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POWER LINE PATH SELECTION METHOD CONSIDERING MULTIPLE INFLUENCING FACTORS

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Abstract. The paper proposes an electric power line path selection method that integrates multiple influencing factors. The method includes factor selection, standardization, weighting, cost construction, corridor planning and path planning. The paper analyzes these processes and introduces a combined weighting method based on principal component analysis and analytic hierarchy process. The spatial cost is constructed on each gird cell. This model uses the quadtree partitioning method as the basic spatial segmentation approach for surface cost model construction. This method is appropriate for the region of significant terrain variation. After the surface cost model is obtained, the Dijkstra algorithm is applied for the corridor planning and the A^* algorithm is employed for optimization of power line path.

1. Introduction

The primary task in designing high-voltage overhead transmission lines is to carry out path planning [24, 25]. Currently, the path planning methods have developed from the computer-assisted routing stage to the computer-automated routing stage [21]. In the computer-assisted routing stage, the basic process for power line routing based on geospatial data [16, 20]. By overlaying image data with digital elevation models and utilizing computer visualization techniques or stereographic mapping technologies, the field scenario of the selected path is reproduced in three dimensions. With the 3D visualization scene, the transmission line path is determined through human-computer interaction [6, 27], upon the given start and end points of the path. However, the above method is objective, and many potential factors cannot be considered properly and quantitatively. To address the challenges, researchers have proposed the method of automated computer-assisted path selection, which is a transmission line routing method based on gird cells [11].

Murta [3] was one of the early researchers to study the path planning problem for transmission lines. He categorized the influencing factors into three types: natural, social, and technical, and assessed the relative importance of each factor in power line routing. He constructed a surface cost model and conducted optimal path analysis on it. Warntz [26] proposed cumulative surface cost to find the shortest path from a starting point to multiple target points during path planning. Monteiro et al. [17, 18] applied dynamic programming algorithms to generate cumulative surface

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cost and then selected transmission lines and economical corridors. Eroglu et al. [5] used genetic algorithms to optimize the transmission line paths, offering several path options to the designers. Shu et al. [22] proposed a method for transmission line path optimization and evaluation using a gird cell from GIS environment. Bagli et al. [2] found that slightly altering the positions of the start or end points on the cost surface during path planning could lead to completely different paths. This suggests that planners should consider using multiple potential starting and ending positions to generate several alternative paths and select the optimal one. Gancalves [9] researched how to plan wide paths on a surface cost model, expanding on the least-cost path modeling method in GIS, which enables the planning of paths with a specified width. Ahmadi et al. [1] argued that evaluating a path based solely on its cost was inadequate since there is no direct relationship between path length and the cost values of influencing factors. They proposed a minimum average algorithm that considers path length as a separate factor to ensure both low costs and short paths. Jewell et al. [8, 12] proposed a method to facilitate public participation in power line routing, ensuring both professional planning and public awareness, which shortened the approval time [10, 28].

This study explores how to comprehensively consider multiple sub-factors by combining the principal component analysis and analytic hierarchy process (PCA-AHP). These sub-factors can be categorized into four different types and their weights are further used to construct the spatial cost for each girder cell. The quadtree method is utilized to ensure each cell has its homogeneous attribute. Finally, the Dijkstra algorithm is applied to obtain the appropriate power corridors first. Subsequently, the A^* algorithm is employed on the selected corridor to obtain the optimization of power line path.

2. The process of power line routing

The theoretical foundation of power line routing is the cost distance analysis of continuous space. Cost distance refers to the cost incurred when a path passes through different grid cells. Cost distance analysis evaluates the spatial relationship between each grid cell and the source (destination) based on the distance from each grid cell to the source [15].

Cost distance analysis is primarily calculated using cost distance weighting methods and directional data. Figure 1(a) illustrates the cost distance weighting data passing each grid cell. Figure 1(b) represents the path direction from each cell along the least accumulated cost path to the nearest source. The direction value ranging from 1 to 8 is explained in Figure 1(c).

Distance direction data indicates the direction of the path from each grid cell to the source along the path of the lowest cumulative cost. For example, Figure 1(b) shows that the direction of the lowest cost path from a grid cell with a cost value of 912 to the source is southwest (4 in Figure 1(c)).

