Natural Gas Transmission Pipeline Route Selection Using GIS and AHP

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Abstract

In accordance with demands and needs, the natural gas transmission pipeline (NGTP) is one of the most appropriate transportation methods used in the distribution of existing reserves. Decreasing the cost and time of construction and minimizing environmental damage for such projects all depend on the determination of the optimum route at the beginning. Route determination is a complex process in which many variables are simultaneously analyzed, and thus, is one of the most important steps in NGTP projects. However, in developing countries such as Turkey, route determination is usually carried out manually with the help of traditional methods. This technique is not effective in many situations because it does not take into consideration the factors that affect the route as a whole. Technical, economic, environmental and sociological issues should all be considered and examined in the route determination process. This study was aimed at carrying out route determinations and dynamically creating an optimal NGTP route by developing a raster-based decision-support model based on geographical information system (GIS) technologies. In this context, the main factors affecting the NGTP route, along with the required geographical data coverage, were determined and classified based on the standards. Weights of factors and sub-factors were determined using the analytic hierarchy process (AHP) and a raster-based route determination model was developed. A GIS-based interface was then developed in accordance with the requirements of this model. Using this interface, the factor selection was done dynamically, based on current integral data in the interface, and alternative routes for different purposes were then determined by optionally changing pre-determined factor weights. The model was applied for the optimization of the current Bayburt (Demirozu) - Trabzon NGTP, having a length of 104 km, and in this process, the model was tested for such criteria as performance, speed and accuracy. The effectiveness of this method was proven by comparing the existing route with the optimal route determined by using this model.

1. Introduction

Pipeline systems are very important for transporting gas, oil and petroleum products because they are the most cost-effective way of moving fluid products over long distances. A pipeline project involves many concerns and stages, beginning with safety and environmental considerations, and moving on to routing, engineering, right of way acquisition, surveying, mapping, utilizing Geographical Information System (GIS) technology and finally, construction. Stakeholders invest a great deal of time in analyzing data and determining the original routing of a pipeline and must work within the parameters imposed by the chosen route. In the planning stage, there is one key component that all pipeline projects have in common: the effect that the initial routing of the pipeline will have on the eventual interface of all activities required for the project (Nussbaum, 2012).

GIS carry out the collecting, hiding, and processing of graphic and nongraphic information and present it to users as a whole. The GIS consists of computer aided equipment which charts land forms and incidents of land forms onto the map and analyzes them. This technology is capable of combining mutual databases; for instance, visual and geographical analysis advantages are presented to users as query and statistical analyses. With regard to this distinct feature, GIS is different from other information systems and, as a consequence, is used by both public and private sectors in order to identify the incidents in a service area and to form strategic plans by making forward-looking predictions (Yomralioglu, 2009). Route determination requires spatial data from different organizations and state institutions; in addition, it needs to be carefully chosen, saved, queried and analyzed. Today, this type of rapid analysis and its results are possible with GIS, thus making it an effective engineering tool for systematically organizing factors affecting route determination. Once these factors are identified, based on the length of the project, a GIS should be used to evaluate these factors simultaneously. Additionally, the GIS-based visualization technologies and cartographic abilities are generally adequate to determine the most effective routes (Yildirim et al., 2012).

Multiple-criteria decision-making (MCDM) methods have been developed to enable the analysis of multiple-criteria decision situations. They are typically used for dealing with planning situations in which one needs to holistically evaluate different decision alternatives, and in which comprehensive evaluation is hindered, especially by the multiplicity of decision criteria that are difficult to compare, and by conflicting interests affecting the decision-making process (Kangas, 2005). These MCDM methods belong to the wide spectrum of operations research methods. Numerous MCDM methods have been developed and each method has its own special characteristics. Different techniques are suitable for application in different types of decision situations; for example, some methods have been especially developed to manage risks and uncertainty, or non-linearity of evaluations, while others are intended for applications in conflict-management tasks or for making use of incomplete or low-quality information (i.e., data on an ordinal scale, etc.). Moreover, many methods come with a variety of settings and modified versions, such as fuzzy or stochastic versions. The methods have also been modified to some extent to better meet the demands of tasks in forest management. Of course, all the problems faced in forest planning cannot be solved by means of operations research; however, MCDM methods can serve as platforms where results provided by different fields of science can be comprehensively employed in decision-making processes.

