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Research Article

Towards a similarity index of network paths in spatial networks

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Abstract: The mathematical analysis of a spatial network using graph theory and Geographical Information Systems (GIS) for path finding, has created the need to compare possible solutions to better solve spatial problems in road networks. The paper aims to provide a comprehensive and documented selection of the identification of similar routes on a spatial network through the development of a spatial Similarity Index. The index compares the geographical characteristics of routes (altitude, length, distance from points of interest) drawn in a spatial network and calculates the percentage of similarity between the routes and the criteria that contributed to their drawing. The purpose of this multicriteria indicator is to select the optimal solution for spatial problems that occur in a network, such as transport, energy, environment, sport, and tourism. This leads to the Similarity Index serving as a reliable tool in decision-making for local and regional development. The case study is the Greek island of Lesbos, with a complex road network that develops over a relief with strong differences in altitude. In addition, there are many points of tourist, cultural and economic interest on the island, which helps to find the path that largely fulfils all geographical parameters.

Keywords: Network Analysis, Spatial Networks, Spatial Similarity Index, GIS, Spatial Analysis

Highlights:

- Search algorithm to find paths in spatial networks using GIS and graph theory.
- Network analysis to find similar paths with the same spatial characteristics.
- Decision making on local development using spatial network analysis.

1. Introduction

Spatial analysis of networks has been gaining popularity in recent years, especially with the use of advanced geographic information systems (GIS) for visualisation and analysis (Sevtsuk and Mekonnen, 2012; Rodrigue, 2013; Huang et al., 2020; Sushma et al., 2021). Among the plethora of approaches and applications, some of the most popular relevant algorithms focus on the identification of "shortest paths", such as Dijkstra's algorithm (Dijkstra, 1959) for road networks.

Network analysis approaches can also be used in policy-making, especially in the analysis of accessibility and proximity to public facilities such as hospitals and schools. In general, this can also include the study of cities or geographical areas from a sustainable development perspective, especially if we are concerned with public service provision and equity of service delivery (Boeing, 2022). Batsaris et al. (2021) developed a Spatial Decision Support System (SDSS) to minimise school travel by combining shortest path algorithms on road networks and location assignment analysis. Paraskevopoulos et al. (2019) describes how the degree of connectivity in a spatial network affects spatial relationships and contributes to the calculation of population accessibility in island settlements for tourism development. Finally, Gaglione et al. (2022) offer a method for classifying a neighbourhood as more or less accessible by finding convenient and safe walking routes for older people to reach urban services based on their favourable characteristics.

Road network analysis has been the focus of some notable works, particularly route optimisation and routing methods (Derekenaris et al., 2001; Panahi et al., 2008; Ahmed et al., 2017; Chen, et al., 2019, Batsaris et al. 2019). Issues related to the road network have also been discussed, such as traffic congestion problems (Elsheikh et al., 2016) and management of traffic accidents (Vaitis et al., 2019; Durduran, 2010; Shafabakhsh et al., 2017; Okabe and Sugihara, 2012). From a network topological aspect, there are some algorithms that combine graph theory and GIS (Zeng et al., 2009; Ahmadzai et al., 2019).

Paths in spatial networks are used in network routing and service accessibility analysis. Paths can be viewed as a sequence of nodes and vertices in a spatial network that traverse the spatial network and connect a start node to an end node, usually referred to as source and destination nodes. The shortest path is the shortest possible path between source and destination nodes that is efficient and does not traverse the same node twice. In a spatial network, it is the optimal path in terms of distance between two nodes. It is mostly used in accessibility studies and can be measured in abstract measures (time, cost, etc.) or a combination of all these measures.

There are some cases where we need to identify the similarity between two paths in a spatial network. For example, we need to identify network paths that have some similarity to important routes such as the route of the Olympic marathon. This can be very interesting for athletes to identify similar paths in their vicinity for training purposes, while reducing the cost of travelling to the actual area where the marathon takes place. This identification of similarities should also consider the inclusion of attributes of the nodes/edges (length, height, slope, aspect, etc.) for the quantification of similarity (Agourogiannis et al., 2018).

