1	2	3
13	D2	0.11	0.2778	0.6111	1	2	3
14	D3	0.11	0.2778	0.6111	1	2	3
15	E1	0.45	0.4833	0.40	3	2	1
16	H1	400 km/h	350 Km/h	340 km/h	1	1	3
17	H2	77100 m	82200m	77500m	3	3	1
18	H3	0	0	1	1	1	3

$$\mathbf{c}_{ij} = \left[\frac{\sum_{k \in C\ i,j)} \left| \mathbf{w\ (k)} \right|^{\alpha}}{\sum_{k} \left| \mathbf{w\ (k)} \right|^{\alpha}} \right]^{1/\alpha} \qquad (3)$$

The elements d_{ij} of the discordance matrix are defined thus:

$$\mathbf{d}_{ij} = \left[\frac{\sum_{k \in C\ (i,j)} \left| \mathbf{w\ (k)} \right|^{\alpha} * \left| \mathbf{p\ (i,k) - p\ (j,k)} \right|^{\alpha}}{\sum_{j} \left| \mathbf{w\ (k)} \right|^{\alpha} * \left| \mathbf{p\ (i,k) - p\ (j,k)} \right|^{\alpha}} \right]^{1/\alpha} \qquad (4)$$

Where: **a** is a parameter that can be defined by the user and it makes it possible to give greater weight to the dominant terms of the summations over minor terms.
It is easy to ascertain that for each *i* and *j*, we have:

$$0 \le c(i,j) \le 1 \qquad 0 \le d(i,j) \le 1 \qquad (5)$$

According to the above ratios, if the *c* (i, j) value is high and the *d* (i, j) value is low, the i^{th} alternative is better than the j^{th} alternative, and in particular, when i = j, we have *c* (i, j) = 1 and *d* (i, j) = 0.
The C and D matrices are produced taking into account only criteria for which each alternative, in comparison with the pairs mentioned above is better or worse than the others, to create the concordance or discordance matrix respectively. The concordance matrix reflects the satisfaction of the decision-maker who prefers *Ai* rather than *Aj* for each criterion. Since the sum of the criteria's total weights is 1, the element *cij* can assume values between 0 and 1, as follows:

- *Cij*=1, when *Ai* is preferred to *Aj* for all criteria;
- *Cij*=0, when *Ai* is not preferred to *Aj* in any criterion;
- 0<*Cij*<1, when *Ai* is preferred to *Aj* in specific criteria;

Same considerations are applied to the *dij* element which can assume values between 0 and 1: when the value is high, the discordance increases. This parameter reflects regret at discarding the *Aj* alternative rather than the *Ai* alternative. A measure to assess the supremacy of the i^{th} alternative over the others is provided by the concordance index (*Ic*) for each viewpoint: this index is equal to the difference between the sum of the values placed in the i^{th} row of the *concordance matrix (C)* and the sum of the values placed in the i^{th} column of the same matrix (see equation 6).

$$Ic_i = \sum_{j=1}^{m} c_{ij} - \sum_{j=1}^{m} c_{ji} \qquad C = \begin{pmatrix} - & c_{12} & c_{1i} & c_{1m} \\ c_{21} & - & c_{ii} & \cdots \\ c_{i1} & c_{ij} & - & c_{im} \\ c_{m1} & \cdots & c_{mi} & - \end{pmatrix} \qquad (6)$$

However, the *concordance index (Ic)* symbolizes the total satisfaction of the decision-maker choosing the *Ai* alternative instead of the *Aj* alternative; *Ic* can take values from 1 - m (negative values) to m - 1 (positive values): positive values indicate that the Ai alternative is entirely preferred to others, while negative values indicate that the Ai alternative is not predominant over the others. The *discordance index* (*I_d*) is assessed using the discordance matrix and the same procedure is used to estimate the *concordance index*(see equation. 7).

$$Id_i = \sum_{j=1}^{m} d_{ij} - \sum_{j=1}^{m} d_{ji} \qquad D = \begin{pmatrix} - & d_{12} & d_{1i} & d_{1m} \\ d_{21} & - & d_{ji} & \dots \\ d_{i1} & d_{ij} & - & d_{im} \\ d_{m1} & \dots & d_{mi} & - \end{pmatrix} \tag{7}$$

