Road Planning for a Scenic Environment Based on the Dijkstra Algorithm: Case Study of Nanjing Niushou Mountain Scenic Spot in China

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Abstract: Road planning for a scenic environment should not only comprehensively research many factors such as landforms, vegetation, water bodies, etc., but also pay due attention to ecology, function, reasonable engineering workload, aesthetic requirements, etc., and is therefore a multi-object systematic project. The parameterization method used in this paper provides a reliable scientific basis for road planning for a scenic environment, being more methodical, accurate, efficient and practicable in comparison with traditional methods of line selection based on experience. For this research, a road planning algorithm based on the ArcGIS software platform is used to construct a model of parameterized road planning for a scenic environment, taking as an example the Northern Area of Niushou Mountain Scenic Spot, Nanjing, China.

Keywords: Parameterization, scenic environment, road planning, model building

1 Introduction

The Specification for the Planning of Famous Scenic Spots (GB50298-1999) promulgated by the Chinese Government states that the planning of traffic and roads shall be convenient, reliable, and suitable for the characteristics of scenic areas, and form a reasonable network system; and also shall make reasonable use of landforms, select lines according to local conditions, integrate with local landscapes and environment, and avoid deep excavations and high fills[1]. Road planning for a scenic environment therefore does not simply aspire after shortcuts, but seeks to form a good serial relationship with each landscape node, and to form a good traffic network system with landscape nodes as line control points.

Generally, in a scenic environment, the topography and landforms are relatively complicated, and there are ecologically-sensitive areas. Therefore, the line selection for roads in scenic areas should match the topography and landforms with a flexible alignment that bends, rises and falls according to local conditions, at the same time trying to avoid excessive earthworks and minimizing artificial disturbance to the scenic environment. Roads well matched to local conditions not only facilitate tourist traffic, but form an integral part of the scenery. Road planning for a scenic environment is a multi-object systematic project which should not only comprehensively research factors such as landforms, vegetation, water bodies, etc., but also take into account ecology, function, reasonable engineering workload, aesthetic requirements, etc.

Traditional road planning relies on the engineers' analysis of factors such as the landforms of the line selection area, etc., based on calculations and plotting of the road plan on relief maps of relatively large scale. Based on the drawing schemes, road engineers carry out field surveys, lay off section by section, make repeated comparisons, and then determine a rela-

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tively economical and reasonable scheme. Artificial line selection not only requires road engineers to have abundant practical experience and technical skill, but also is time consuming and laborious, and the economic efficiency and rationality of line selection can only be based on approximation, and is contingent on the different experience, skill levels and methods of the planning team. Newer technologies like aerial surveying, use of computers and information technology, etc. are more effective than traditional methods for road planning, which reached a new level in 1958 when Professor Charles Leslie Miller of Massachusetts Institute of Technology proposed the Digital Terrain Model (DTM) in order to realize the automation of the highway line selection process [2].

With regard to road planning for a scenic environment, this research employs the integrated cost and shortest path algorithm model, based on spatial optimum path simulation and calculation using a digital elevation model (DEM) with GIS grid data and adjacency relationships to research restrictive conditions like slope classification expense, maximum slope length, maximum vertical slope and line selection scope, etc., and calculate the optimum path using the shortest path analysis tool and applying a cost grid matrix [3]. The advantages of this model are firstly that the algorithm based on an integrated cost chart meets the basic requirements of landscaped roads in earthwork, vertical slope, linear type, etc., and meanwhile effectively detours restrictive regions like ecologically-sensitive areas, areas of dense runoff, etc.; secondly, through evaluation, this model converts various factors affecting line selection into a basic “cost” map, taking the results of early-stage analysis on the planning and design of landscaped parks like ecologically-sensitive areas, etc., and converting them into a basic chart of factors affecting line selection; and finally, the model is simple and extremely easy to implement.