One of the most popular analytical techniques for complex decision-making problems is the Analytical Hierarchy Process (AHP). Developed this process, which breaks down a decision-making problem into a system of hierarchies of objectives, attributes and alternatives. An AHP hierarchy can have as many levels as needed to fully characterize a particular decision situation. A number of functional characteristics which make AHP a useful methodology include the ability to handle decision situations involving subjective judgments and multiple decision makers and the ability to provide measures of consistency of preference (Triantaphyllou, 2000). Designed to reflect the way people actually think, AHP continues to be the most highly-regarded and widely-used decision-making method. The AHP can efficiently deal with tangible as well as non-tangible attributes, especially where the subjective judgments of different individuals constitute an important part of the decision process (Gayatri and Chetan, 2013).

In classical MCDM methods, the ratings and the weights of the criteria are known precisely, and a survey of these methods is presented in Hwang and Yoon. The technique for order performance by similarity to ideal solution (TOPSIS), another well-known classical MCDM method, was first developed by Hwang and Yoon for solving a MCDM problem (Jahanshahloo et al., 2006). It is based upon the concept that the chosen alternative should have the shortest distance from the positive ideal solution and the farthest from the negative ideal solution. A similar concept has also been pointed out by Zeleny. In the process of TOPSIS, the performance ratings and the weights of the criteria are given as exact values. Recently, Abo-sinna and Amer have extended the TOPSIS approach to solve multi-objective nonlinear programming problems. Chen extended the concept of TOPSIS to develop a methodology for solving multi-person multi-criteria decision-making problems in a fuzzy environment. Under many conditions, exact data are inadequate to model real-life situations. For example, human judgments, including preferences, are often vague and cannot be estimated with exact numerical data; therefore, these data may have some structures such as bounded data, ordinal data, interval data, and fuzzy data. In this study, it was difficult to determine precisely the exact value of the attributes in some cases, and as a result, their values were considered as intervals; therefore, the concept of TOPSIS was extended to develop a methodology for solving MCDM problems with interval data (Jahanshahloo et al., 2006).

The other known classical MCDM method is the Simple Additive Weighting (SAW) method. It is the simplest and still the most widely-used MCDM method. In this method, each attribute is given a weight, and the sum of all weights must be 1. Each alternative is assessed with regard to every attribute.

Previously it was argued that the SAW method should be used only when the decision attributes could be expressed in identical units of measure. However, if all the elements of the decision table are normalized, then SAW can be used for any type and any number of attributes. Proposed a simple method to assess weights for each attribute that reflect its relative importance to the decision. For a start, the attributes are ranked in order of importance and 10 points are assigned to the least important attribute. Then, the next-least important attribute is chosen, more points are assigned to it, and so on in order to reflect their relative importance. The final weights are obtained by normalizing the sum of the points to one (Gayatri and Chetan, 2013).

Spatial data models describe two fundamentally different conceptions of space. The field view represents space as a continuously varying distribution of geographic variables, and the raster data model is often used to approximate this view by discretizing an absolute space and subdividing it at regular intervals. In contrast, the object view focuses on discrete entities which have location, some level of spatial extension and attributes, and are usually represented as spatial features (i.e., points, lines or polygons) using a vector data model. Though many phenomena can be reasonably represented as either fields or objects, some geographic phenomena have both field and object characteristics, and might require a combination of these views. One example is an aggregation of many discrete objects, created as outputs from an optimization algorithm, which represents a solution space as a field of objects (Cova and Goodchild, 2002). Alternatively, an object, like a storm cell, can exhibit continuous spatial variation (e.g., wind speed) within its spatial extent (Yuan, 2001). The raster data model is the most useful data format for carrying out arithmetic operations among pixels of the same coverage or different coverage of the same geographical location. Many researchers, realizing the importance of the raster approach in the route determination process, have carried out various studies and have provided solutions to eliminate the past and present deficiencies of this method (Rosado et al., 2005).

