A Multi-Layer Evolution Algorithm for Optimizing Highway Alignments

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ABSTRACT

A multi-layer approach to optimize highway design is developed to significantly improve the efficiency and solution quality of traditional model. The multi-layer evolution algorithm is designed to achieve feasibility and effectiveness respectively adopting knowledge base and particle swarm algorithm before it is determined the recommendation by genetic algorithm. Such approach not only overcomes the shortcomings of the three existing algorithms but also simplifies the search space of every layer to a certain extent. Moreover, the model perfects the initial generation solution of the second and third layers, as well as the final solution quality. The algorithm is applied to a field road design program at Kunlun Mountain of Qinghai-Tibet Plateau. The results suggest that the multi-layer approach is promising for obtaining an optimal solution to satisfy design standards in reality and practice.

KEYWORDS: Road engineering; Alignments optimization; Multi-layer evolution algorithm; Feasible domain; Effective domain; Recommend domain

INTRODUCTION

Highway design is a complex multi-objective and multi-level gradual optimization process. In the previous studies, highways were selected using multi-objective intelligent optimization, while the traditional method of stepwise selection was neglected, resulting in time consuming calculation and unreliable solution. Therefore, the multi-level evolutionary algorithm proposed in this paper has important significance to improve the practicability of highway intelligent optimization model.

A good highway alignment optimization model (HAO) was extensively proposed (Jong,1998), in which genetic algorithms((Jong 2000, Xu and Wang 2003, Jong and Schonfeld 2003, Ma 2006,) and GIS(Yang and Han 2009, Jong and Schonfeld 2001) were integrated. The model has been proved to be effective in simultaneously optimizing horizontal and vertical alignments by exploring a better solution through successive generations. A feasible gate (FG) method (Kang and Schonfeld, 2007) for horizontal(HFG) and vertical (VFG) alignments was proposed to ensure that complex preferences and environmental requirements were satisfied in the search process of the HAO model. Swarm intelligence algorithm(Miu 2011, Shafahi and Bagherian, 2013) was applied to solve the problem of highway alignment optimization to exploiting the entire search space without getting stuck in local optima.

Highway optimization model based on genetic algorithm cost too much time evaluating solutions and it is easily stuck in local optima. Thus it can make the final result with a low quality and efficiency. Another prevalent optimization method swarm algorithm converge rapidly but cannot generate diversity solutions. In order to solve the above problems, the multi-layer evolution algorithm is raised in this paper but does not intend to replace existing ones. After knowledge and particle swarm algorithm are separately adopted to find the feasible and effective domain in a larger search space, the method perfect the traditional highway optimization models. The proposed algorithm not only simplifies the search space of genetic algorithm and improves the computational efficiency, but also makes the genetic algorithm obtaining a better initial solution and improves the quality of optimal alignment.

HIERARCHICAL DIVISION

Now the basic geographic database covers various geographic data in the macro, meso and micro levels. Maps from small scale to large scale contain different details such as space forms and structures. Analyzing search spaces separately from macroscopic, meso and microscopic view (Wang and Chen 2004, Wang and Yan 2016) sharply shortens the processing time of optimization model and effectively improves the stability of optimization model. Factors affecting highway in different scales are described in detail, as shown in figure 1.

The features in topographic maps vary with the scale. Map with scale 1: 250000 cannot convey the large geographical elements (large mountains, water systems, etc.) and road network. Map with scale of 1: 50000~ 1: 5000 shows simple geometric elements, where highway is represented with a line. Detail characteristics as bridges, rivers and other specific elements gradually can be presented as the map scale increases. Considering the highway factors, scale of 1: 50000 is viewed as search space for feasible domain in the first level, and scale of 1: 10000 is for effective domain in the second level. The elements in scale of 1: 2000 and 1: 500 are almost the same. To avoid extra elements analyzing, 1: 2000 is chosen for determining the recommendation domain.