The similarity of network paths has not yet been extensively studied in the relevant literature. Drawing on theoretical approaches from other scientific fields can help to understand the concept of network similarity. This applies to the scientific field of ecology as described in the work of

Johnston (1975), such as the Jaccard similarity index introduced by botanist Paul Jaccard in 1901 (Jaccard, 1901) as a measure of similarity between numerical sets. However, there are more recent studies that incorporate geographical variables, such as the similarity of characteristic plant species when they occur in ecological communities of different geographical areas (Srivastava and Shukla, 2016; López, 2019; Oluyinka Christopher, 2020). The concept of similarity has been used in spatial networks to compare the properties of trajectories, such as the distance and time travelled by an object as it moves. Tiakas et al. (2009) study the similarity of trajectories in spatial networks by defining two similarity measures (a) one that refers to the distance Dnet within a network and (b) the distance Dtime that refers to the distance in a network as a function of time. Spatial networks are also addressed by Shang et al. (2017), where the similarity of trajectories is exported by an algorithm based on spatio-temporal features and merged into a final result. Finally, at the same scientific level is the work of Hwang et al. (2005), which studies the similarity of trajectories by fully exploiting the spatial characteristics of a road network in conjunction with the temporal similarity features. On the other hand, the works of Magdy et al. (2016), Buchin et al. (2011) and Lee et al. (2007) are interesting, in which similarity algorithms are applied to the trajectory of Euclidean space, the last two of which compute the similarity in sub-segments of the total trajectory by decomposing the original problem into smaller parts to obtain fast and reliable results.

However, a path in geographical space can be described by features such as altitude, slope, aspect, distance from points of interest, which makes it a multivariate model. Spatial variables can describe the path in terms of a table containing all the values to which finding algorithms and weighting coefficients are applied. A typical example is the work of Agourogiannis et al, 2021, which represents the spatial network in a mathematical Graph form. This approach creates tables of geographic features for nodes and edges, and finally applies spatial queries to find optimal paths. Thus, there is a need to develop a path similarity index that integrates all geographic factors of an area, regardless of whether they occur in networks of the same study area or in different geographic areas. And regardless of whether the geographical points of interest are on the network or whether the points of interest are outside the network itself. By using distance measures between the points of interest and the associated node/vertex of the network, we can then characterise the attributes of the network based on their proximity to the points of interest.

In this paper, we present a multivariable similarity index of network paths for decision making in spatial networks (roads) that identifies the optimal path by comparing the number of paths. The innovation lies in combining many variables with multivariate analysis methods to produce a multivariate index of path suitability based on weighting sub-factors of a geographical nature. This article differs from previous publications in that it presents a new similarity index that incorporates both the geographical information of many network units (development of metric spatial relationships such as the distance of the network from points of interest) and the weighted variability.

The proposed weighted similarity index is based on geographical data and uses spatial networks for its calculations. It is a geographical approach as it uses geographical data (proximity, length, slope, etc.) and the results include paths of a spatial network.

This weighted similarity index will help to design an integrated decision-making system to find and document optimal routes at local and regional level in terms of sustainable development. Through sporting events for running or exercising, walks to highlight historical, cultural and environmental elements, each area will be promoted to attract visitors and strengthen the local economy.

2. Methodology

The proposed similarity algorithm is demonstrated in this section. More specifically, we quantify the similarity between some network paths, as a percentage (%) showing the overall weighted similarity between geometric paths in a spatial network (e.g., road network).

Initially, we determine the proposed network paths and then we apply the Similarity Index (S) by calculating the similarity of the paths found in relation to the target path. The similarity algorithm uses not only the geometric attributes of each path, but also the weighted geographic characteristics such as for example: proximity, visibility, and slope. The process of the algorithm is a filtering process, during which, after calculating the values for each of the criteria, each potential path is then eliminated from the list. Finally, the algorithm ends up with a proposed set of potential solutions which are then weighted and shorted based on the overall score.

The following formula, depicts the overall similarity approach which is applied to each of the shortlisted network paths. It yields a single percentage illustrating the overall similarity of a path to the target network path.

$$Similarity\ Index\ (S) = 1 - \left| 1 - \frac{Ncr}{\sum\left(\frac{Scrn}{Tcrn}\right)} \right| \tag{1}$$

Ncr: Number of criteria,

Tcrn: Target path criteria values,

Scrn: Solution values after searching.