2 Algorithm Selection: Road Planning Algorithm Based on an ArcGIS Platform

GIS spatial data analysis is mainly based on two models, namely grid and vector. Road planning uses the distance tool in ArcGIS, with calculation and analysis based on the grid model using the three algorithms of cost distance, path distance and cost path [4], wherein, “cost distance” and “path distance” have basically the same arithmetic logic. This paper selects “path distance algorithm” and “cost path algorithm” as the basic algorithms for road planning for a scenic environment, and the reasons for this choice will be stated in detail hereafter.

2.1 Comparison of Cost Distance Algorithm and Path Distance Algorithm

The word “distance” expresses the degree of proximity between two physical objects, and in spatial analysis, distance includes not only the straight line distance between two points, but also the “resistance” or “expense” for moving from one point to another point, creating a functional relationship of the distance between two points. In the GIS line selection algorithm, the concept of “cost” is specific and not limited to “value measured with currency”: “cost distance” indicates the “cost” or “expense” incurred by moving from one point in space to another, and adds a weighted function of cost distance to the calculation. To take walking as an example, it is easier to walk on a trail in a park than on a muddy road in the countryside, because even though the straight-line distance is the same, the resistance encountered will be different. Cost Distance Algorithm, based on the weighted function of cost distance, could calculate and obtain from every grid the minimum cumulative cost for going the shortest distance at the lowest cost, and thus obtain the cost direction data and cost distribution data, whereby the cost direction data shows the path of the minimum cumulative cost between two points.

Comparatively speaking, both the path distance algorithm and the cost distance algorithm could be used to calculate the minimum cumulative travel cost for going between two points on the surface of a grid. However, the path distance algorithm can take into account more complicated factors such as horizontal and vertical dimensions to yield actual distance moved. When driving a car, the friction of the road surface and wind resistance will affect the movement, and as the road surface rises and falls, the actual distance travelled is greater than the straight-line distance between two points [5]. Compared with the cost distance algorithm, the path distance algorithm can incorporate rises and falls in the landform and slopes as parameters to the computing process, so it is more suitable for road planning for a scenic environment (Table 1).

Table 1: Comparison of Parameters in the Cost Distance Algorithm and Path Distance Algorithm

Parameters		Cost Distance Algorithm	Path Distance Algorithm
Influential Factors		√	√
Classification		√	√
Hierarchical Assignment		√	√
Road Nodes	**Starting Point**	√	√
	Ending Point	√	√
	Middle Point	√	√
Surface Grid		×	√
Vertical Coefficient	**Vertical Grid**	×	√
	Vertical Coefficient Angle	×	√
	SLOPE VALUE	×	√

Among path distance algorithm, the most important parameter is the elevation grid, which determines the actual surface distance from one point to another one through the calculation of the surface grid. Compared with plane ("straight-line") distance, actual surface distance corresponds more accurately to the movement of people or cars in a scenic environment where the more uneven the surface is, the greater the travel distance will be; the greater the distance, the higher the cost incurred; and where tracts of land with excessive rises and falls of terrain are not suitable for the construction of roads. Another important parameter is vertical coefficient, which reflects the relationship between a slope and movement resistance where the greater the vertical coefficient, the steeper the slope and the higher the resistance to movement. According to the requirements of road design, a vertical slope designed for landscaped roads should be relatively broad in comparison with urban roads and highways. Nevertheless, land sections with a slope greater than 30 % are still not suitable for construction, and this parameter will be reflected through the vertical coefficient. Figure 1 reflects the comparison of functional relations of linear symmetry between the Vertical coefficient (VF) and vertical relative movement angle (VRMA) when the cutting angle is ±90° and the SLOPE (modified slope) is respectively 1/90(0.01111), 1/45(0.02222) and 1/30(0.03333). For road planning for a scenic environment, both up-slope and down-slope are embodied as slope, namely the angle between landform and horizontal plane, is a necessary factor in calculating the cost of vertical movement, the linear symmetry function is adopted for computing. Because areas with a slope of greater than 30 % are not suitable for construction, the cutting angle is limited to ±30°, implying that the degree of difficulty in moving in areas with a slope of more than 30° tends to be unlimited.

