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Models and Algorithms of Locomotive Layout Optimization in Regional Heavy Haul Rail Network

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Abstract: The locomotive layout which is extremely hard to modify after the construction, has direct impact on the daily transport efficiency and economic benefit of the railway transportation company. Therefore, it should be optimized once the rail network pattern is changed. The regional heavy haul rail network is a half open transportation system. Constant changes exist in the long period. As a result, the modification of locomotive system productivity layout is hard to be timely and effective. This problem differs from the normal logistic location problem and has complex influencing factors. Existing literatures mainly focus on the qualitative solutions which cannot precisely show the advantages and disadvantages of the alternative solutions and lack enough persuasion. The two key points of this problem is (1) Reasonable and reliable index system and (2) Feasible and practical models and algorithms. The numerical example takes the regional heavy haul rail network of Shenhua Group. The evaluation index system that can reflect the random factors is built. Then the model and the corresponding algorithm that can comprehensively evaluate the alternative solutions are proposed, through the combination of the fuzzy analytical hierarchy process and gray correlation analysis method. The locomotive layout optimization results conform to the reality well and promote the locomotive operational efficiency which will have positive impact on the development of the long-locomotive-line operation mode.

Key words: Locomotive layout, heavy haul rail network, fuzzy hierarchy correlation analysis method

INTRODUCTION

Whether the Locomotive layout is rational has an impact on not only the locomotive application efficiency, the stability of transportation safety and the smooth level but also the benefits of railway transport enterprises (Li and He, 2006).

After Shenhua Group's Batuta-Diandaigou Railway and Tarangaole-Hanjiacun Railway were constructed in China, they linked the Dongsheng-Wuhai Railway and Datong-Xuejiawan Railway together westwards and reached to the Datong-Qinghuangdao Railway with the connected Dazhun Railway eastwards. This railway has been a new line which traverses the west area of Autonomous Region, on the coal transportation lines network and finally became a main line for Shenhua Company's coal transportation to Shuohuang Railway. But it also has an impact on the existing locomotive layout of coal transportation lines. To meet the development requirements of coal transportation network, the existing locomotive layout needs to be optimized and adjusted, so that locomotive application efficiency can be increased and transport demand can be satisfied.

There have been many experts and scholars studying about the optimization of locomotive layout. Based on the analysis of influence factors of locomotive layout, Li and He (2006) and Ge (1994) have built the layout evaluation index system for the locomotive optimization problem and compares and selects the locomotive layout problem solutions with the method of AHP (Analytic Hierarchy Process). By analyzing the new locomotive routing layout influenced by the completion of Shanghai South Station, Cai (2003) evaluates different alternative solutions with the qualitative analysis method. However, both AHP method and qualitative analysis method which analyze problems from qualitative perspective and fail to reflect the advantages and disadvantages of alternative solutions accurately, are not convincing enough.

This study introduces a method integrating both the fuzzy analytic hierarchy process and the gray relative analysis method and builds the locomotive layout optimization model, then makes comprehensive evaluations of alternative solutions, to achieve the purpose of optimizing the locomotive layout.