Ncr term is the count of all criteria applied to this approach. Tcrn is the score of the target path for each of these criteria separately. Finally, Scrn is the score of a path on each of the criteria. In other words, the algorithm quantifies in a percentage, the overall weighted deviation of a path from the original target path. This is, the aggregated and weighted deviation of all criteria, from the target path.

Adding weighting values to each criterion, we quantify the contribution of each criterion to the solution. These arbitrary weights are based on policy priorities from the local authorities. In other terms, these weights form the overall importance of the local authorities to favor some geographical aspects of the area, against some others. For example, some local authorities may emphasize the proximity to archeological sites more than the proximity of a path to schools or urban environment.

Weights should reflect local policies and focus on the objectives of local development. In other words, specific criteria that are aligned with local policies (example: proximity to hotels) may have greater weight than others. Weighting system is introduced in order to give a degree of flexibility on calculating optimal routes in a road network. Thus, the similarity index is converted to:

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$$Similarity\ Index(Sw) = 1 - \left|1 - \frac{1}{\sum\left[\left(\frac{Scrn}{Tcrn}\right) * Wn\right]}\right| \tag{2}$$

Tcrn: Target path criteria values,

Scrn: Solution values after searching,

Wn: The weight of each criterion

By considering the prioritisation of optimal pathfinding criteria and the use of gravity coefficients in the similarity index, we can perform a sensitivity analysis of the model. This allows us to ensure the accuracy of our results while providing a variety of options for alternative routes.

The overall similarity number is the actual result of the above formula. This is the overall similarity of a path based on some criteria. This overall number can be used for comparison between possible solutions in order to select the optimal solution. This methodology is based on geographical data and their attributes to calculate similarity. It uses spatial networks as „search space" and its results consist of paths along a spatial network.

3. Case Study & Results

Calculating the similarity of routes can be effectively applied in areas where they are described by a variety of geographical features, and we can measure different aspects of the locations in the spatial network. The study area in this paper is the island of Lesvos in Greece (Margariti, 2022; Mitsi et al., 2020). Lesvos is described by an intense relief, where there is a complex road network of more than 4000 km. Moreover, there are many areas of interest on the island of Lesvos, such as cultural, ecological and tourist sites, which are the criteria for path search and similarity calculation.

For the spatial network analysis, we used the methodology and search algorithm proposed in the article by Agourogiannis et al, 2021. This process involves preparing the network based on graph theory (creating a spatial network with nodes and edges), inserting geographic information at nodes and edges such as distance, altitude and distance from points of interest, and finally searching for paths with spatial criteria.

Open spatial data (Table 1) such as the road network of Lesvos and points of interest from the Open Street Map (Bartzokas-Tsiompras, 2022) were used to conduct the analysis. The Digital Elevation Model (DEM) was provided by the European Copernicus platform with a spatial resolution of 25 metres. All data were produced in the Greek Projection System (Greek Grid), ensuring the same metric system and scale. Finally, the spatial analysis of the data was carried out using geoinformatics methods and tools such as the R programming language (CRAN, 2019) and the PostgreSql geographic database using the PostGIS (https://postgis.net) and PgRouting (https://pgrouting.org/index.html)

Table 1. Spatial data used in spatial network analysis.

Title	Format	Source	Project System
Lesvos Road Network	Spatial (Polyline)	Open Street Map	Greek Grid
Lesvos DEM	Spatial (Raster)	Copernicus	Greek Grid
Lesvos Settlements	Spatial (Point)	Open Street Map	Greek Grid
Lesvos Cultural Sites (archaeological and religion sites)	Spatial (Point)	Open Street Map	Greek Grid
Lesvos Tourism Accommodation	Spatial (Point)	Open Street Map	Greek Grid

The criteria used were: the length of the route, the mathematical difference between the starting altitude and the finishing altitude, and the average distance from points of interest (such as traditional settlements, cultural sites and tourist establishments, as shown in Table 2). The aim is to identify routes based on the spatial criteria in order to combine sporting, cultural and tourist features to contribute to the promotion and local development of the study area (Agourogiannis et al., 2019). Also, the distribution of the weights in each criterion (the values of the weights were assigned based on experimental scenarios to find cultural routes with geographical features that would be similar to the route of the Classic Marathon) contributed to finding the specific routes and limiting the results to the type of routes searched.