2.1. Multi-Criteria Decision-Making Process.

Multi-Criteria Decision-Making Process. Power line routing is a Spatial Multicriteria Decision Making (SMCDM) problem. Its first feature is that multiple

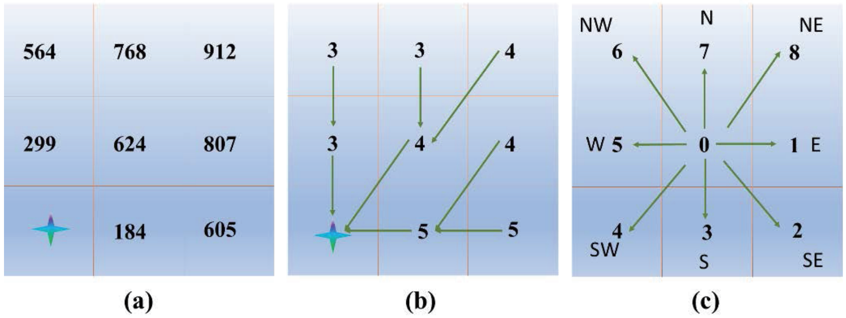

FIGURE 1. Cost distance weighted data and direction data diagram.

influencing factors should be considered in the decision-making process. For example, when planning transmission lines, factors such as slope, distance, geology, environment, traffic conditions, and technology need to be considered. The second feature is that these factors are not commensurable, meaning there is no unified standard for comparison. For instance, the slope is measured in degrees, distance in kilometers, and geological conditions are typically expressed qualitatively as excellent, good, or poor. These factors have different meanings and lack a common unit of measurement. The third feature is that there is a degree of conflict between the factors. Emphasizing one factor may lead to the inability to meet others.

Due to the conflicts and incommensurability between the multiple influencing factors in multicriteria decision-making problems, SMCDM methods aim to achieve optimal coordination of these interrelated and interdependent factors to arrive at the best decision. SMCDM integrates multicriteria decision-making with GIS to solve spatial decision-making problems. It is a process that combines and transforms geographic data and evaluation criteria to obtain decision results [22]. Based on the framework of multicriteria decision analysis proposed by Malczewski [14] Chen et al. [13] analyzed the process of spatial multicriteria decision-making, which consists of six stages: defining the decision problem, establishing the evaluation criteria system, quantifying and standardizing the criteria, determining the weights, multicriteria aggregation, and decision result analysis. This process is illustrated in Figure 2. The following sections provide an explanation of each stage.

2.2. **General Power Line Routing Methods.** Based on the spatial multicriteria decision-making process and the cost distance analysis method in continuous space, this paper proposes a general method for power line routing. The main point is that the PCA-AHP method is adopted to determine the weights of sub-factors. Furthermore, to reduce the calculation time for path selection, corridor planning is firstly performed. The process of this method is shown in Figure 3.

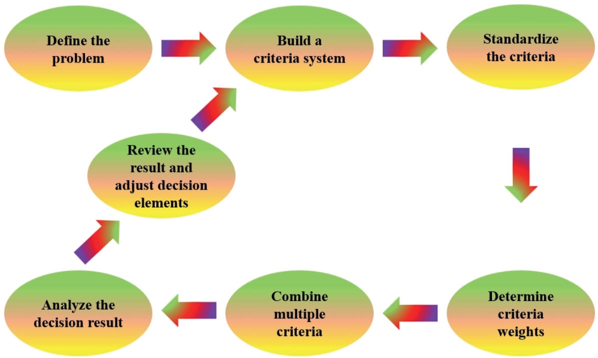

FIGURE 2. Spatial Multi-Criteria Decision-Making Process.

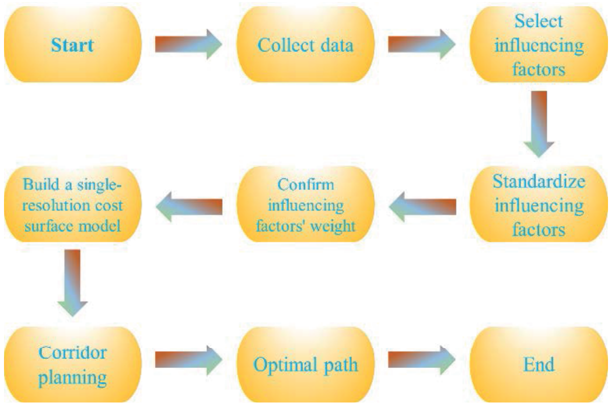

FIGURE 3. General Power Line Routing Process.