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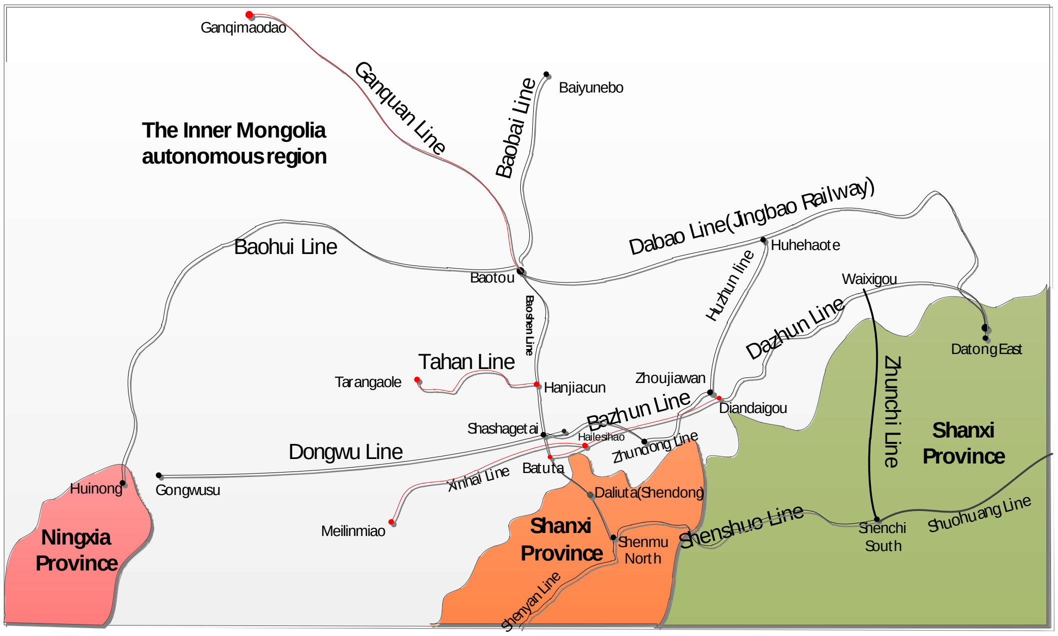

Fig. 1: Railway lines of the Shenhua group

Table 1: Evaluation index system of locomotive layout optimization

Objective layer	Criteria layer	Index layer
Locomotive layout evaluation index system D	Satisfying transportation demands D1	Coordination with the direction and intensity of flow D11
		Coordination with the capability of the locomotive station D12
	Application of locomotive D2	Amount of locomotives C21
		Crew working time D22
		Locomotive turnover time D23
	Capability of locomotive facilities D3	Conditions of repair facilities D31
		Conditions of preparation facilities D32
	Economic factors D4	Amount of investment D41
	Geographic factors D5	Local regionalism D51
		Conditions of transformation and extension D52

PREPARATION

Influencing factors of the locomotive layout problem: To optimize locomotive layout, factors such as satisfying the demands of transportation, application of locomotive and conditions of locomotive facilities should be in consideration, besides, economic and geographic factors should also be considered. Factors that influence locomotive layout are summarized below:

- **Satisfying transportation demands:** Layout of locomotive should meet the transportation demands. It should be in harmony with the direction and intensity of flow and the capability of locomotive station, as to ensure the reasonableness of optimization
- **Application of locomotive:** On the basis of satisfying demands, locomotive layout should fully increase efficiency, decrease the amount of locomotives and ensure that the crew will not have to work overtime
- **Capability of locomotive facilities:** Locomotive facilities include repair facilities and maintenance facilities. Capability of repair and maintenance should not only meet the actual demands, it must have some reserve to match the planning transportation volume
- **Economic factors:** Based on the demand satisfaction, it's important to promote the economic benefits of enterprises with little investment and more profits
- **Geographic factors:** Geographic factor means the possibility of locomotive depot transformation and extension. In addition, local geographic regionalism should also be taken into account
- **Evaluation index system:** By analyzing the influence factors above, an evaluation index system can be constructed. The index system is divided as three layers including the objective layer, criteria layer and index layer, as shown in Table 1

MATERIALS AND METHODS

Optimization method of locomotive layout: The integration of fuzzy analytical hierarchy process and gray correlation analysis method, or the fuzzy hierarchy correlation analysis method, is used to optimize the locomotive layout, of which the method has been widely applied in a number of practices (Chen and Li, 2006; He *et al*., 2008). However, the application in the aspect of optimization of railway locomotive layout has not been seen. According to the multi-criteria decision making problem of locomotive layout, the integrated use of the fuzzy analytical hierarchy process and gray correlation analysis method, on one hand, resolves the drawbacks of fuzzy analytical hierarchy process: the ignorance of the relations among factors or indexes when building the relation matrix, on the other hand, solves the vagueness of weight parameters when using gray correlation analysis method alone.