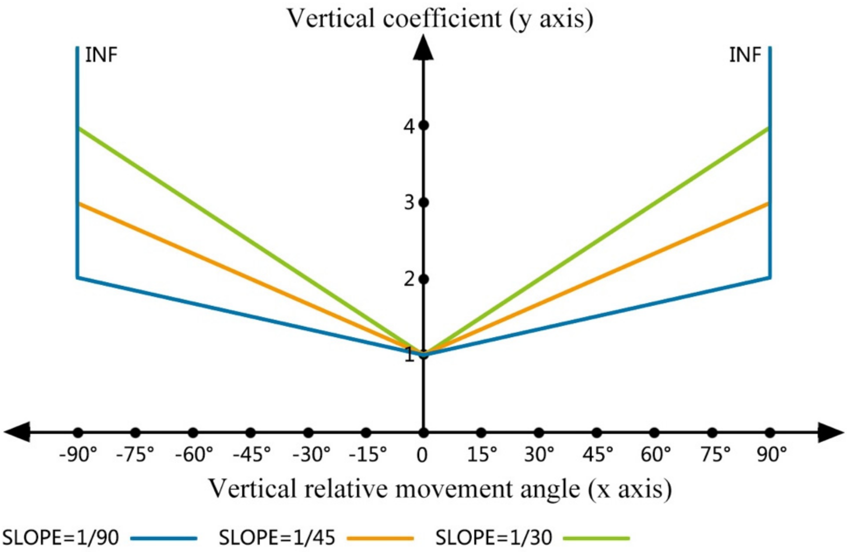

Fig. 1: Vertical coefficient chart of symmetry linear functions corresponding to different SLOPE values (vertical parameter angle = ±90°)

2.2 Cost Path Algorithm

Both cost distance and path distance algorithms calculate the minimum cumulative travel cost from one point to another on the surface of a grid. The Dijkstra algorithm is adopted to establish the shortest path in ArcGIS, and therefore the calculation of cost path is to obtain the minimum cost from a single starting point or a group of points to a single destination or group of destinations through the shortest path function. The “shortest path” in ArcGIS indicates not only “the shortest straight line”, but with “cost” added the “shortest path” with the minimum “cost”. However, based on calculation alone cost path line selection algorithms cannot meet the actual situations of scenic environments, and it is therefore necessary to pertinently adjust and optimize the line selection parameters based on existing algorithms and taking into account the individual characteristics of the roads in a scenic environment.

3 Model Building: Building a Model of Road Planning for Scenic Environments

The road planning model (Figure 2) for landscape planning and design is constructed based on cost distance or path distance algorithms and the cost path algorithm. Consistent with the sequence in which the two algorithms compute, the model is divided into two parameterized computing sections and a final man-machine interaction section, as follows: calculation of integrated cost, generation of optimum path, and screening and optimization of path. Firstly, the calculation of integrated cost includes three processes, i. e. selection of critical factors, allocation of factor weighting, and superposed analysis of factors. These three processes are completed in GIS, and the integrated cost chart obtained will be input as a parameter to the next computing stage. Secondly, at the cost path computing stage, the road nodes and integrated cost chart are input as parameters, and the primary optimum line selection is obtained through the shortest path analysis according to given conditions. Finally, the lines initially selected are screened out and optimized through man-machine interface to eliminate unreasonable paths and obtain a final road plan.