3. POWER LINE PATH SELECTION METHOD INTEGRATES MULTIPLE INFLUENCING FACTORS

3.1. **Influencing Factors.** Transmission lines have distinct geographical characteristics, and their path planning is easily influenced by various factors, such as the length of the line, geological conditions, terrain, construction convenience, pollution level (polluted areas), and ice zones. In power line routing, the first issue to address is determining the influencing factors to consider and establishing a reasonable indicator system.

In this study, the multiple sub-factors are categorized into the four main factors, and they are: natural environmental factors, engineering factors, restricted zones, socioeconomic factors, see Figure 4.

3.2. **Standardization.** The Delphi method [4] is adopted in this study to standardize the multiple sub-factors. This method relies on consulting experts on these factors. For a specific sub-factor, an expert can evaluate its effect on the power

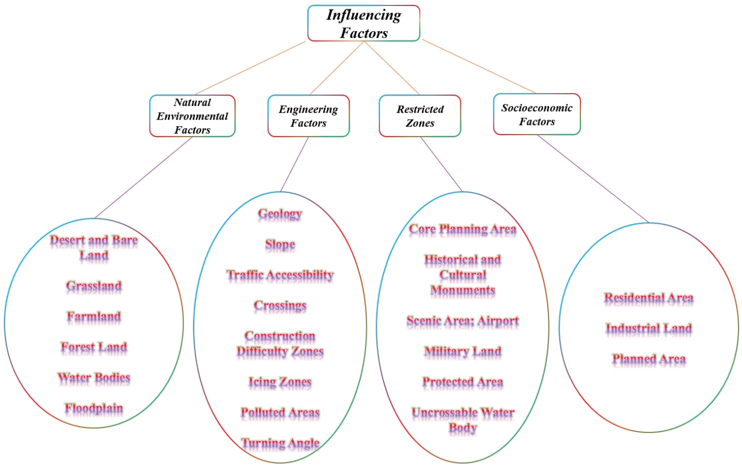

FIGURE 4. Influence Factor Diagram.

line selection according the Figure 5. The values "1" and "9" means the most appropriate and the most inappropriate conditions for the power line.

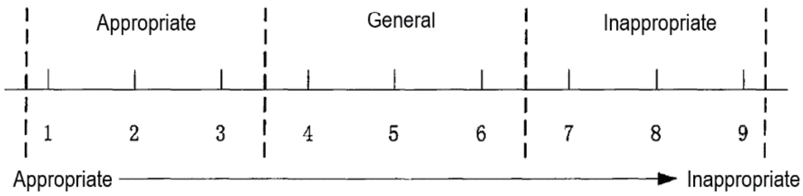

FIGURE 5. The values required in the Delphi method.

3.3. **Obtaining weights for sub-factor by PCA-AHP method.** Conventional Analytic Hierarchy Process (AHP) method would introduce the subjective opinions to determine the weights for these sub-factors. In this study, we combine the Principal Component Analysis and Analytic Hierarchy Process to form the so-called "PCA-AHP" method.

Supposing there are experts commenting on sub-factors, with the Delphi method. Hence, we obtain the sampling matrix as:

$$X = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}. \tag{3.1}$$

The covariance matrix Σ of the sampling matrix X is calculated as:

$$\Sigma = E\left(X - E(X)\right)\left(X - E(X)\right)' \tag{3.2}$$

where $E(X)$ is the expectation of the matrix X

The principal values and corresponding principal vectors (also principal components) of the covariance matrix Σ is obtained as: $\lambda_1 \geq \lambda_2 \geq \cdots \geq \lambda_n$ and Y_1, $Y_2 ... Y_n$. The contribute rate of the i-th principal component Y_i, denoted as η_i, is evaluated as:

$$\eta_i = \frac{\lambda_i}{\sum_{s=1}^{n} \lambda_s}. \tag{3.3}$$

The first h principal values are selected to satisfy:

$$\eta_h = \frac{\sum_{i=1}^{h} \lambda_i}{\sum_{s=1}^{n} \lambda_s} \geqslant 0.85. \tag{3.4}$$