Fuzzy hierarchy correlation analysis method

Mathematical model:

The precedence relation matrix: Assume that there exists a factor set F = {a_1, a_2...a_n}. If a matrix R satisfies the condition: r_{ii} = 0.5 and $r_{ij}+r_{ji}$ = 1, then it is called the fuzzy reciprocal matrix, or the precedence relation matrix. r_{ij} is the membership degree of how a_i is more important to a_j. The bigger the r_{ij} is, the more important the a_i is to a_j.

The precedence relation matrix describes the comparison of importance between the factor in the upper layer and the corresponding factors in this layer. In order to get a quantitative description of the relative importance degree of any two factors according to a specific criterion, the approach of 0.1-0.9 Scale Method can be taken to get quantitative scales. Assume that a_1, a_2, a_3,..., a_n in this layer are associated with A in the upper layer, the fuzzy judgment matrix can be defined as follow according to the meaning of 0.1-0.9 scale process:

$$R=\left(r_{ij}\right)_{n\times n}=\begin{Bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{11} & r_{12} & \cdots & r_{1n} \\ \cdots & \cdots & \cdots & \cdots \\ r_{11} & r_{12} & \cdots & r_{1n} \end{Bmatrix}$$

Conversion method of the fuzzy consistent matrix: The formula below can be used in the conversion process from the precedence relation matrix to the fuzzy consistent matrix (He *et al*., 2008):

$$r_{ij}^{'}=\frac{\left(\prod_{1=1}^{n} r_{il} r_{lj}\right)}{\left(\prod_{1=1}^{n} r_{il} r_{lj}\right)^{1/n}+\left(\prod_{1=1}^{n} r_{jl} r_{li}\right)^{1/n}} \tag{1}$$

Weight parameters: The formula below can be used to decide the weight parameters in each layer:

$$\omega_i(j)=\frac{1}{n}-\frac{1}{2\alpha}+\frac{\sum_{j=1}^{n} r_{ij}^{'}}{n\alpha},\ i,j=1,2,\ldots,n \tag{2}$$

Consistency check of the fuzzy reciprocal matrix: In order to ensure the rationality and effectiveness of weight parameters, consistency check is needed at last:

Mathematical model of gray correlation analysis

Gray correlation parameters: The gray correlation parameters mainly describe the correlation degree between a certain sequence and the standard sequence.

Table 2: Explanation of The 0.1-0.9 scale method

Scale	Definition	Explanation
0.5	Equally important	The 2 compared factors gain the same importance
0.6	Slightly more important	One factor gains slightly more importance than the other factor
0.7	Obviously more important	One factor gains obviously more importance than the other factor
0.8	Far more important	One factor gains far more importance than the other factor
0.9	Extremely more important	One factor gains extremely more importance than the other factor
0.1, 0.2, 0.3, 0.4	Reverse comparison	If the scale degree of a_i contrasted to a_j is r_{ij}, then that of a_j to a_i is r_{ji} = 1-r_{ij}

Table 3: Basic situation of hailesihao south locomotive depot

Items	Recent	Forward	Items	Recent	Forward
Running kilometer day^{-1} (km)	172492	196752	Number of minor repair stations	1.524	1.738
Running kilometer year^{-1} (1000 km)	6295.958	7181.449	Number of auxiliary repair stations	1.732	1.975
Number of Overhauled locomotives year^{-1}	34.978	39.897	Total No. of repair stations	3.255	3.713
Number of medium repaired locomotives year^{-1}	104.933	119.691	Number of On-line locomotives	247	282
Number of minor repaired locomotives year^{-1}	384.753	438.866	Total No. of locomotives	291	332
Number of auxiliary repaired locomotives year^{-1}	874.439	997.423	Sand consumption day^{-1} (m^3 day^{-1})	25.87	29.51
Number of medium repair staions	0.762	0.869	Number of repaired locomotives day^{-1}	150	152