It may not be possible to determine in advance the Natural Gas Transmission Pipeline (NGTP) routes, as they are affected by many factors causing environmental and economic problems for these projects. These factors include potential landslide areas, protected areas, flora/fauna areas, wetlands, rocky areas, soil types, other infrastructure lands and agricultural land. In addition, especially in Turkey, there are many current projects in which pipelines passing through landslides have had to be reconstructed. Sometimes the NGTP passes through the breeding area of a specific animal and construction must wait until the end of the breeding period. Hard rock and steep slopes pose other difficulties and areas must be reconstructed in order to avoid sharp turns in the pipeline. There is also additional cost for a project which crosses streams and wetlands unnecessarily (Orhan and Yilmazer, 2006). In other countries, in addition to these problems, there have been projects where a NGTP passing through fault lines or beds and residential areas has caused the deaths of many people (Rowland, 2005). Moreover, some projects have been cancelled before the estimated operating time for the pipelines was completed. Others have required repeated repairs, resulting in excessive maintenance costs because factors affecting the occupancy of the NGTP, such as corruption and abrasion caused by groundwater, had not been determined beforehand (Dey, 2001).

2. Natural Gas Transmission Pipeline Routing Using GIS

The GIS software is highly structured, multifunctional and complex, making it very difficult for managers and practitioners to use it with all its functions. In practice, decision-makers want to get new information as soon as possible by performing the necessary queries and analyses using the relevant data in their individual applications, i.e., to use information in its database quickly and optimally (Yomralioglu, 2009).

The idea of developing a process for selecting an optimum pipeline alignment between two points is not new. A number of previous route-selection studies have been conducted for large transmission pipelines similar to the POMA. While there are some differences in the ways the studies were conducted, the same basic issues were addressed, including cost, availability of land, and public concerns in the communities through which the pipelines were aligned. In general, GIS technology can be thought of as a way to attach information to graphics. A GIS may contain the same lines and symbols as a simple CAD drawing, but GIS allows data to be referenced to each graphical entity. These data are stored in a database, allowing the GIS user to sort and analyze this information in an infinite number of ways. As a result, GIS technology is ideally suited for a pipeline route selection study because of the extremely large amount of data that must be managed for a project of this size (Luettinger and Clark, 2005).

Digital mapping includes various kinds of spatial and non-spatial data such as recent aerial photography, state and local parks, wildlife management areas, forests, public lands, associated landowner information, foreign pipelines and other utilities that cross the proposed route, road, railroad and water crossings, boundaries of states/provinces, counties, and cities, threatened and endangered species, and also wetlands and other environmentally sensitive properties (Luettinger and Clark, 2005).

The deficiency of location data, including coverage of large areas that is required by different corporations in Turkey, has a negative influence on GIS studies which are held on a regional scale. Many public corporations use 1:25.000 scaled topographical maps produced by the General Command of Mapping (GCM). Corporations provide needed data (roads, rivers, residential areas, natural resources, etc.) with these maps. However, the process of updating these maps throughout the country requires a great deal of time. Furthermore, the maps produced for defense purposes are inadequate for usage in other disciplines.

The first stage of the GIS-based route determination method was to obtain the necessary location data/information by taking into account the factors and sub-factors affecting the route. In this process, the majority of the data used as a base were in the location data.

After factors were identified and relevant data layers were created, in the second stage, the weights of these factors and sub-criteria needed to be identified. In this study, routing studies criteria were taken into consideration by using classical methods. The views of experienced and professional people and legal procedures and practices carried out in developed countries were examined as a whole. Then, the process of determining the weight of the factors was begun. In this process, the most important procedural step was the conducting of interviews in various institutions and organizations engaged in NGTP. As a result of determining the weights of the factors, supported by the interview results and by other studies in the literature, the weights of the factors and sub-criteria affecting the NGTP route determination were identified by AHP. This process is a multi-attribute decision tool that allows financial and non-financial, quantitative and qualitative measures to be considered and trade-offs among them to be addressed. The AHP is aimed at integrating different measures into a single; overall score for ranking decision alternatives. Its main characteristic is that it is based on pair-wise comparison judgments (Rangone, 1996). The description is developed in three steps (Onut and Soner, 2007)

The steps of the AHP method are as follows:

Step 1: Composing a pair-wise comparison decision matrix (A).

$$A = [a_{im}] = \begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ \frac{1}{a_{12}} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \cdots & 1 \end{bmatrix} \qquad i, m = 1, 2, \ldots, n.$$

Let *C*1, *C*2, …, *Cn* denote the set of elements, while *aim* represents a quantified judgment on a pair of elements, *Ci* and *Cm*. Saaty instituted a measurement scale for pair-wise comparison. Hence, verbal judgments can be expressed by degree of preference: *Equally preferred* with *1*, *Moderately preferred* with *3*, *Strongly preferred* with *5*, *Very strongly preferred* with 7 and *Extremely preferred* with *9*; *2*, *4*, *6* and *8* are used for compromises between the above values.