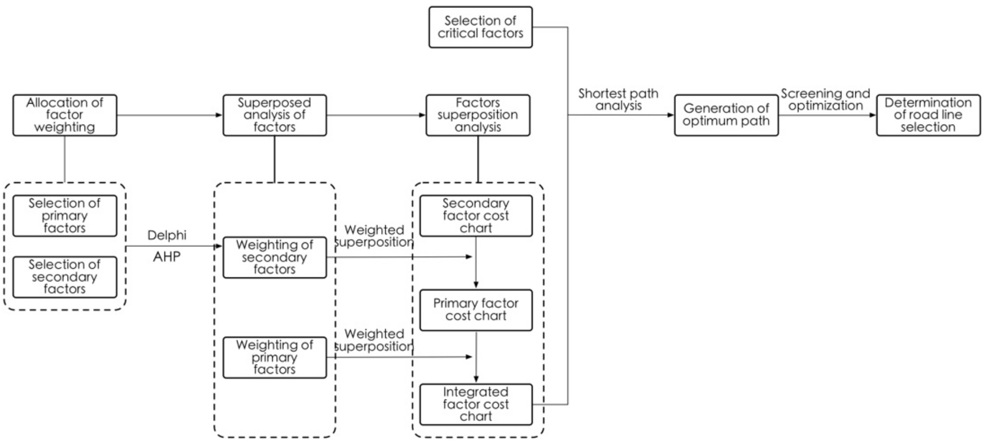

Fig. 2: Road planning model for parameterized landscape planning and design

3.1 Selection of Critical Factors

There are many complicated factors affecting road planning which vary according to different situations and regions requiring different planning and design solutions, and it is necessary to determine the critical factors affecting the designated site. Under most circumstances, the conditions to be satisfied by road planning are threefold: first, the control point factor, which includes the starting, end, and mid-point that the line must pass, and thus determines the length of route; the second type of factors are geographical, such as topography and landforms, hydrological and other conditions, etc.; and the third type are restrictive factors, which in landscape planning and design include not only ecologically-sensitive areas, but also reserved surface features like buildings, infrastructure, vegetation, etc.

3.2 Determination of Factor Weighting

In road planning for a landscaped environment, slope, undulation, ecologically-sensitive areas, and catchment areas, etc. are all factors to be considered, and so become “costs” of road construction. Table 2 shows the critical factors involved in road planning generally. After determination of critical factors, the Delphi method and AHP (analytic hierarchy process) are adopted to judge the weighting of factors. At different sites, the critical factors of road planning and the weighting of such factors differ: generally, the decisive factors such as the slope, undulation, etc., have a relatively high weighting. In scenic environments, some roads are allowed to pass through water bodies, to enrich the spatial hierarchy with bridges and thus to provide different travel experiences for tourists, so the factored weighting of water bodies is not too great. Undoubtedly, road construction based on existing roads and infrastructure will involve relatively low costs and have relatively low impact on the environment, but if the weighting of the two factors is too high, the correctness of line selection will be affected to a certain degree. The weighting of factors, as an important parameter for the generation of an integrated cost chart, has a direct effect on the rationality of the whole line selection, and unreasonable weighting values will detract from the effectiveness of line selection, so correct appraisal of each factor is necessary. Meanwhile, analysis is conducted based on primary line selection, and if the lines first selected prove unreasonable, it will be necessary to re-calculate the integrated cost chart and re-allocate the weighting of each factor.

Table 2: Factors affecting road planning for scenic environments and the weighting table

<table>
<tr><th>Evaluation Objects</th><th>Primary Evaluation Factors</th><th>Weighting</th><th>Secondary Evaluation Factors</th><th>Weighting</th></tr>
<tr><td rowspan="9">Critical factors for road line selection in scenic environ-ment</td><td rowspan="3">Topography and landforms</td><td rowspan="3">W1</td><td>Elevation</td><td>W11</td></tr>
<tr><td>Slope</td><td>W12</td></tr>
<tr><td>Undulation</td><td>W13</td></tr>
<tr><td rowspan="3">Hydrological conditions</td><td rowspan="3">W2</td><td>Water body</td><td>W21</td></tr>
<tr><td>Catchment area</td><td>W22</td></tr>
<tr><td>Runoff area</td><td>W23</td></tr>
<tr><td>Ecologically-sensitive area</td><td>W3</td><td>–</td><td>–</td></tr>
<tr><td rowspan="2">LAND USE</td><td rowspan="2">W4</td><td>Current road</td><td>W41</td></tr>
<tr><td>Reserved facilities</td><td>W42</td></tr>
</table>