HIGHWAY OPTIMIZATION MODEL

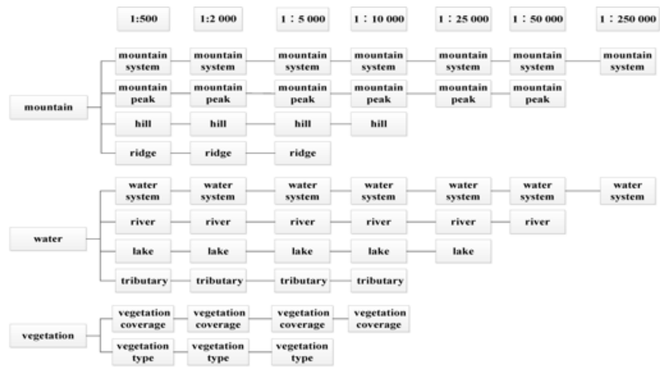
Decision variables

The decision variables are the 3-Dimensional coordinates (PI's) (Jong and Schonfeld 2003). The starting and ending points of highway are set to be $S = (x_S, y_S, z_S)$, $E = (x_E, y_E, z_E)$, where SE demotes the line for connection, and n is the longitudinal cutting plane intersecting SE at O_i. If line SE is divided into n+1 sections (as shown in figure 2), then highway alignment optimization problem can be treated as finding series of optimal intersection points on these cutting planes, and it is used to specify both the horizontal and vertical alignments of a highway. Assuming that the distance from the intersection to SE is d_i, the spatial coordinates is represented by Eq.1.

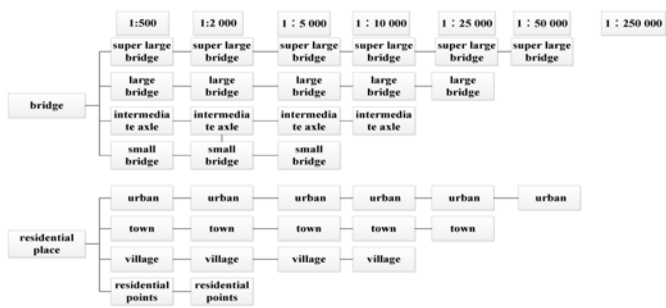
$$\begin{bmatrix} x_{PI_i} \\ y_{PI_i} \\ z_{PI_i} \end{bmatrix} = \begin{bmatrix} x_{O_i} \\ y_{O_i} \\ 0 \end{bmatrix} + \begin{bmatrix} d_i \cos\theta \\ d_i \sin\theta \\ z_i \end{bmatrix} \tag{1}$$

where PI_i = the ith point of intersection; x_i, y_i, z_i represent x, y, z coordinates respectively of the

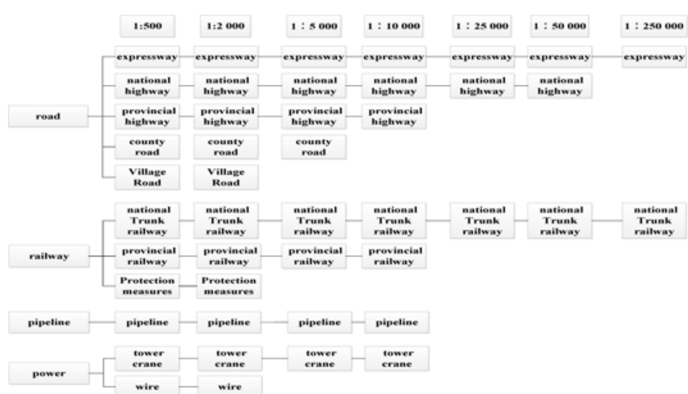
ith PI_i; (x_{Oi}, y_{Oi}) = the ith intersection of SE and longitudinal cutting surface; θ= angle between longitudinal cutting plane and XY plane.



(a) Topographies and landforms in different scales



(b) Structures and buildings in different scales



(c) Linear projects in different scales

Figure 1. Factors affecting highway in different scales

PI_{i} can be a planar intersection and a slope change point at the same time, or one of them, the judgement states as follows:

1. When the angle of two adjacent intersection XY coordinates is 0°, the point is not the intersection of planar lines;
2. 2. When the Z coordinates of three consecutive intersections are equal, the point is not the intersection of the longitudinal section.

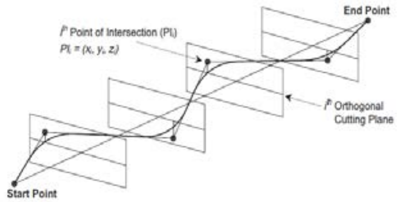


Figure 2. An alignment generated with PI's

Model formulation

Transportation agencies intend to construct new highways that save cost for their suppliers, provide motorists of operational efficiency and safety, in the same time of minimal negative impacts on local residents and the environment. Many optimization objectives have been discussed and applied (Yang and Li 2010; Yang and Kang 2014). Therefore, the following four criterias based on the different needs are identified as the most practical ways during the life cycle of highway:

M1: Minimize right-of-way cost (before construction), including costs spent on land, land compensation (damages, and migration fees) and land assessment fees;

M2: Minimize construction cost (construction): including costs spent on earthwork, pavement, bridge, tunnel, maintenance and other structure expenses.