Step 2: Normalization of the decision matrix.
Each set of column values is totaled. Then, each value is divided by its respective column total value. Finally, the average of the rows is calculated and the weights of the decision-maker's objectives are obtained. A set of *n* numerical weights $w_1, w_2, \ldots, w_i$ are obtained.

Step 3: Consistency analysis.

$$A * w_i = \lambda_{\max} * w_i, \quad i = 1, 2, \ldots, n.$$

Then the consistency index (CI) is calculated as:

$$\mathrm{CI} = \frac{\lambda_{\max} - n}{n - 1}.$$

The consistency index of a randomly-generated reciprocal matrix shall be called to the *random index* (RI), with reciprocals forced. An average RI for the matrices of order 1–15 was generated by using a sample size of 100. The table of random indexes of the matrices of order 1–15 can be seen in Saaty (1980).

The last ratio that must be calculated is the CR (consistency ratio). Generally, if CR is less than 0.1, the judgments are consistent, so the derived weights can be used. The formulation of CR is:

$$\mathrm{CR} = \frac{\mathrm{CI}}{\mathrm{RI}}.$$

In the raster-based route determination model, after needed factors were identified and properly formed, some limitations needed to be introduced. These limitations do not take any weight value and define a barrier. In route planning, the lands where the passing is strictly forbidden is defined as an "absolute barrier", and the lands in which passing is likely despite difficulty are defined as a "relative barrier". Absolute barriers are determined in light of the benefits expected from the entire project by users. In the generated route-planning model, residential zones, landslide areas, wetlands and fault lines were defined as absolute barriers and their weights were exemplified by defining them as "∞" (Table 1).

Table 1. Factor and sub-factor weights affecting the NGTP route

Factors / Sub-Factors	Weights	CR
Land Cover	**0.263**	**0.0247**
Forest	0.096	
Cultivated Areas (Seasonal Agriculture)	0.043	
Agricultural Areas	0.063	
Wetland (absolute barrier)	0.134	∞
Rocky Areas	0.226	
Pasture Areas	0.028	
Settlement Areas (absolute barrier)	0.411	∞
Slope	**0.211**	**0.0108**
$<10^0$	0.031	
$10 - 20^0$	0.060	
$20 - 30^0$	0.081	
$30 - 40^0$	0.124	
$40 - 50^0$	0.152	
$50 - 60^0$	0.185	
$>60^0$	0.367	
Geology	**0.162**	**0.0443**
Acid-Intermediate Intrusives	0.473	
Basic-Ultrabasic Rocks	0.288	
Metamorphic Rocks	0.149	
Volcanic Rocks	0.054	
Sedimentary Rocks	0.036	
Soil	**0.130**	**0.0278**
I. Class soils – Excellent Agricultural	0.269	
II. Class soils	0.251	
III. Class soils	0.193	
IV. Class soils	0.104	
V. Class soils	0.081	
VI. Class soils	0.045	
VII. Class soils	0.037	
VIII. Class soils – Non Agricultural	0.020	
Landslide	**0.092**	**0.0334**
Active Landslide Areas (absolute barrier)	0.633	∞
Potential Landslide Areas	0.260	
Old Landslide Areas	0.106	
Stream	**0.040**	**0.0063**
River	0.444	
Stream	0.053	
Canal	0.262	
Brook	0.153	
Creek	0.089	
Road	**0.030**	**0.0238**
Highway	0.486	
Three-Lane Road	0.222	
Two-Lane Road	0.121	
Stabilized Road (two- lane)	0.090	
Stabilized Road (one- lane)	0.044	
Seasonal Road	0.037	
Protected Area	**0.049**	**0.0290**
Level I	0.407	
Level II	0.129	
Level III	0.079	
Urban Protected Areas	0.052	
Historical Protected Areas	0.333	
Recreation	**0.023**	**0.0167**
Upland	0.039	
Tourism Center	0.262	
Historical Monument	0.492	
Picnic Areas	0.069	
Promenade Areas	0.138	
Fault Line (absolute barrier)	∞	

In general, the development of a NGTP route model is as follows:

1. Determination of the factors and spatial data layers that will be affected,
2. Determination of standards for factors and sub-factors,
3. Determination of factor weights and difficulty degrees of factors,
4. Finally, implementation and testing of the NGTP route model.