Consequently, the comprehensive evaluation matrix F is constructed as:

$$F = \eta_1 Y_1 + \eta_2 Y_2 + ... + \eta_h Y_h. \tag{3.5}$$

The evaluation matrix F reflect the subjectivity of the sampling matrix X, and it can lead to the subjective judgment matrix B^{sub} as:

$$B^{sub} = \begin{bmatrix} lb_{11}^{sub} & b_{12}^{sub} & ... & b_{1m}^{sub} \\ b_{21}^{sub} & b_{22}^{sub} & ... & b_{21}^{sub} \\ ... & ... & ... & ... \\ b_{m1}^{sub} & b_{m2}^{sub} & ... & b_{mm}^{sub} \end{bmatrix} = \begin{bmatrix} l1 & f_1/f_2 & ... & f_1/f_m \\ f_2/f_1 & 1 & ... & f_2/f_m \\ ... & ... & ... & ... \\ f_m/f_1 & f_m/f_2 & ... & 1 \end{bmatrix} \tag{3.6}$$

where f_i represents the i-th element in the evaluation matrix $F (i = 1, 2, \ldots, m)$.

On the other hand, the objective judgment matrix B^{obj} is constructed as:

$$B^{obj} = \begin{bmatrix} lb_{11}^{obj} & b_{12}^{obj} & ... & b_{1m}^{obj} \\ b_{21}^{obj} & b_{22}^{obj} & ... & b_{21}^{obj} \\ ... & ... & ... & ... \\ b_{m1}^{obj} & b_{m2}^{obj} & ... & b_{mm}^{obj} \end{bmatrix} \tag{3.7}$$

where the element $b_{ij}^{'}$ $(i, j, = 1, 2, \ldots, m)$ in B^{obj} represents the comparative importance between the i-th sub-factor and j-th sub-vector, and satisfies $b_{ij}^{'} = 1/b_{ji}^{'}$. The element $b_{ij}^{'}$ is quantified according to Table 1.

Table 1. Determination of element $b_{ij}^{'}$ in objective judgment matrix B^{obj}.

	Meaning			
The importance of the i -th sub-factor over the j -th sub-vector ($b_{ij}^{'}$)	1	Equally important	7	Strongly important
	3	Slightly important	9	Extremely important
	5	Apparently important	2,4,6,8	Between above values

After obtaining the subjective judgment matrix B^{sub} and the objective judgment matrix B^{obj}, we can construct the comprehensive judgment matrix B^{com}. Its element can be computed from:

$$b_{ij}^{com} = \sqrt{b_{ij}^{sub} \times b_{ij}^{obj}}. \tag{3.8}$$

Finally, the principal vector $\boldsymbol{\omega}$, corresponding to the maximum principal value $\lambda_{\max}^{com}$, of the comprehensive judgment matrix B^{com} is calculated as:

$$B^{com}\boldsymbol{\omega} = \lambda_{\max}^{com}\boldsymbol{\omega}. \tag{3.9}$$

It is notice that normalization of the principal vector $\boldsymbol{\omega}$ should be performed. The i-th element ω_i $(i = 1, 2, \ldots, m)$ in the normalized vector $\boldsymbol{\omega}$ is the weight, obtained from PCA-AHP method, for the i-th sub-factor.

3.4. **Spatial cost for grid cells.** After standardization of the sub-factors and obtaining their corresponding weights, the spatial cost of the grid cell C is the last variable to be obtained before optimizing the power line path. The spatial cost of a specified grid cell stands for the cost moving form the cell to the neighboring cells.

In this study, the spatial cost C is related to the sub-factors of terrain C_{terr} and other sub-factors C_{other}, as

$$C = C_{terr} + C_{other}. \tag{3.10}$$

The terrain cost C_{terr} is only related to the slop, as:

$$C_{terr} = \omega_{slope} \cdot f_{slope} \tag{3.11}$$

where ω_{slope} and f_{slope} are the weight of the slop and its value.