The application of the criteria in the search algorithm resulted in 3 routes in the study area (Figure 1). Table 2 shows the values describing the possible "solution routes" of the spatial network. In a first interpretation of the results, we notice that the values of the paths are quite close to each other. Path 1 (Figure 2) and Path 3 (Figure 4) are located in areas with intense topography, while Path 2 (Figure 3) is located in an area with relatively low levels and valley aspects. However, all paths are of similar length and pass close enough to the points-of-interest to approach the values of the finding criteria.

Figure 1 shows the entire study area with the settlements, tourist and cultural sites. The three proposed solutions (routes), which were chosen because of their similarity, are also shown on this map. As can be seen, they are located in different areas of the island and have quite different shapes. However, their characteristics are very similar to the target path we used, namely the Marathon. Now we need to quantify the overall weighted similarity with our proposed weighted measure for each of the possible solutions in order to select the best solution. Figures 2-

3-4 show the maps for each of these three solutions. The following table (Table 3) depicts the measures for each of the 5 features we used to measure similarity.

Table 2: Details of the target path we need to identify on the road network.

Target Path			Weight Value
Criterion 1	Total Length (m)	42000	0.3
Criterion 2	Starting-Ending altitude difference (m)	60	0.3
Criterion 3	Distance Settlements (m)	1500	0.2
Criterion 4	Distance Tourism Accommodations (m)	5500	0.1
Criterion 5	Distance Cultural sites (m)	1250	0.1

3.1 Calculation of paths Similarity

The calculations of path-similarity are depicted in detail in the following table 4. Using the above formula (Formula 2) we calculated the overall weighted similarity for each of the 3 possible solutions. The formula of combining target-path-values with each solution-path-value takes the following form:

$$SimilarityIndex(Sw) = 1 - \left|1 - \frac{1}{\Sigma\left[\left(\frac{Scrn}{Tcrn}\right)*w\right]}\right|, \tag{3}$$

Similarity for Solution Path 1:

$$SimilarityIndex(Sw) = 1 - \left|1 - \frac{1}{\left[\left(\frac{Scr1}{Tcr1}\right)*w1\right]+\left[\left(\frac{Scr2}{Tcr2}\right)*w2\right]+\left[\left(\frac{Scr3}{Tcr3}\right)*w3\right]+\left[\left(\frac{Scr4}{Tcr4}\right)*w4\right]+\left[\left(\frac{Scr5}{Tcr5}\right)*w5\right]}\right|,$$

Similarity for Solution Path 2:

$$SimilarityIndex(Sw) = 1 - \left|1 - \frac{1}{\left[\left(\frac{Scr1}{Tcr1}\right)*w1\right]+\left[\left(\frac{Scr2}{Tcr2}\right)*w2\right]+\left[\left(\frac{Scr3}{Tcr3}\right)*w3\right]+\left[\left(\frac{Scr4}{Tcr4}\right)*w4\right]+\left[\left(\frac{Scr5}{Tcr5}\right)*w5\right]}\right|,$$

Similarity for Solution Path 3:

$$SimilarityIndex(Sw) = 1 - \left|1 - \frac{1}{\left[\left(\frac{Scr1}{Tcr1}\right)*w1\right]+\left[\left(\frac{Scr2}{Tcr2}\right)*w2\right]+\left[\left(\frac{Scr3}{Tcr3}\right)*w3\right]+\left[\left(\frac{Scr4}{Tcr4}\right)*w4\right]+\left[\left(\frac{Scr5}{Tcr5}\right)*w5\right]}\right|,$$

The three possible solutions represent spatial paths that can be shown to be very similar to the marathon's finishing path, such as the classical marathon of Athens. In the "Value" column, the measure for each of the criteria is given. For example, criterion 1 is the total length of the course in metres. The second column ("Weighting") is the representation of the weighting for each criterion, which adds up to 100% for all 5 criteria. This represents the importance we have given to each of the criteria based on our expertise and the opinion of the decision makers. Finally, the overall weighted similarity is shown at the bottom of the table as a percentage. The optimal solution is path 2, as it has 98.7% similarity with our chosen target path (Marathon) according to our calculations. The weights used play a very important role in the final selection of the solution. Changing the initial weights can lead to different solutions. The use of weights is important as it reflects the priorities set by decision makers for identifying important aspects of a path based on local knowledge of the area and the feature that local authorities most need to promote.