3. The Case Study

3.1. Study area

Trabzon Province is situated between longitude 39° 7′ 30″ and 40° 30′ E and latitude 40° 30′ to 41° 7′ N in the middle of the Eastern Black Sea Region of Turkey (Figure 1). The province has 17 districts and 537 villages within 4685 km2. The elevation exceeds 3325 m above sea level in some parts. Generally, the land within the province of Trabzon consists of mountains, hills and high plateaus. The provinces of Bayburt and Gumushane lie south of Trabzon. There is an existing pipeline between Bayburt-Demirozu and Trabzon-Bulak, so this area was chosen in order to compare the existing route with the optimum route which was determined after cost/distance analyses via the new algorithms.

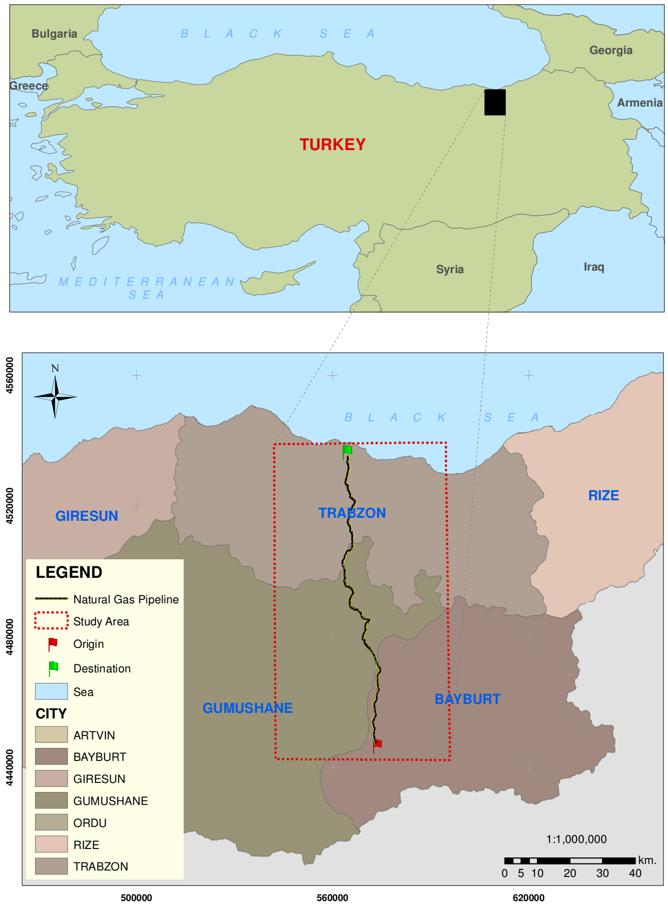


Figure 1. Study area.

3.2. Database design

Multidiscipline data were derived from different data sources. All these data were standardized under the same projection system and the same layer systems (Figure 2). Then, all these vector data were converted to raster data at 20 × 20 m pixel dimension. Then all these vector and raster datasets were used in analyses for finding the optimum route.