The *discordance index (Id)* reflects the regret of the decision-maker choosing the *Ai* alternative instead of the *Aj* alternative. The values of the Id index fall within the same range of the previous index; in particular, when Id has positive values, this index reflects how the *Ai* alternative is totally less predominant than the others: so if the Id index is lower, the Ai alternative preference is greater for alternative *Aj*. The *Ic* and *Id* indices are structured successively according to two different vectors (the concordance and discordance vector) where each element represents the concordance and discordance assessment for each alternative in relation to all the others. Then, the alternatives are structured by increasing the concordance index and decreasing the discordance index to obtain two lists which do not generally coincide. The best alternative has a maximum *Ic* and minimum *Id*; when one of these conditions is not met, as often happens, we must evaluate the trade-off between the values of the two indices to find a suitable alternative. The information included in the concordance formula is significantly different for that contained in the discordance formula: this makes them complementary. The concordance reflects the differences between the criteria weights, while the discordance reflects the differences between the alternative performances. This dual math process makes it possible to carry out a suitable analysis and it is an essential advantage compared with other methods. Therefore, the best alternative selection addresses the maximization of their concordance indices and, at the same time, the minimization of their discordance indices. Alternatives with low concordance indices and high discordance indices can be removed. To apply the above technique, it is necessary to have quantitative variables available. Otherwise, if the problem is characterized by qualitative variables, it is necessary to transform the qualitative variables into quantitative ones. A highly effective technique for carrying out these transformations is the *expected value* technique. The content and characteristics of this technique follow.

3.2. Expected value

We assign a given value p(j) between O and *i* to each element of the set of *J* elements to be quantified, where the p(j) meet the requirements of the following chain of inequalities:

$$1 \geq p(1) \geq p(2) \geq \cdots \geq p(J) \geq 0$$
$$with\ \sum_j p(j) = 1 \tag{8}$$

A fundamental hypothesis is that the $p(j)$are probably distributed uniformly within the intervals allowed by the (8). The greater the qualitative importance of the element, the higher the quantitative value assigned, in line with the general aim of the programme. In other words, the (8), which is the only information available can be interpreted as limits in space $0 \leq p(j) \leq 1$ from which to choose, in one way or another, the most likely (or the most frequent) among all the infinite possible sequences to assign to the elements $p(j)$.The set of theJ cardinalised elements in a given setof values is thus understood as a particular configuration in space of the states (1), associating to each possible configuration a constant probability that, by forcing the system with a random draw, it may be configured, among the infinite possible sequences, in a particular state, i.e., in a particular sequence of p(j) in compliance with (8). The average values of the sets of values that the various elements can take on are considered as the most likely configuration in the analytic case (the most frequent in the case of drawing random numbers) and it is the one whose elements, one by one in order, are then assigned as the quantitative values of the weights. The term p(j) indicates an element in a generic vector Pwhich can be understood both as a jth column in the impact matrixEof elementse(i, j), and as the jth element of the matrixWof elementsp(j, v). Assuming a constant probability for every possible sequence of values for the elementsp(j)in the space defined by the (8), it seems that it gives rise to the following density of probability F for p(j):

$$F = \begin{cases} (J-1)!J! & 0 \le p(1) \le 1/J \\ & p(1) \le p(2) \le \frac{1}{(J-1)} - \frac{p(1)}{J-1} \\ & p(J-2) \le p(J-1) \le \frac{1}{2} - \frac{p(1)}{2} - \cdots - \frac{p(J-2)}{2} \\ 0 & elesewhere \end{cases} \tag{9}$$

Thus is $p(1) \dots p(J-1)$, are known, the value of $p(J)$ can be found as:

$$p(J) = 1 - \sum_j p(j) \tag{10}$$

Carrying out the necessary integrations, it is possible to obtain the following values of the average distribution value F:

$$p(1) = \frac{1}{J^2}$$
$$p(2) = \frac{1}{J^2} + \frac{1}{[J(J-1)]}$$
$$\dots$$
$$p(J-1) = \frac{1}{J^2} + \frac{1}{[J(J-1)]} + \cdots + \frac{1}{2J}$$
$$p(J) = \frac{1}{J^2} + \frac{1}{[J(J-1)]} + \cdots + \frac{1}{2J} + \frac{1}{J} \tag{11}$$

Thus, this method gives the elements $p(j)$ quantitative values predetermined analytically and fixed for a given total number$J$of the elements.