M3: Minimize the environmental impact (construction): which, in this study, is measured as the total area of the affected environmentally, such as permafrost.

M4: Minimize usage cost (after construction): which are measured here as the money spent on traffic accidents, running time and road maintenance and so on.

M1,M2 and M4 can be accessed directly by cost, while M3 is formulated with reference to the construction method of Yang and Lu (2009), which are freely combined according to different objectives as model formulation.

Constraint

The constraints of terrain, geology and specification are given in the highway design, Some of which have been considered in model formulation. The technical specifications of plane and longitudinal section are mainly viewed as the constraints in optimization model, such as maximum gradient and minimum plane curve length.

Penalty cost functions(Dayanik 2010, Doshi and Hung 2016) are imposed to satisfy other constraints and avoid design violations when generating a smooth, continuous and safe alignment. It should be noted that the model automatically discourage the use of plane and vertical alignment by high penalties which differs from the degree of non-compliance with the relevant specification.

Methodology

Based on system engineering theory and ArcGIS, multi-level evolutionary algorithm for highway alignment optimization model is constructed. Firstly decision variables, objective functions and constraint conditions of every level are determined based on optimizing highway alignments. Then combined with different terrain elements and highway targets in different levels, a multi-layer evolution alogorithm is proposed. Knowledge base, improved particle swarm, and genetic algorithm are applied in three levels respectively. The methodology is an shown in figure 3.

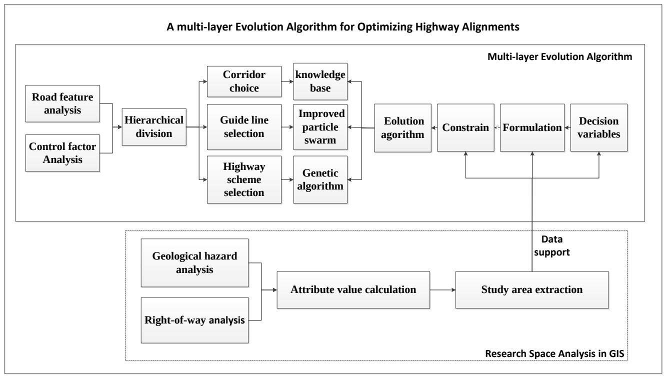


Figure 3. A multi-layer evolution alogorithm

MULTI-LAYER EVOLUTION ALOGORITHM

The knowledge base for the corridor selection

In the first level (1: 50000), the search space is large but relatively simple, where the political, economic, and topographic factors are mainly considered. To exclude major infeasible areas, the knowledge base is carried with the concept of the highway selection from coarse to fine, from contour to concrete, and gradually depth to discriminate search space, determine the feasible of corridor selection. The global layout knowledge base and route corridor selection knowledge base are mainly adopted (Ullman 1988, Li 2013, Shin and Wang, 2016), and the rules are generally based on operational experience and expert knowledge, which is described by if-then:

"If" section describes the premise of judgment rules. For multiple variables, it can be used the rule of “and”or “or”.

“Then” section describes the corresponding conclusion of rules. For some case, it can make a through appropriate measures.

Constrains, such as average longitudinal slope, slope length, adjacent gradient difference and control point elevation, are considered by a series of rules. Figure 4 shows the determining feasible domain process. It will now be described more clearly with the following example.

Space environmental knowledge:

IF terrain conditions, THEN the region is the mountain hilly area;

IF highway grade, design speed and number of lanes, THEN relevant design specification values for the area are determined.

Corridor identification:

IF some points or areas are keys, THEN passing through these points or areas.

IF some points or areas for the environmental sensitivity, THEN bypass them.

Corridor optimization:

IF the permafrost area thermal interference, THEN the distance from highway should be greater than 40m;

IF the average longitudinal slope and the slope length of the highest point and the lowest of the area exceed the limit value, THEN adjusting the maximum or minimum elevation of the area.