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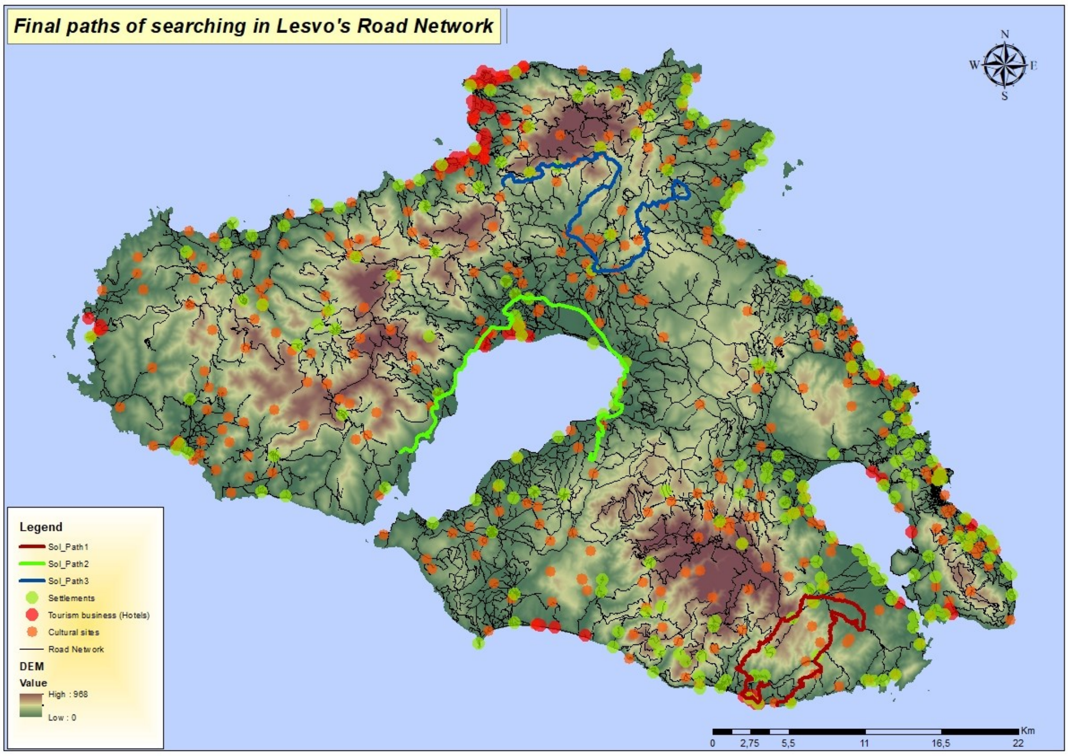

Figure 1. Three acceptable paths in the road network of Lesvos Island, after searching using spatial criteria in spatial algorithm. spatial criteria describe the target path.