The correlation degree between sequence X_i and the standard sequence X_0 based on the index $X_i(k)$ is (Ren and Li, 2009):

$$\xi_i(k)=\frac{\min_i \min_k |x_0(k)-x_i(k)|+\rho \max_i \max_k |x_0(k)-x_i(k)|}{x_0(k)-x_i(k)+\rho \max_i \max_k |x_0(k)-x_i(k)|} \tag{3}$$

$\rho(\rho\epsilon(0, 1))$ is the resolution coefficient. ρ is usually determined as 0.5. k stands for the object waiting to be estimated

Gray correlation degree: The formula below can be used to calculate the gray correlation degree:

$$r_k = \sum_i^n \{w_i(k)\times \xi_i(k)\} \tag{4}$$

Optimization steps: The integration of the fuzzy analytical hierarchy process and gray correlation analysis method is used in the optimization analysis of the locomotive layout problem. Detailed steps are as follows:

- Build the precedence relation matrix and convert it to the fuzzy consistence matrix using Eq. 1. Then carry out the consistency check process
- Calculate the weight parameter in each layer using Eq. 2 and convert them to the comprehensive weight under the general objective with the formula below:

$$W = \{w_i(k)|w_i(k) = \omega_i(j)\times w'_j(k)\}$$
$$i = 1, 2...n, k = 1, 2...m \tag{5}$$

$\omega_i(j)$ is the weight of the criteria layer comparing to the, $\omega'_j(k)$ is the weight of the indexes layer comparing to the criteria layer

- Calculate the gray correlation coefficient $\xi_i(k)$ using Eq. 3
- Calculate the correlation degree r_k using Eq. 5. The larger r_k is, the better the solution is

RESULTS AND DISCUSSION

Analysis of the existing locomotive facilities of batuta-diandaigou railway: Hailesihao south locomotive depot, part of batuta-diandaigou railway, serves for the repair and maintenance works of the HXD1 electric locomotives owned by the depot itself which has the repair capacity of 12 minor or auxiliary repair stations for electric locomotives and the maintenance capacity of 6 maintenance stations (another 2 are reserved) for electric locomotives. Hailesihao south locomotive depot locates in the center of railway transportation network for coal and owns a number of locomotives, leading to the large amount of repair and maintenance capacity of it which makes it appropriate to use long locomotive routing to improve the transport capacity and the locomotive efficiency.

Alternative solutions: Considering the transportation demands and the layout, properties and scales of locomotive facilities of batuta-diandaigou railway, baotou-shenmu railway, datong-xuejiawan railway, 3 alternative solutions are proposed, of which the advantages and disadvantages are listed at last.

Solution 1: Tasks for each depot:

- **Hailesihao south locomotive depot:** Locomotive operation of batuta-diandaigou railway and sections from batuta-diandaigou railway to huanghuagang station and yanzhuang station

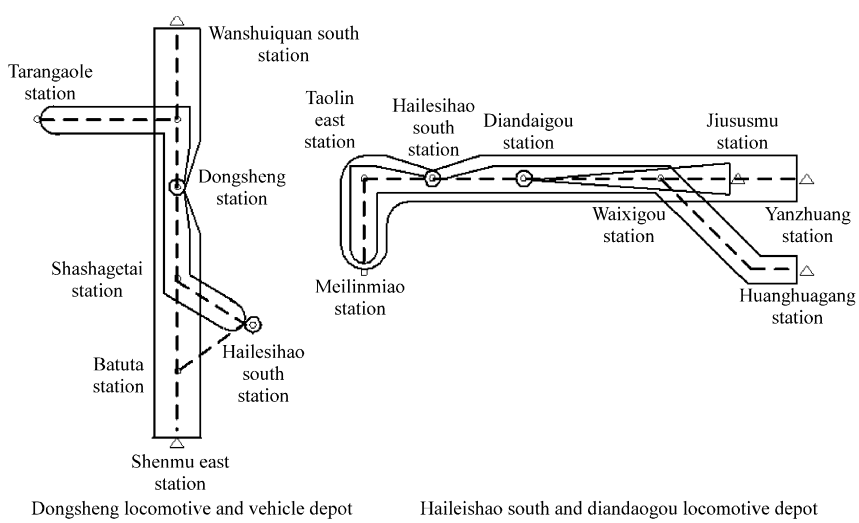

Fig. 2: Locomotive routing of solution 1

- **Dongsheng locomotive and vehicle depot:** Locomotive operation of sections from baotou-shenmu railway to hailesihao south station
- **Diandaigou locomotive depot:** Locomotive operation of sections from diandaigou station to jiusumu station and hudong station