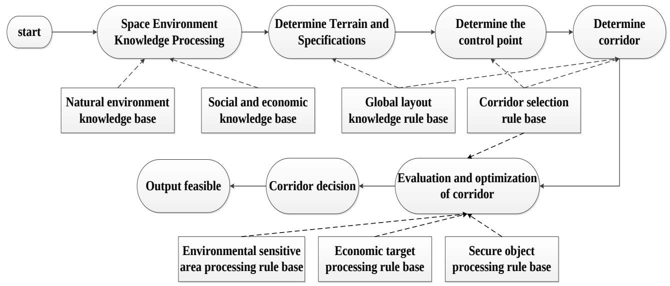


Figure 4. Knowledge base for the corridor selection

The improved particle swarm for the guide line

The main work of highway optimization in the second level (1: 10000) is to make further analysis of the feasible region for a better search space conductive to the guide line selection. The correct choice of the optimization algorithm is critical to the optimization speed, ease of adoption, and accuracy of the model. To clarify the distribution of adverse geological areas and select the effective domain quickly and appropriately, the improved particle swarm optimization algorithm which moves information unidirectionally from a swarm to another and with quickly converge in the early stage is a better way to determine the effective domain for the guide line.

Particle swarm optimization (PSO) is inspired by bird swarm (Eberhart and Shi 2001). Each particle, as the potential solution, adjusts its speed and position with reference to itself plus the group's best position and objective function. However, PSO is too directional to guarantee global optimization, while knowledge base has chosen the feasibility in the first level, guaranteed global optimization. It is notable that one of the capabilities of PSO global search and local search capabilities will increase accompanied by a decrease in the other. The weakening of the local search ability will be premature, while the weakening of the global search will slow down the operate speed. The improved particle swarm in the paper includes the basic search and improved search. The intersection of *SE* and the longitudinal cutting plane is taken as the initial solution of the particle swarm algorithm. The objective function and constrains except feasible boundary are the same as the first level.

1. Basic search

The idea of basic search is a imulation of birds behavior. Suppose the position of any particle i in three-dimensional space is $Pi=(x_i,\ y_i,\ z_i)^{\mathrm{T}}$. The next flight speed and position of each particle are determined by the optimal position experienced by itself and the population, which are expressed as Eq. 2 and Eq. 3:

$$v_{id}^{t+1} = wv_{id}^{t} + c_1 \cdot rand_1\left(pbest_{id}^{t} - P_{id}^{t}\right) + c_2 \cdot rand_2\left(gbest_{id}^{t} - P_{id}^{t}\right) \tag{2}$$

$$P_{id}^{t+1} = P_{id}^{t} + v_{id}^{t+1} \tag{3}$$

Where, $v_{id}{}^{t}$=the speed of the ith particle in the d direction; $x_{id}{}^{t}$=the position of the ith particle in the d direction; $pbest_{id}{}^{t}$=the best position of the ith particle before the tth update; $gbest_{id}{}^{t}$=the best position of all particle before the tth update; c_1, c_2=reference factor; $rand_1$,$rand_2$= a random number in the range [0,1]; w=weight.

2. Improved search

The idea of improved search is to enhance the local search ability of the algorithm through detecting (Rosenbroek, 1960). Improved search is mainly used for the case where the solution is stuck in local optima. the first position in which the local optimal objective function remains invariant is assumed to be P_0. Detection in the jth direction can be described as Eq. 4:

$$y^{(i+1)} = y^{(i)} + \delta_j d^{(j)} \tag{4}$$

Where, $d^{(1)}$,$d^{(2)}$,$d^{(3)}$= the initial three orthogonal units direction; δ_1, δ_2, δ_3= the step distance; $y^{(i)}$,$y^{(i+1)}$= The start and end point of the tth round detection.

If $f(y^{(i+1)}) < f(y^{(i)})$ is satisfied, it means a better solution is successfully found by detection. At the same time, let $\delta_j = \alpha\ \delta_j$. Otherwise if it is failed, and let $\delta_j = \beta\ \delta_j$ and $y^{(i+1)} = y^{(i)}$. A cycle is viewed as respectively finishing the detection of three directions, as shown in figure 5.