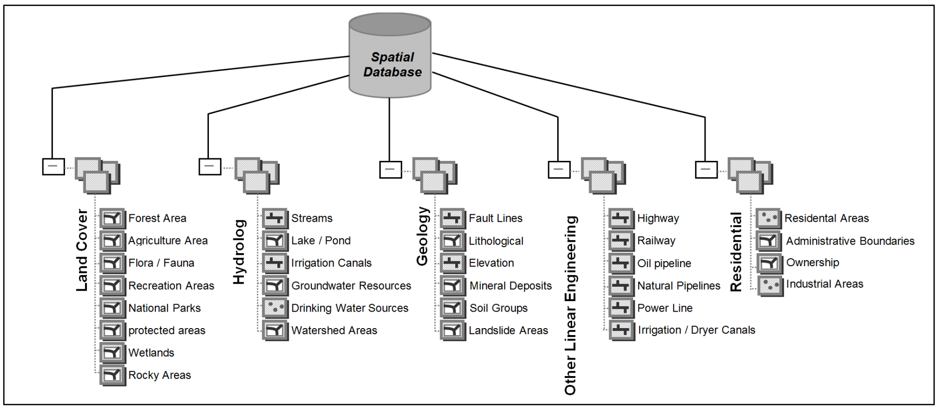


Figure 2. Spatial database design for natural gas transmission pipeline routing.

3.3. Bayburt (Demirozu)– Trabzon natural gas transmission pipeline

The main aim of the Bayburt (Demirozu)-Trabzon NGTP is to deliver natural gas to Trabzon. The branch line is divided into two sections: 42 + 300 km for the provinces of Bayburt and Rize and 68 + 260 of this line for the province of Gumushane.

Generally, the NGTP runs down to the Black Sea coastline through the high and rugged Eastern Black Sea Region, usually following the ridges of the mountains lying in a north-east and south-west direction with narrow alluvial plains between them. The line which crosses the Gumushane-Bayburt highway, about 59 + 250 km, continues up the Nalliarin Hill with a slope of approximately 35-40% and travels along this ridge, after which the elevation reaches 2000-2500 m. After 55-60 km at this elevation, the route follows morphological ridges and between these ridges for about 115-120 km, where the elevation of the alluvial plains and valleys gradually drops below 2000 m and continues to decrease towards the coastline. The line finishes at the municipal reconstruction zone, about1.5-2 km from the Black Sea Technical University.

The area through which the pipeline passes generally consists of pasture and agricultural land and also includes forests, although there is no forest area on the Erzincan, Bayburt and Gumushane side of the line. The pipeline does not pass over pasture or forest lands in these provinces, where agricultural lands are generally used for wheat and barley, although some sections are next to streams along which orchards are commonly found. The land in Trabzon Province, on the other hand, has forest characteristics. There are some settlements in the forest and agricultural areas, along with tea and hazelnut plantations.

3.4. Pipeline routing

The sub-criteria of the data sets were necessary to determine the challenges posed for pipeline crossings. For this, the weight values based on the information shown in Table 1 were submitted in an attempt to classify the data layers corresponding to pixels created in each of the sub-factors. This classification process involved both a generalization and sub-factor weights. For example, areas with slope values between 0-10 were converted into a single feature because of the difficulty of the transition, and its value of difficulty degree was defined as 0.031.

In the next step, the weighted cost consisting of data layers created separately for each layer was subjected to pixel-based arithmetic. The weight for each layer is shown in Table 1. On this cost surface, the value of the pixel refers to the total cost of transition over the surface belonging to that area (Figure 3).

P_w : P_i*W_i
P_w : Cost Surface
P_i : i^{th} data coverage pixel
W_i : i^{th} data coverage cost value

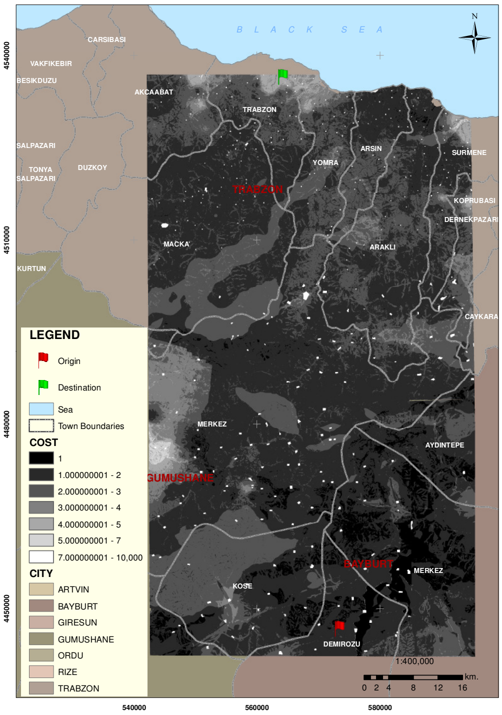


Figure 3. Weighted cost surface map.