Solution 2: Tasks for each depot:

- **Hailesihao south locomotive depot:** Locomotive operation of batuta-diandaigou railway and of sections from batuta-diandaigou railway to huanghuangang station and yanzhuang station, from baotou-shenmu railway(including baotou north staion and tarangaole-hanjiacun railway) to hailesihao south station
- **Dongsheng locomotive and vehicle depot:** Locomotive operation of Baotou-Shenmu Railway
- **Diandaigou locomotive depot:** Locomotive operation of sections from diandaigou station to jiusumu station and hudong station

Solution 3: Tasks of each depot:

- **Transform batuta station into locomotive depot and bear the tasks:** Locomotive operation of baotou-shenmu railway and of sections from baotou-shenmu railway to hailesihao south station. Dongsheng locomotive depot only serves for shunting locomotives
- **Hailesihao south locomotive depot:** Locomotive operation of batuta-diandaigou railway and of sections from batuta-diandaigou railway to huanghuagang station and yanzhuang station
- **Diandaigou locomotive depot:** Locomotive operation of sections from diandaigou station to jiusumu station and hudong station

Solutions evaluation and selection

Value of corresponding factors:

- As for the quantifiable factors such as the membership degree of locomotive number, working time of crew and locomotive turnover time, membership function is required to be built

  If it becomes more appropriate for the value of some factors to be larger, the weight of those factors X_{ij} can be calculated as:

$$X_{ij}=\frac{(Y_{ij}-Y_0)}{(Y_m-Y_0)} \tag{6}$$

If it becomes more appropriate for the value of some factors to be smaller, the weight of those factors X'_{ij} can be calculated as:

$$X'_{ij}=\frac{(Y_m-Y_{ij})}{(Y_m-Y_0)} \tag{7}$$

Y_0 and Y_m are the minimum and maximum of the specific factor, respectively

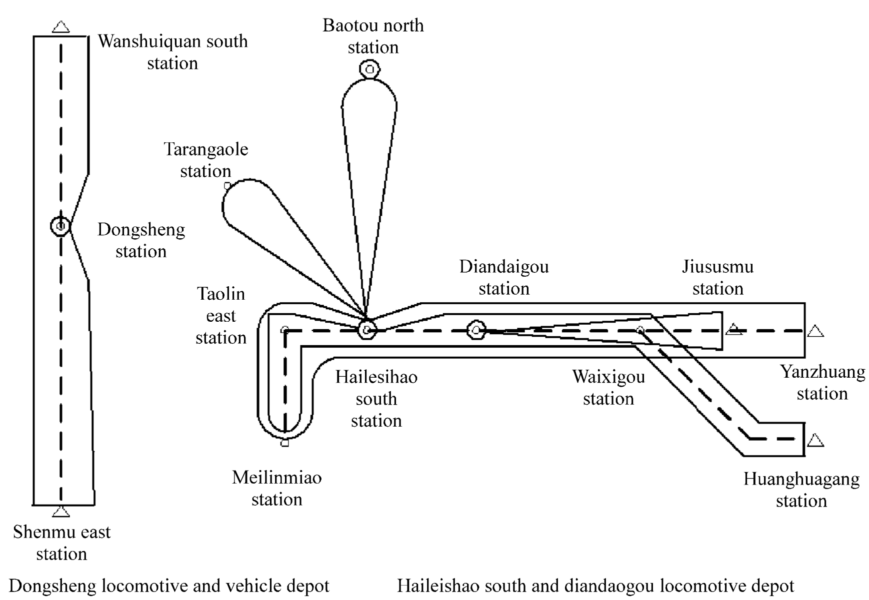

Fig. 3: Locomotive routing of solution 2

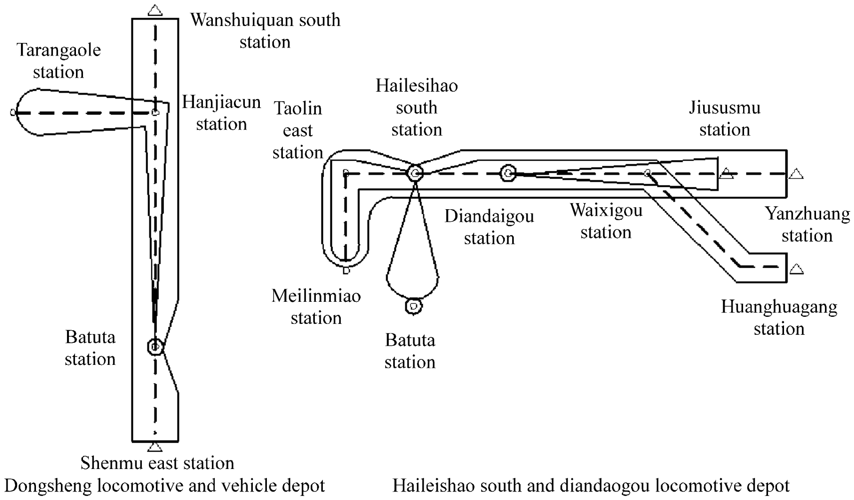

Fig. 4: Locomotive routing of solution 3

Table 4: Advantages and disadvantages of different solutions

Solution	Advantages	Disadvantages
Solution 1	1.Good physical conditions in dongsheng 2.Full usage of the facilities of dongsheng locomotive and vehicle depot	More transportation pressure for Batuta-Diandaigou Railway due to the extension of capacity of Dongsheng Depot, as Baotou-Shenmu Railway is already saturated 2.Sufficient funds is needed for land acquisition, infrastructure extension and locomotive purchase.
Solution 2	1. Full usage of the facilities of dongsheng locomotive and vehicle depot; 2. Convenience for applying long locomotive routing as hailesihao south depot serving as the basic depot; 3.Conformity to the requirements of the forward network plan.	1.Increasing of the repair and maintenance pressure for hailesihao south locomotive depot as all the locomotives around entering and being repaired in it; 2.More transportation pressure for Hailesihao South Station at the same time.
Solution 3	1. Sharing of the transportation pressure of dongsheng locomotive and vehicle depot 2.Convenientce for applying long locomotive routing as with good Cooperation of batuta and hailesihao south locomotive depot.	1.Huge amount of funds needed for facilities transformation, infrastructure extension and locomotive purchase; 2.Not enough usage of facilities in dongsheng depot

- As for the unquantifiable factors such as C11, C12, C13, C31 etc.: GOOD(0.9-1), PREFERABLE(0.75-0.9), MEDIUM(0.6-0.75), BAD(0.45-0.6), POOR(0.2-0.45)
- As for C51 that means the administrative district of the locomotive depot: PROVINCE(1.0), CITY(0.8), COUNTY(0.6), VILLAGE(0.4)

Solution evaluation table: The value of different factors under different evaluation indexes based on the corresponding value determination methods is listed below in Table 5:

Weight parameters: Compare the importance degree between every 2 factors based on the rules in Table 2 and we can get the following precedence relation matrixes:

$$R=\begin{bmatrix}0.5 & 0.7 & 0.6 & 0.9 & 0.8\\ 0.3 & 0.2 & 0.4 & 0.7 & 0.6\\ 0.4 & 0.6 & 0.5 & 0.8 & 0.9\\ 0.1 & 0.3 & 0.2 & 0.5 & 0.4\\ 0.2 & 0.1 & 0.3 & 0.6 & 0.5\end{bmatrix},\quad R_1=\begin{bmatrix}0.5 & 0.6\\ 0.4 & 0.5\end{bmatrix},\quad R_2=\begin{bmatrix}0.5 & 0.6 & 0.4\\ 0.4 & 0.5 & 0.3\\ 0.5 & 0.7 & 0.5\end{bmatrix}$$

$$R_3=\begin{bmatrix}0.5 & 0.4\\ 0.6 & 0.5\end{bmatrix},\quad R_4=[0.5],\quad R_5=\begin{bmatrix}0.5 & 0.4\\ 0.6 & 0.5\end{bmatrix}$$

Transform all the precedence relation matrixes to the fuzzy consistent matrixes using Eq. 1, of which the results have passed the consistence check. Then the comprehensive weight of all factors can be calculated with Eq. 2 and 3. The results are:

$$W = \{0.1818, 0.1212, 0.0744, 0.0472, 0.0817, 0.0986, 0.1478, 0.0970, 0.0601, 0.0902\}$$

Correlation degree

Calculation of the correlation coefficients: The correlation coefficient of each solution is calculate based on Eq. 4 and list below:

- **Solution 1:** $\xi_1 = \{0.714, 0.833, 1, 0.333, 1, 0.833, 1, 0.625, 1, 0.714\}$
- **Solution 2:** $\xi_2 = \{1, 1, 0.333, 1, 0.333, 0.833, 1, 1, 0.556, 1\}$
- **Solution 3:** $\xi_3 = \{0.833, 0.833, 1, 0.333, 1, 1, 0.833, 0.333, 0.556, 0.625\}$

Calculation of the correlation degree:

- **Solution 1:** $r_1 = 0.818$

Table 5: Solution evaluation table

Factors	Solution 1 Value	Solution 1 Weight	Solution 2 Value	Solution 2 Weight	Solution 3 Value	Solution 3 Weight	Standard sequence
D11	Medium	0.7	Good	0.9	Preferable	0.8	0.9
D12	Preferable	0.8	Good	0.9	Preferable	0.8	0.9
D21	377	1.0	380	0.0	377	1.0	1.0
D22	9.5	0.0	8.7	1.0	9.5	0.0	1.0
D23	17	0.5	15	0.0	17	1.0	1.0
D31	Preferable	0.8	Preferable	0.8	Good	0.9	0.9
D32	Preferable	0.8	Preferable	0.8	Medium	0.7	0.8
D41	2800	0.7	0	1.0	9200	0.0	1.0
D51	City	0.8	Village	0.4	Village	0.4	0.8
D52	Medium	0.7	Preferable	0.9	Bad	0.6	0.9

The value of crew working time and the locomotive turnover time is the average value (h) upon all routings

- **Solution 2:** r_2 = 0.853
- **Solution 3:** r_3 = 0.768

The sort of the 3 solutions based on the correlation degree is $r_2>r_1>r_3$. So solution II is the best locomotive layout solution.

CONCLUSION

As the construction accomplishment of batuta-diandaigou railway is coming soon, in order to meet the development requirements of the long locomotive routings in the future, batuta-diandaigou railway and the railways around it including baotou-shenmu railway and datong-xuejiawan railway need to optimize and adjust their locomotive layout. The influence factors of the locomotive layout problem are analyzed to build the evaluation index system, in which the indexes are quantified by the fuzzy analytical hierarchy process and the weight of each index is calculated. The example of the locomotive layout optimization problem of batuta-diandaigou railway is then introduced. Three alternative locomotive layout solutions are put forward considering the transportation demand in and around batuta-diandaigou railway and the existing locomotive layout, properties and scale. Those solutions are sorted by the correlation degrees which are calculated by the gray correlation analysis method, so that the optimized solution is thus decided.

The fuzzy hierarchy correlation analysis method, the integration of fuzzy analytical hierarchy process and gray correlation analysis method, is used so that the disadvantages of using only qualitative or quantitative method are overcome which leads to a much more precise evaluation of different locomotive layout problems.

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