3.3 Superposed Analysis of Factors

Based on the determination of the weighting of each critical factor, ArcGIS software is used to non-dimensionalize, reclassify and uniformly assign all factors into a single evaluation system for superposition. Reclassification charts are superposed to obtain the integrated cost chart, which is the basic drawing for line selection. The integrated cost classification is consistent with the classification of each factor, so the classification and assignment of factors will directly affect integrated cost. Classification determines the hierarchical standard of integrated cost, so the richer the hierarchy, the greater the cost "value", and hence according to the algorithmic calculation rules the corresponding line selection results will be more accurate. The above analysis shows that the selection of critical factors, the judgment of factor weighting, and the classification of single factors will determine the selection of the optimum path.

3.4 Selection of Road Nodes

Road nodes indicate the starting, ending, and mid-points that a road must pass. The road nodes and the integrated cost chart generated at the last stage will be the input parameters to cost distance, path distance and cost path. Scenic environments are mostly areas of medium to large size, so the road system is generally a network with multiple access points to facilitate traffic movement in a manner significantly different from that of general urban roads and highways.

Firstly, to determine the starting point and ending point of roads, a starting point will be input as a parameter to a cost distance or path distance algorithm. The exits and entrances of a designated area are set as starting points and taken as the converting nodes for external and internal traffic connections. Where there are multiple entrances and exits, the main entrance will certainly be taken as the starting point, with additional entrances and exits as auxiliary starting points. Given the characteristic network of roads in scenic environments, there is no ending point in a general sense. The positioning of other projects related to the site development will be connected by road, so it may be considered that the projects are linked with the starting point of the road and taken as "ending points" for purposes of line selection. The cost path tool supports the input of single or multiple sources as parameters, so all projects can be input as multiple sources, and supplementary points on the path will be treated as ending points together with project nodes. For example, if the line selected does not pass by one side of an escarpment, but the scenery at that location is outstanding, and the plan incorporates guiding tourists here for sightseeing experiences, it will be possible to add the location as a supplementary point according to circumstances.

3.5 Cost Distance Analysis

By inputting an integrated cost chart and road starting points as parameters into the cost distance tool, we may obtain drawings of cost-weighed distance and cost-weighted direction related to the starting point, indicating the cumulative cost of moving from each point to the position of the nearest source, and the direction from each point in the cost distance grid to the source. Compared with cost distance, the path distance tool requires the input of more parameters such as surface grid, angle restriction values in relation to the calculation of Vertical coefficients, SLOPE value, etc. These input parameters will be helpful to further stipulate the line selection path according to landscape planning and design requirements.

3.6 Optimum Route Generation

According to the number of ending points input, the optimum route generated is calculated as the optimum path between two points and among multiple points. Features including landscape and building nodes are connected with the main entrance, with partial access to secondary entrances. There are generally more than one construction features, and if the sequence of nodes in line selection is determined artificially, and the optimum path between two points is calculated subsequently, the path obtained from line selection will be artificially biased. In addition, the workload corresponding to the full-area road network generated from the operation will be excessive, and in large-scale scenic areas numerous road nodes will be involved, thus it is difficult to generate a road network based only on two-point line selection. Therefore, the paper adopts multiple points for simultaneous calculation, which not only satisfies a logical traffic relationship between project nodes and entrances & exits, but also facilitates the formation of an internal road network. Every project node will generate a path leading to the starting point so the number of projects determines the number of paths, and correspondingly to the density of the road network formed.