Taking into account the starting point of the route and the pixel size, the accumulated total cost surface was created over the weighted cost surface, according to the working principle of the raster-based network analysis algorithm. This data set on the route transition was based on values determined for each pixel.

According to the working principles of determining route algorithms, before determining the direction, a separate layer is formed on the surface of the route. The direction layer shows flow direction from the starting point to the end point. The final route was created from the lowest cost pixels according to this direction layer (Figure 4- 5).

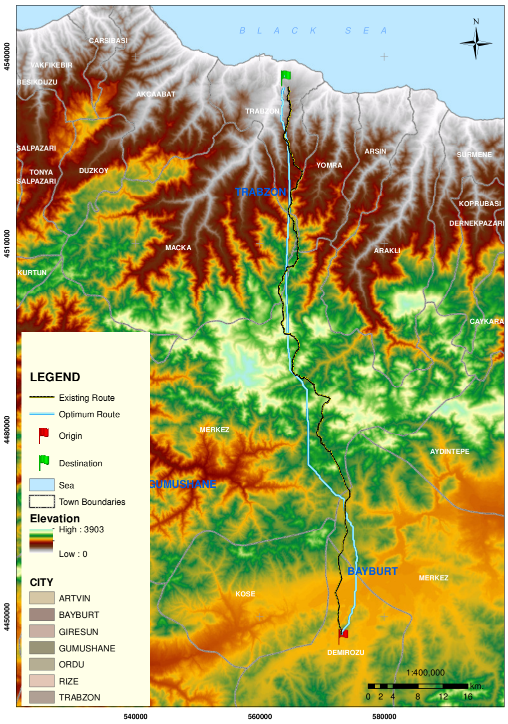
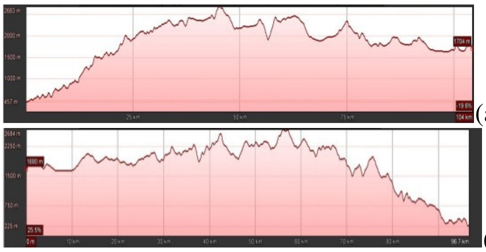


Figure 4. Optimum and existing routes on elevation map.


(a)
(b)
Figure 5. Elevation profile of optimum route (a) and existing route (b).

4. Results

After many analyses, as shown in the figure 4, a new optimum route was found which is more effective than the existing route. The new route passes fewer environmental zones compared to the existing route. The new route runs through fewer quality soil areas and follows the same route as highway and transportation lines. The new route is about 95 km in length, whilst the existing one is more than 103 km. However, the average slope of the new route is steeper than the existing one, due to the classifying of the slope sub-factor. Detailed information can be seen in Table 2. Environmental factors were targeted first, and then the economic view was calculated

Table 2. Compared Results

Factors	***Existing Route***	***Optimum Route***
River Crossing	13	8
Stream Crossing	75	98
Canal Crossing	1	1
Brook Crossing	26	10
Creek Crossing	6	5
Highway Crossing	5	4
Stabilized Road Crossing	54	34
Seasonal Road Crossing	144	91
Electricity Line Crossing	26	15
Telephone Line Crossing	8	7
Length	103.6 km.	95.2 km.
Average Slope	10%	13%

5. Conclusions

Route identification for NGTP is complex and requires the analysis of a large quantity of data and many parameters, depending on the length of the project. One of the tools used to perform this analysis effectively is GIS, which provides a large number of analytical functions that are capable of replacing traditional and manual methods of natural gas pipeline route planning. This powerful tool integrates thematic layers in an automated environment to compute the shortest possible route along with associated costs, and thus, eventually reduces the operating expenses and time needed for project execution. The integration of GIS and AHP provides a baseline for complex decision making in which the variant nature of the criteria and stakeholder factors can be accounted for successfully.

Raster-based data models and raster-based network analysis are necessary to determine the surface resistance and to model the NGTP route determination appropriately. One of the basic steps of route determination is to identify the factors that affect the route and their weights. At this stage, AHP presents effective solutions.

This model can easily be adapted to determine the necessary factors and calculate the weights for linear engineering structures such as pipelines, waterlines, roads, canals, railways, and energy transfer lines.

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