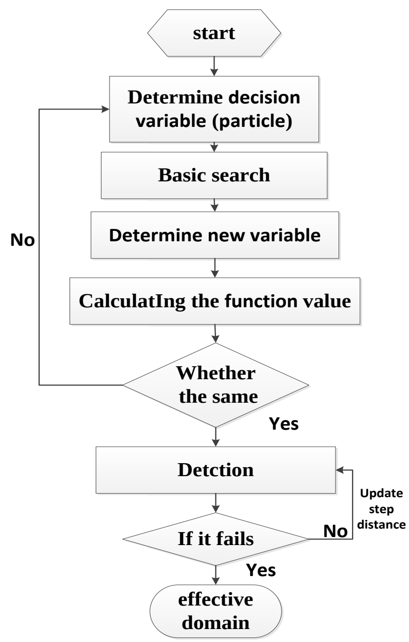


Fig. 5 Improved particle swarm for the guide line

Genetic algorithm for highway

The main work in the third level (1: 2000) is to make further analysis of the effcetive region for a better search space conductive to the highway scheme determination. With the optimal node in the last level as the initial population, the multi-objective genetic algorithm is applied to determine the recommend domain for the highway. The optimization process is shown in figure 6.

All criteria are acted as the objective function this level. Floating-point encoding is employed to transfer nodes into gene-structured data. Proper genetic parameters are selected to deal with 8 kinds of genetic operators on initial gene groups. The non-dominated solution set is constructed to adjusted operation through exclusion and prioritization strategies based on the of effective boundary and related standard constraints, and at the time when the objective function results show no obvious improvement, the algorithm stops. Moreover, the judgment and repairmen of intersection are added to avoid computation time wasting on evaluating infeasible solutions, which are achieved by Eq.5 and Eq.6. When $Df_i^h \leq 0$ and $\theta \mathrm{PI}_i \geq \theta \mathrm{PI}_{i+1}$, the intersection point should go to *SE*, otherwise to the opposite direction.

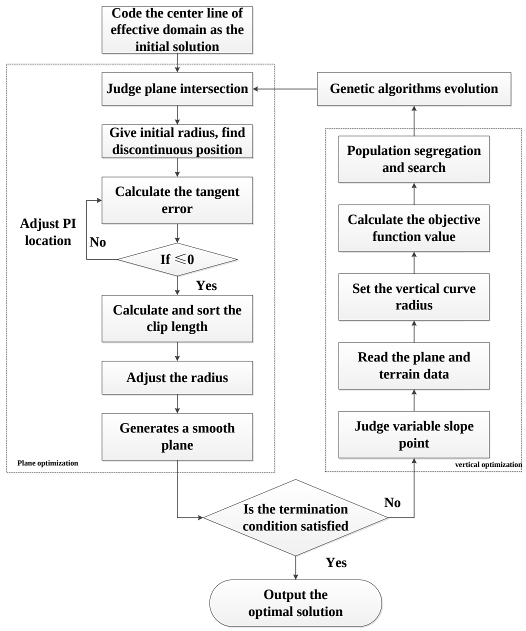


Fig. 6. Genetic algorithm for highway

$$Df_i^{\,h} = \left[R_i \times \tan\left(\frac{\theta_{PI_i}}{2}\right) + R_{i+1} \times \tan\left(\frac{\theta_{PI_{i+1}}}{2}\right) \right] - \left| PI_{i+1} - PI_i \right| \tag{5}$$

$$\theta_{PI_i} = \cos^{-1}\left(\frac{\left(PI_{i+1} - PI_i\right) \cdot \left(PI_i - PI_{i-1}\right)}{\left|PI_{i+1} - PI_i\right| \cdot \left|PI_i - PI_{i-1}\right|} \right) \tag{6}$$

APPLICATION

To verify the practicality and effectiveness of a multi-layer evolution algorithm for optimizing highway alignments, The Kunlun Mountains on the Qinghai-Tibet Plateau is taken as search space for highway, as shown in Figure 7. There are mainly two factors: elevation (mainly mountain) and environment (mainly lake and underground ice). Geographic information and unit road cost of the study area are provided by GIS. The required parameters in the optimization model of the multi-level evolutionary algorithm are shown in table 1.

Knowledge base for the corridor selection

Figure 7 shows that topography is complicated, and highway along river is prioritized. Because of the permafrost, more rules are established in expert knowledge base. Figure 8 is a study area of 1:50000 extracted from GIS. The area is mainly the overlay of elevation map and permafrost regional distribution. The feasible for corridor selection (the gray dashed frame) identified important sites and avoided the regions where the elevation is not suitable for wiring, and also be considered the linear interference of the railway, and it is consistent with the expected.