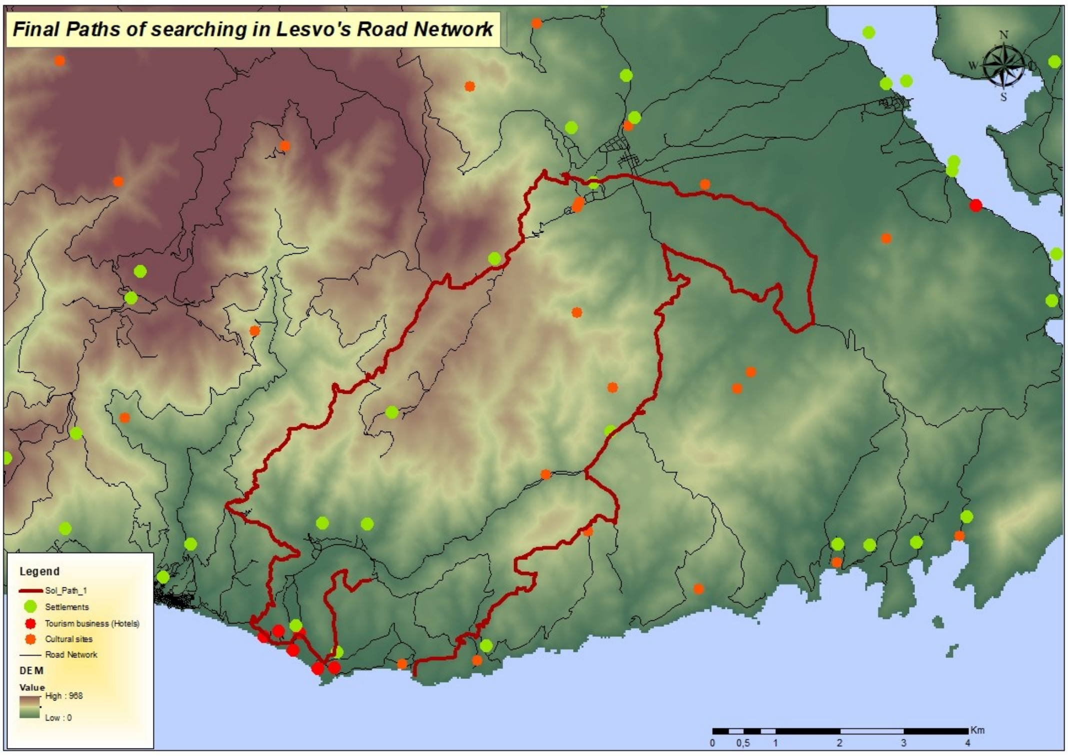

Figure 2. First solution path in the road network South-East of Lesvos Island. In this area there are many tourism accommodations.

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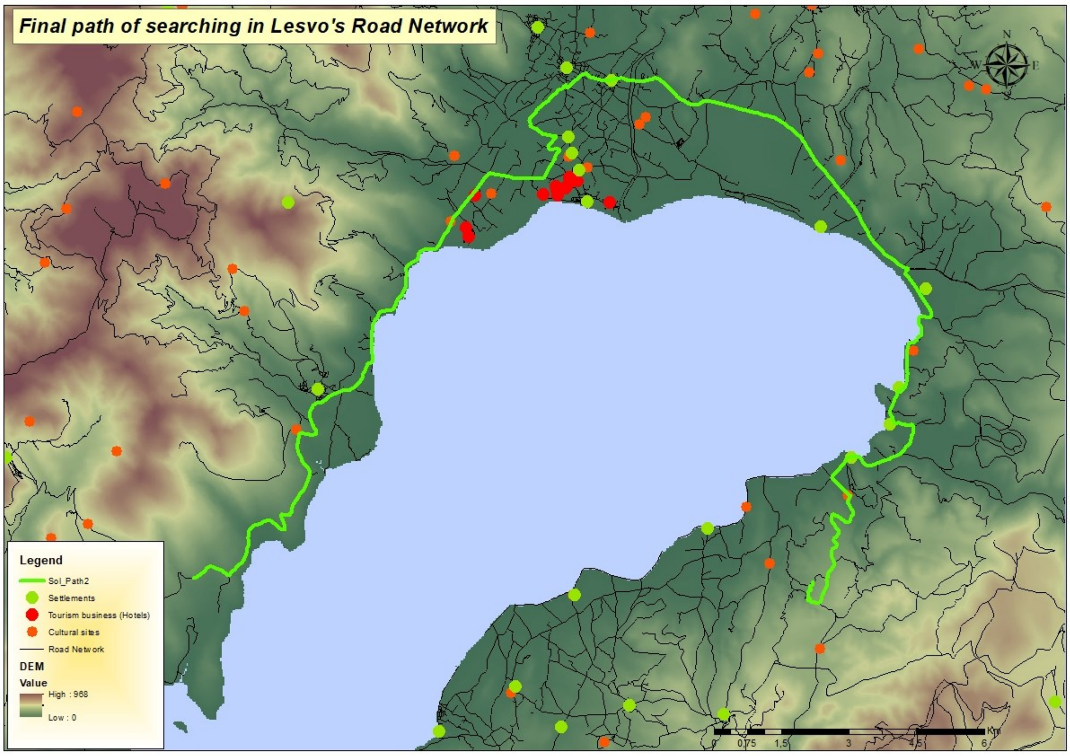

Figure 3. Second solution path in the road network South of Lesvos Island. In this area there are many cultural sites and traditional Settlements around the most important wetland called Kalloni Gulf.