The other non-terrain sub-factor cost C_{other} is evaluated as:

$$C_{other} = \sum_{i=1}^{K} \omega_i \cdot f_i \tag{3.12}$$

where K is the number of non-terrain sub-factors.

For the grid cell where the slop of terrain varies drastically, the quadtree subdivision is adopted as the spatial subdivision method for surface cost model construction. The quadtree subdivision method successively divides a coarser cell into four equal sub-cells, until each sub-cell owns its unique attribute. Figure 6a shows an 8×8 cells with three attributes, and Figure 6(b) illustrates its corresponding quadtree. It can be seen that the process treats a continuous region as a root node. If the region's properties are inconsistent, it is divided into four subregions (NW, NE, SE, SW), and the process is repeated for all subregions until they all have consistent properties.

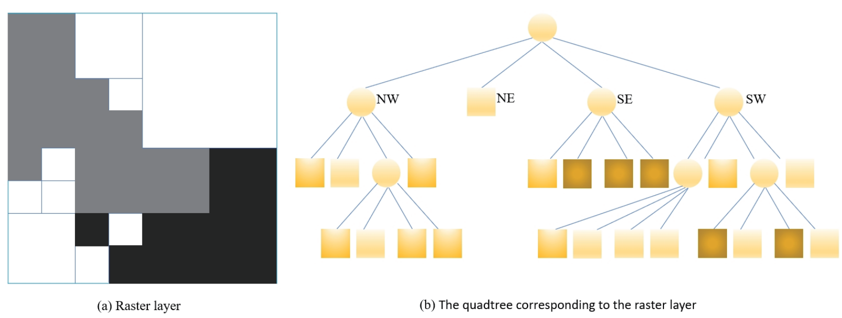

FIGURE 6. Quadtree Segmentation.

3.5. **Power path optimization.** In this paper, the Dijkstra algorithm [19] is employed during the corridor planning stage. During the iterative process of the Dijkstra algorithm, all node labels are treated as temporary labels. In each iteration, only the temporary labels are revised once. It is only when all iterations are completed that the labels of all nodes are simultaneously converted into permanent labels, allowing for the determination of the shortest path from the starting point to any given point.

This paper will employ a heuristic search algorithm for the path planning phase. Common heuristic search algorithms include branch and bound methods, the A^* algorithm, bidirectional search, subgoal methods, and hierarchical algorithms.

The estimated total length of the transmission line and the straight-line distance between the start and end points are used as a constraint in the A^* algorithm [23]. This constraint is represented by Eq (3.2). As shown in Figure 7, where the sum of the distances from each point on the ellipse to the start and end points does not exceed a multiple of l_{min} noted as ϕ.The total length l consists of two parts: the actual distance from the start point to the current node, denoted as l_1, and the estimated distance from the current node to the endpoint denoted as l_2. The parameter ϕ represents the ratio between l and l_{min}, its typical range is $(1, 1.5]$ [7].

$$l = l_1 + l_2 \leqslant \varphi l_{\min}. \tag{3.13}$$

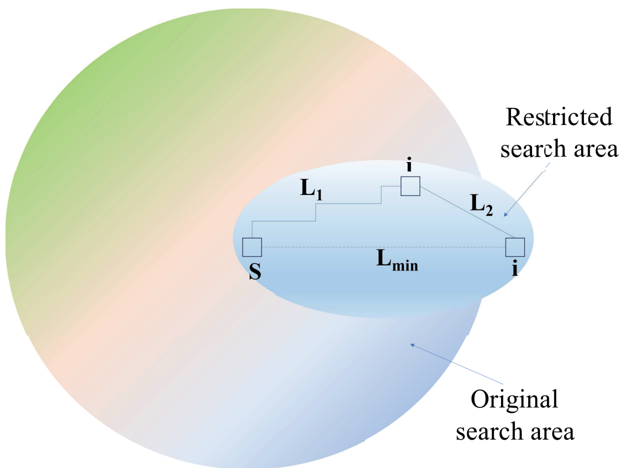

FIGURE 7. Restrict Search Range.

4. CASE STUDY

4.1. **Factor Level Scale.** In this example, the area to be planned is 100km × 100km. The main factors selected are natural environmental factors (NE), and engineering factors (E), and socioeconomic factors (SE). There are totally 10 experts commenting on these factors according to the Delphi method in Sect. 3.2.