4. Results

The multiple criteria evaluation of the tracks was carried out based on the performances of each track on various defined indicator “objective data” and the relative importance of each indicator, criterion and objectives in relation to the other indicators, criterion and objectives of “subjective data”. The objective data was estimated using GIS and where necessary through surveys. The Multi Criterion Method was applied to the data collected in the following steps. First, a criteria/alternatives matrix was constructed after transforming the qualitative variables into quantitative variables using the expected value technique illustrated in the previous paragraph. In these tables, the alternatives are represented by the three tracks (Track 1, Track2, Track 3) while the criteria are represented by the 18 indicators shown in the table 2. Then, the weights matrix or points of view matrix was constructed (see last three columns of table 2). In particular, three different points of view were taken into consideration:

- *Point of view 1, Conservative*: greater importance was given to environmental and social criteria, aiming to disturb environmental and social equilibria in the territory by the construction of the railway line.
- *Point of view 2, Compromise*: in this case a solution was sought (potentially almost equidistributed), the consequence of a compromise between environmental, technical and social techniques.
- *Point of view 3, Innovative*: here, the technical and functional characteristics of the infrastructure were taken into account, considering the environmental and social aspects as secondary.

Each criterion was given a weight for each point of view. The logic of the scale of points was such that the lowest weight was 1, 2 was intermediate, and 3 the highest.

The multicriteria analysis applied to the matrix shown in table 1, using specialist software, gave the results shown in tables 3 and 4. In table 3, the classification obtained for the three tracks in relation to the three different points of view is shown. The result of this process is given in the "so-called effect table" which is only shown in Table 3.Furthermore, table 4 shows the classification based on point of view. For the conservative point of view, the corridor with the highest score was number 3, followed by number 1 and number 2. As for the compromised point of view, the preferential corridor with the highest score was, on the hand, number 1, followed by number 2, while number 3 obtained a score of zero.

Table 3. Appraisal scores

	Track 1	**Track 2**	**Track 3**
Point of view:Conservative	1.00	0.811	1.90
Point of view: Compromise	2.00	0.766	0.184
Point of view: Innovative	2.00	0.288	0.000

Table 4. Ranking of the corridors

Point of view	**Score**
Conservative	Track 3
Compromise	Track 1
Innovative	Track 1

5. Conclusion

The value-focused approach MCDA, applied in this study, helped in the design, evaluation, and also provides improvements to the three alternative HSR tracks. In developing the stated goal to its objectives, criteria and finally into various measurable indicators, the designers and decision makers were able to see how the various options performed against such criteria. This study contains a multi-criteria analysis in a GIS environment, which has led to three hypotheses for preferential corridors suited to the creation of the high-speed line along the part of the track situated in the south of Italy and belonging to Corridor 1 (Palermo-Berlin). For the three possible corridors, three different points of view were considered: conservative, compromised, and innovative. From an analysis of the data using multi-criteria analysis, the following configuration emerged. For the conservative point of view, which gives more importance to environmental and social parameters, the best solution is corridor 3 (Track 3). For the compromised point of view, which represents a very balanced solution among the environmental, technical, and social characteristics, the best solution is corridor 1 (Track 1). Lastly, for the innovative point of view, which tends to privilege the technical characteristics of the infrastructure, the best solution is represented once again by preferential corridor (Track 1). It is thought that this approach, multicriteria analysis in a GIS environment, can be a valid support system for decision makers in situations of this type. An important advantage of this methodology is that it is able to support the decision maker in his final decision as the inclusion of different points of view leads to a general prioritisation of the proposed policy measures. Currently, the authors are working to improve this system, not only with reference to this case study, but also other situations. In particular, in order to supplement and support the system, another procedure is being developed through which it is possible to simulate the effects of the track on the territory, (and in particular, the effects on the environment). This procedure, which is being perfected at the moment, has already given some important indications on some new variables to take into consideration when setting up the Alternative/Criteria matrix.

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