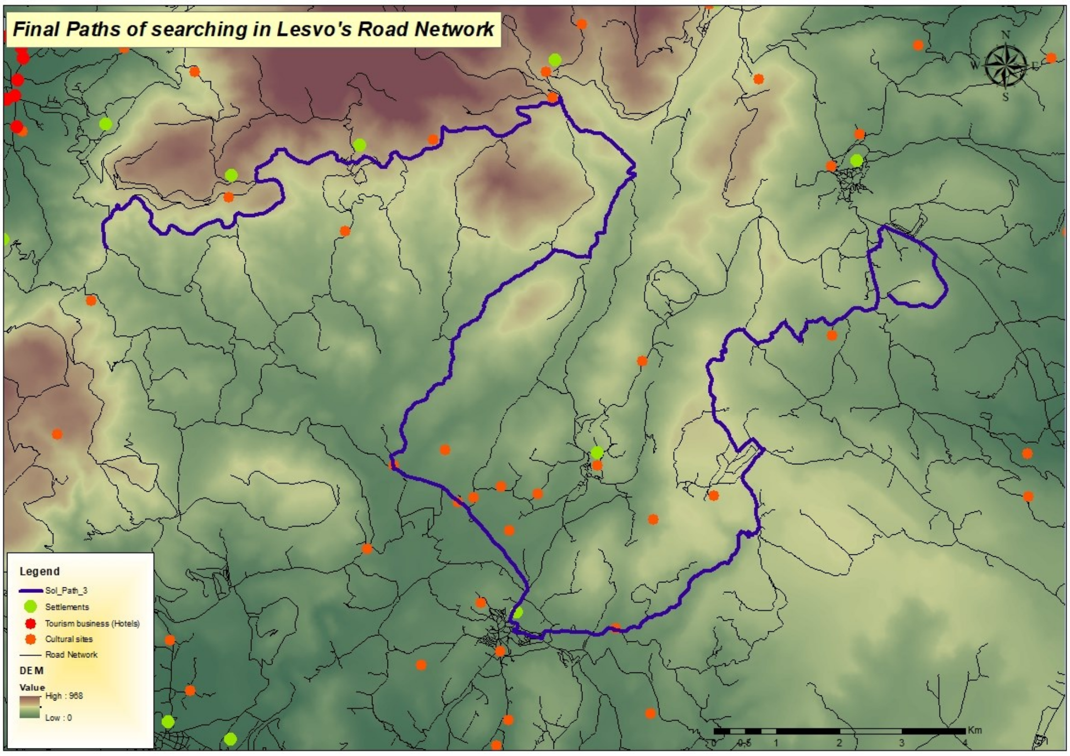

Figure 4. Third solution paths in the road network central of Lesvos Island. In this area the altitude has many differences and the path pass-through of cultural sites.

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Table 3. Values of three acceptable solution paths in the road network of Lesvos Island

Solutions Path				
		Solution 1	Solution 2	Solution 3
Criterion 1	Total Length (m)	40000	40000	42000
Criterion 2	Starting-Ending altitude difference (m)	59	63	75
Criterion 3	Distance Settlements (m)	1216	1614	1789
Criterion 4	Distance Tourism Accommodations (m)	3472	5210	7331
Criterion 5	Distance Cultural sites (m)	1464	1282	975

Table 4. Calculations of paths similarity based on 5 criteria. The overall similarity is depicted in blue color.