The grading details are summarized in Tables 2∼4.

Table 2. Natural environmental factors (NE)

	Expert									
	one	two	three	four	five	six	seven	eight	nine	ten
Water bodies	9	9	8	9	9	7	9	9	9	9
Floodplains	8	9	8	7	8	7	6	7	7	9
Forest land	6	7	7	6	7	6	5	6	5	9
Farmland	4	7	5	3	4	5	3	3	3	4
Grassland	3	2	2	2	3	2	1	1	2	1
Deserts and exposed land	1	1	1	1	2	1	1	1	2	1

Table 3. Socioeconomic factors (SE)

	Expert									
	one	two	three	four	five	six	seven	eight	nine	ten
Residential area	9	9	9	8	9	9	8	9	7	6
Planned area	4	6	3	5	3	6	5	3	3	4
Industrial land	5	6	5	6	4	4	7	7	3	6

Table 4. Engineering factors (E)

	Expert									
	one	two	three	four	five	six	seven	eight	nine	ten
Geology	1	2	3	4	5	6	7	8	9	10
Slope	3	6	5	3	4	2	6	7	6	4
Intersection with traffic lines	3	4	3	3	3	3	4	5	3	3
Ice zone	5	7	8	6	8	7	4	5	6	7
Contaminated area	3	5	5	6	3	4	4	3	2	2
Turning angle	8	9	9	9	9	8	9	9	9	9
Traffic accessibility	4	3	4	4	4	5	4	4	3	3
Construction difficulty zone	4	4	4	3	3	4	2	4	3	4

4.2. **Factor Weight Determination.** Based on Principal Component Analysis (PCA), the principal values and vectors are obtained. For natural environmental factors, the first two principal values are selected ($\lambda_1 = 95.78$, $\lambda_2 = 3.169$), with the cumulative contribution $\eta_p = 0.98$. For socioeconomic factors, the first two principal values are selected ($\lambda_1 = 50.57$, $\lambda_2 = 6.1$), with the cumulative contribution$\eta_p = 0.88$. For engineering factors, the first three principal components are selected ($\lambda_1 = 31.78$, $\lambda_2 = 4.52$, $\lambda_3 = 2.92$, $\eta_p = 0.89$).

Accordingly, the comprehensive evaluation matrices are obtained for the three factors:

$$F_{SE} = [22.7, 10.6, 13.2], \tag{4.1}$$

$$F_{NE} = [26.0, 22.9, 19.4, 12.3, 5.6, 3.5],$$

$$F_E = [12.3, 11.6, 8.0, 6.8, 11.0, 14.9, 8.6, 21.2, 8.9, 8.27].$$

The weights of all these 6, 3 and 8 sub-factors for natural environmental factors, socioeconomic factors and engineering factors are therefore obtained as:

$$\omega_{SE} = [0.63, 0.15, 0.22], \tag{4.2}$$

$$\omega_{NE} = [0.38, 0.25, 0.18, 0.10, 0.05, 0.03],$$

$$\omega_E = [0.11, 0.08, 0.05, 0.04, 0.07, 0.13, 0.060.28, 0.09, 0.59].$$

4.3. **Information Layer Acquisition.** Using the ArcGIS platform, multiple cost surface models were generated for different factors, with each model divided into a geographic grid matrix containing 100 $\times$ 100 cells. As shown in Figure 8, the grid of the water body area (marked in black) is used as an example.

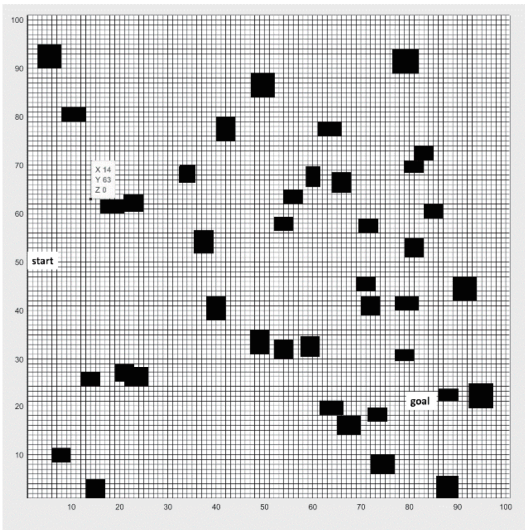

FIGURE 8. The cost surface model (using water bodies as an example).