Improved particle swarm for the guide line

Further analysis is made based on feasible domain. The unit cost of permafrost in GIS is graded by the influence of temperature, ice content, depth in permafrost zone on the route plan, and the sensitivity of the road alignment is graded by the location of the lake. As it is shown in figure 9, elevation is obviously no longer a major factor, and the effective domain determined by the improved particle swarm perfectly utilizes the terrain and avoids the environment-sensitive region.

Table 1. Value of the parameter

Parameter	Value
Design speed	100km/h
Roadbed width	24.5m
Maximum permissible longitudinal slope	4%
Diesel unit price	7.4 yuan/L
Gasoline unit price	6.9 yuan/L
Unit accident cost	1482254.30 yuan
Design life	20
Annual average daily traffic	4500
Average annual growth rate of traffic volume	2%
Cost of running time of a passenger car	56 yuan
2A truck running time cost	131.5 yuan
3-S2 the time cost of goods vehicles	151.0 yuan
Proportion of large trucks	5%

Fig. 7 Study Area in the Example

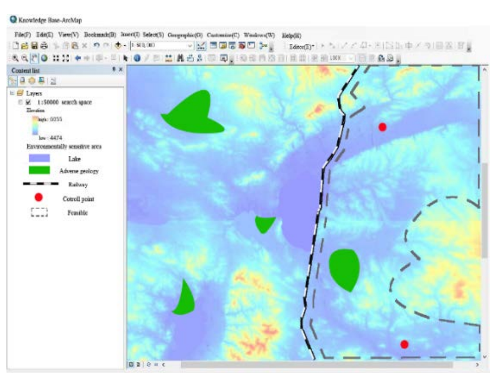


Fig. 8. Result of corridor selection

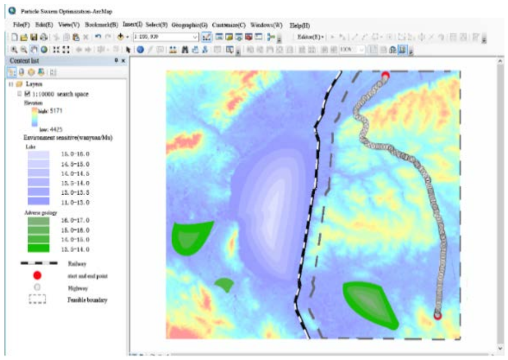


Fig.9 Result of the guide line

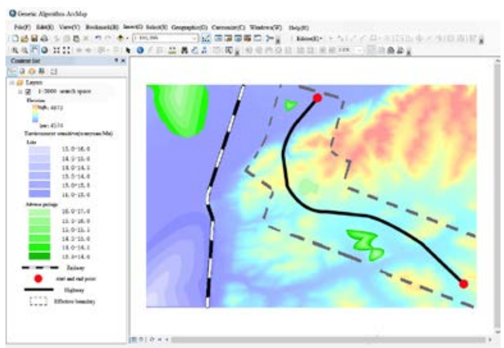


Fig.10 Result of highway

Genetic algorithm for highway scheme

Effective domain is further analyzed for highway in figure 10. The difference of environment sensitivity is larger, and genetic algorithm converged to the optimal recommendation in the 85th generation. The multi-level optimization algorithm reduced the search space, and improved the operation efficiency of genetic algorithm.

Compared with figure 8,9,10, search space is simplified and optimized step by step. The multi-level evolutionary algorithm is complementary to many optimization methods, which greatly verified by practical application.

CONCLUSION

1. Based on the traditional highway design idea, a multi-level evolutionary algorithm is established to improve the computational efficiency and the resolution quality, which makes the highway optimization model more widely used.
2. Scales of 1: 50000,1: 10000 and 1: 2000 are rigorously selected as the three search spaces according to the factors affecting highway and characteristics of various scales. Then the decision variables, objective function and constraints are built.
3. According to the characteristics of search space and the existing optimization algorithms, knowledge base, improved particle swarm optimization algorithm, and genetic algorithm are respectively applied to optimize highway in three levels.
4. The feasibility and efficiency of the model are verified by a case study of the highway in the part of the Kunlun Mountains on the Qinghai-Tibet Plateau.

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