Target Path			Solution Path 1	Solution Path 2	Solution Path 3
	Value	*Weights*	*Solution value 1*	*Solution value 2*	*Solution value 3*
Criterion 1	42000	0.3	40000	40000	42000
Criterion 2	60	0.3	59	63	75
Criterion 3	1500	0.2	1216	1614	1789
Criterion 4	5500	0.1	3472	5210	7331
Criterion 5	1250	0.1	1464	1282	975
Overall weighted Similarity			98.20%	98.70%	85.10%

4. DISCUSSION

The aim of this paper is to quantify the spatial relevance between paths in spatial networks by using a new multivariate spatial similarity index. The index compares the geographical properties of paths derived using a methodology and algorithm for path search in spatial networks, as shown in previous work (Agourogiannis et al., 2021), and calculates the similarity between the values of the solution paths and the target path. The quantification of similarity in geographical aspects is quite novel especially in terms of multivariate, aggregate and weighted similarity. The geographical aspects of each path were also included in the analysis, as they play an important role in the character of a network path in relation to sporting events and/or tourism promotion of an area.

It should be noted that the proposed search path algorithm and spatial similarity index represent an integrated methodology for geographic multivariate analysis of spatial networks, as well as for the management of big spatial data, following the principles of the first law of geography (Tobler, 1970). Identifying similar network paths requires significant computational resources, making it a tedious and difficult task, especially when spatial networks involve a large number of nodes and edges.

From the results, although all three routes have a high percentage of similarity with the found values, there may be a route that optimally complements the original estimates. In this way, the spatial similarity index can be used as a policy and decision support tool in the search for optimal solutions to network problems, but also to strengthen local and regional development.

Specifically, the method described in this paper led to the conclusion that the more geographic data used as input to the search algorithm, the more alternative paths can emerge (a large number of nodes and edges describing a spatial network implies more paths). Conversely, the more criteria used as parameters in the search algorithm, the closer we get to the optimal solution. This is confirmed by the similarity index, which shows the path with the highest similarity value between the target value and the solution value. The proposed weighted similarity algorithm is based on geographical aspects of the road network and its results are actual paths in spatial networks.

An example of this is the drawing of sports routes in different geographical areas that are very similar to the routes of major sporting events such as the classic marathon, which can attract large numbers of athletes and tourists and highlight each region as a centre of high tourism, sport and economic development (Kavroudakis et al., 2019).

5. CONCLUSIONS

This paper illustrates the potential use of a specific algorithm that focuses on the identification, quantification and weighted ranking of network paths based on policy priorities for sporting events. Using the proposed algorithm, we can identify similar paths of a network and quantify the similarity in percentage form.

Similarity is the measure that describes how much the values of different entities coincide or how far apart they are. This paper presents a new Similarity Index for calculating the similarity of spatial paths in a network such as roads.

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The spatial similarity index compares the geographical features (length, altitude difference, distance from points of interest) from a set of paths (solution paths) that can be derived from a route search algorithm on a spatial network to achieve optimal route discovery. The comparison of the paths is done with respect to the initial values (target paths).

The use of weights in the individual path features, which appear as spatial criteria, contributes to the multivariate nature of the index and can lead to the desired path, as shown in the case study. The algorithm can handle weighting and truncating many criteria for each network path as long as the paths contain relevant information.

The innovation in the path finding methodology and the construction of the weighted similarity index is mainly in the use of geographical aspects of each path, which can be used to describe a spatial network, creating a table of values that can be used for Big Data analysis.

Storing, managing, analysing and visualising Big Data and results is done using open source geoinformatics tools (i.e., QGIS) and spatial databases such as PostgreSQL with the PostGIS and PgRouting plugins. The use of the above open source geoinformatics tools can reduce the constraints in obtaining fast, valid and reliable results as many calculations are performed simultaneously on big data tables and take a lot of time. The use of arbitrary weights in the algorithm can be a limitation that could affect the results. However, this is done intentionally to give users the flexibility to apply custom weights for a particular situation. In other words, this arbitrary approach to weighting allows for the inclusion of a wide range of data at the local level.

The proposed similarity index, which is an assessment tool, reinforces a number of applications in the field of road networks for policy making in the context of regional and national sustainable development of areas. The potential of this work makes it a promising spatial tool for the assessment of road networks based on the location of sporting events and training venues.

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