The above cost surface models were superimposed to obtain the final weighted information model for the area to be planned. Each of the 100 $\times$ 100 grid cells in the model was assigned a comprehensive spatial cost. The spatial mobility cost assigned to each grid cell in the weighted information layer is according to Eqs (3.10) $\sim$ (3.12).

The Dijkstra algorithm is adopted for the corridor planning. After removing isolated grid cells, the most appropriate corridor for the later path planning is given as the shaded area in Figure 9.

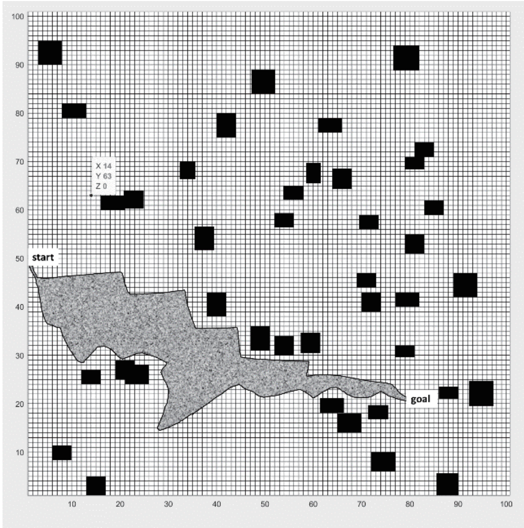

Figure 9. Corridor planning.

After the appropriate corridor is determined, the A^* algorithm is employed to give the optimized power line path in the selected region. It is noted that the "corridor-path" method only requires 1/3 computation time of that of the conventional A^* algorithm performed on the whole region. The final path is shown in Figure 10.

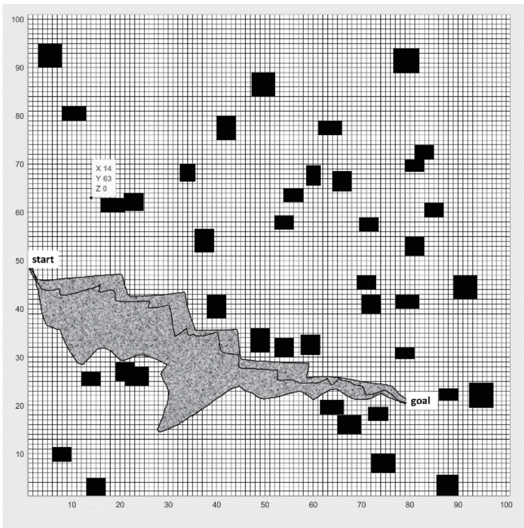

Figure 10. Optimal path planning

5. Conclusion

(1) The multiple sub-factors is taken into account by the the principal component analysis and analytic hierarchy process (PCA-AHP). This method could properly balance the objectivity and subjectively, and standardize these sub-factors. The balanced weights for the sub-factors are employed to construct the spatial surface cost model for a specified gird cell.

(2) This study proposes girder cells based on the quadtree partitioning method. The quadtree partitioning method serves as the fundamental spatial segmentation approach for surface cost model construction. In areas with drastic terrain changes, progressive partitioning is applied to achieve a more precise representation of terrain and feature edges, resulting in accurate girder cells. This modeling method enhances the accuracy of the path calculation by effectively considering terrain and edge precision while mitigating edge effects. Additionally, it reduces data redundancy and improves computational efficiency.

(3) This paper proposes a two-phase path planning algorithm. The first phase involves corridor calculation to narrow the range of path selection and reduce data collection difficulty. Next, path planning is conducted within the corridor. The Dijkstra algorithm is employed during the corridor calculation phase, while a pre-computed heuristic A^* algorithm is used for the path planning phase. The pre-computed heuristic approach outperforms traditional heuristics in terms of efficiency and admissibility, enhancing the reliability of the path selection results. This approach effectively resolves the issue of expansive computational cost and improves the overall rationality of the path.

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