3.7 Path Screening and Optimization

Since the line selection paths output through algorithms under the existing calculation methods and conditions do not completely meet the requirements of the final road network pattern, it is necessary to carry out artificial screening and optimization, eliminate redundant paths and optimize the alignment. In order to make roads looped, some nodes must have direct connections with more than two other nodes simultaneously; and since single line selection and calculation will only establish the connection between two points, it is necessary to carry out the calculation multiple times. The output of the cost path algorithm consists of continuous grids, and after vector output the alignment can be optimized with tools such as “smooth line”, which in combination with artificial methods can be used to generate the final road alignment.

4 Practical Case: Road Planning for Niushou Mountain Scenic Spot in Nanjing

A scenic environment normally includes several scenic spots, so one problem for the road planner is line selection at multiple points. In order to avoid excessive workloads and the interference of bias, this paper proposes a “‘1+N’ multi-point and multi-time line selection method” of road planning for scenic environments, simultaneously taking multiple points as the end points of line selections, forming parameters, and inputting them at one stroke for calculating line selection. In Planning for the North Area of Niushou Mountain Scenic Spot in Nanjing, the author selected a “path distance” algorithm and “cost distance” algorithm, based on the “‘1+N’ multi-point and multi-time line selection method” to illustrate the application of the model of parameterized road planning for a scenic environment.

In order to meet the requirements of vehicle driving and road grading, road construction sets specific requirements for the vertical slope of a route. When the slope of a landform exceeds certain limits, corresponding engineering measures must be adopted to reconstruct the earthwork which will not only raise the construction cost but also greatly disturb the original environment. Landform undulation, which is the maximum relative elevation difference within a unit area, reflects the relative height differences of the ground as a quantitative index describing topography and landforms. Higher undulation in an area reflects relatively greater changes in elevation, and excessive frequency of rising and falling of the road will lower the comfort of travel and induce relatively high construction costs. In addition, where the planned area includes natural water bodies, the construction cost for roads to cross water surfaces will be relatively high, so such situations should be avoided as much as possible; moreover, seasonal rises and falls of water levels in rivers, lakes, etc. will greatly affect areas adjacent to water, where road foundations will be affected by possible inundation, so road construction should be kept at a certain distance from water areas. The critical factors for road planning in the North Area of Niushou Mountain Scenic Spot in Nanjing include slope, water areas, and undulation.

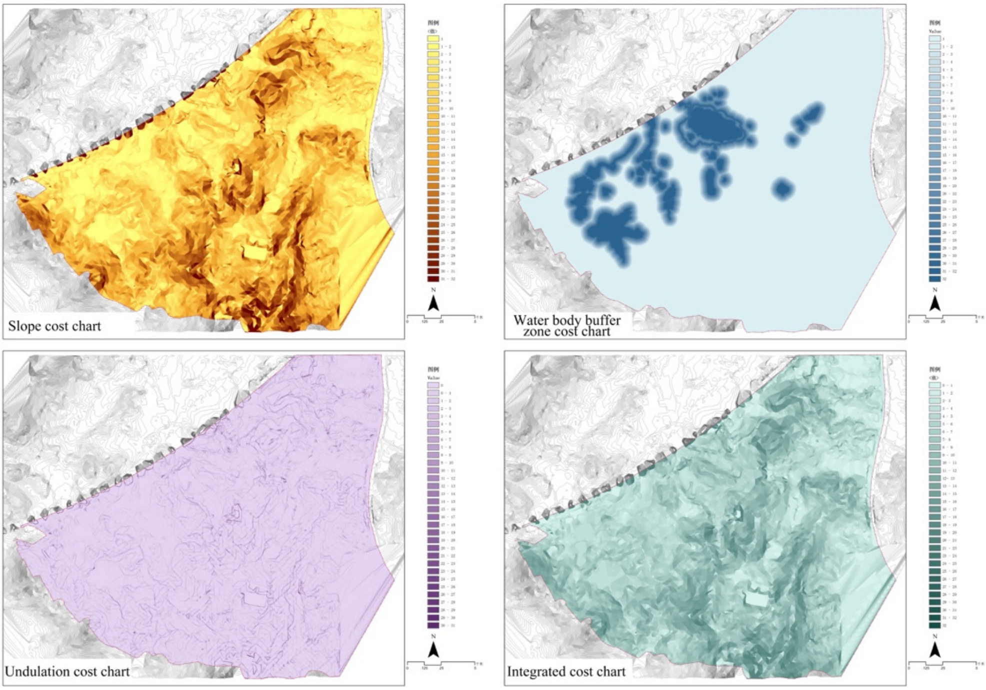

Fig. 3: Generation of integrated cost chart

Firstly, the Delphi method and AHP (analytic hierarchy process) are adopted to determine the weighting of the above critical factors; secondly, the GIS software reclassification function is used to non-dimensionalize and assign each factor; and finally, superposed analysis is conducted to obtain the integrated cost chart (Figure 3). In a scenic environment, landscape nodes need to be connected in series by the road network for the access of tourists, so these nodes all are connected with the road network and become the “control points”, i. e. the starting, mid- and ending points of roads. According to the master plan and project orientation there are multiple entrances and exists to this area, and it should be possible to enter any landscape node smoothly from the main entrance; therefore, the road planning model in this paper inputs the location of the main entrance of this area as starting point parameter, and takes the other landscape nodes as “mid-point” and “end point” parameters. Adopting the path distance algorithms, the parameters are as shown in Table 3, with the path selection result shown in Figure 4. The line selected, as calculated with the grid chart, is a fold line, and since it cannot be taken as the actual line selection, it is necessary to curve the line to meet the requirements of road design. This paper curves the line selected by means of the ArcGIS tool, executes artificial screening and optimization of unreasonable sections, and thus obtains the final line selected. Based on the generation of all road network paths, this paper separates the primary and secondary roads and takes the line selection path as the main road. Finally, through plotting and adjustment with CAD software, this paper obtains the road network for the whole designed area (Figure 5).

Table 3: Parameters for road planning in the North Area of Niushou Mountain Scenic Spot

Parameters		Path Distance Algorithm
Influential Factors		Slope, water areas, undulation
Classification		32
Hierarchical Assignment		Equally separated
Road Nodes	**Starting Point**	2
	Ending Point & Middle Point	38
Surface Grid		Elevation
Vertical Coefficients	**Vertical Grid**	Elevation
	Vertical Coefficient Angle	±30
	SLOPE Value	0.03333

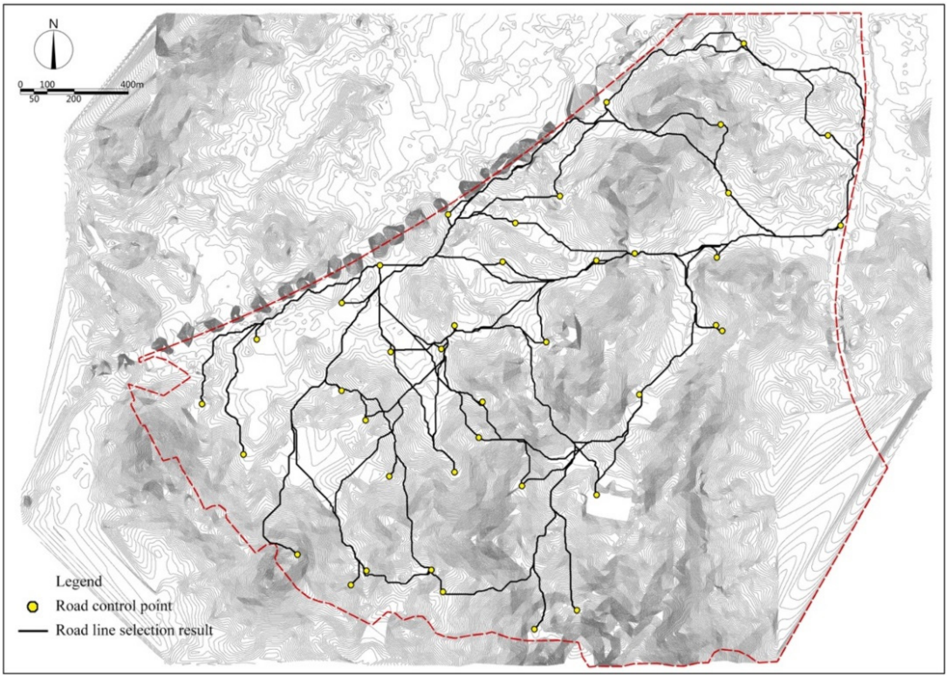

Fig. 4: Result of Road Planning

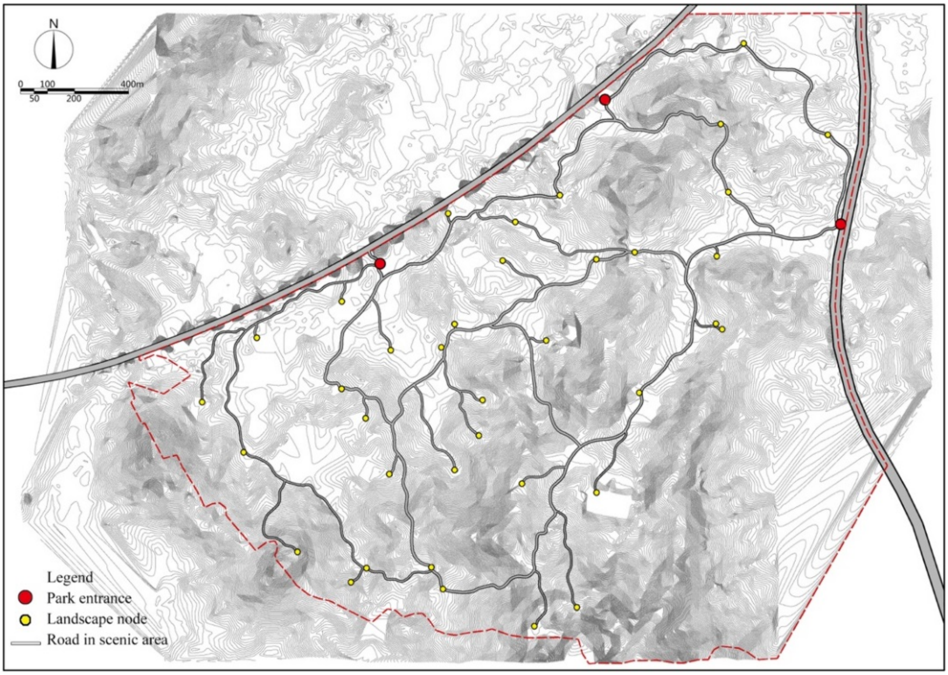

Fig. 5: Final Road Network Generated

5 Conclusion and Outlook

Besides slope, water area and waviness, and other facts affecting road planning, as exhibited in the case study of this paper, ecological sensitive area, characteristic landscape protection area, and other ecological and aesthetic elements, etc. could all become the factors affecting road planning according to the characteristics of different scenic environments, and they could be converted into "cost diagram" and participate in the computing of algorithms, and make the results of road planning more accurate and reasonable.

Science and technology have made great contributions to the advancement of theory and practice in landscape architecture, and parameterized road planning for scenic environments is more scientific, accurate and efficient in comparison with the traditional methods of line selection based solely on experience. Without the subjectivity, randomness and fuzziness of traditional methods, line selection based on computer technology makes the design process precise and controllable through the introduction of parameters, and not only takes account of multiple design objectives simultaneously, but also realizes road planning "adapting to local conditions" according to different scenic environments.

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