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Article

Track maintenance planning and optimization considering unit track section combination

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Abstract: Given the large amount of railway maintenance work in China, whereas the maintenance time window is continuously compressed, this paper proposes a novel network model-based maintenance planning and optimization method, transforming maintenance planning and optimization into an integer linear programming problem. Based on the dynamic inspection data of track geometry, the evaluation index of maintenance benefit and the model of the decay and recovery of the track geometry are constructed. The optimization objective is to maximize the railway network's overall performance index, considering budget constraint, maximum length constraint, maximum number of maintenance activities within one single period constraint, and continuity constraint. Using this method, the track units are divided into several maintenance activities at one time. The combination of surrounding track units can be considered for each maintenance activity, and the specific location, measure, time, cost, and benefit can be determined. Finally, a 100 km high-speed railway network case study is conducted to verify the model's effectiveness in complex optimization scenarios. The results show that this method can output an objective maintenance plan; the combination of unit track sections can be considered to expand the scope of maintenance, share the maintenance cost and improve efficiency; the spatial-temporal integrated maintenance planning and optimization can be achieved to obtain the optimal global solution.

Keywords: railway track; maintenance planning; unit track section combination; network optimization; integer linear programming

1. Introduction

Track is the crucial equipment of the railway system. The department must maintain its high geometry regularity and good condition and reduce the risk of system failure through maintenance. With the expansion of the railway network scale and the increase in traffic, the amount of track maintenance is increasing. In contrast, the time window used for maintenance is constantly compressed, exacerbating the contradiction between transportation and maintenance. Therefore, scientifically and reasonably planning track maintenance is crucial.

According to the railway track maintenance rules (Ministry of Railway of China, 2006, 2012), it is necessary to conduct periodic static and dynamic inspections. The dynamic inspection results are an essential basis for regular maintenance decisions. When the track quality index (TQI) or its constituent indicators exceed the management value, the unit track section (UTS) must be included in the maintenance plan. Through this method, the location of the UTS that needs maintenance can be determined, but when and how to execute the maintenance heavily depends on the experience of technical personnel. It is of solid subjectivity and hard to quantify the quality of decision-making. Recognizing this issue, researchers conducted in-depth research. The most classic method among them is mathematical programming. It can automatically determine the optimal maintenance location, time, measure, and other items based on detection data and considering certain constraints. It can also quantitatively evaluate the maintenance plan, effectively avoiding the limitations of traditional methods. This study also belongs to this category of research.

In maintenance practice, technicians often combine scattered UTSs into one maintenance activity. An obvious benefit is that it can expand the scope of maintenance and evenly share maintenance costs. Especially now, machinery is widely used for maintenance, and the combination of UTSs can improve work efficiency and fully leverage the advantages of modern mechanical operations. Therefore, combining UTSs can effectively alleviate the contradiction between transportation and maintenance, bringing significant benefits to railway transportation. However, to the authors' knowledge, there are no reports on using mathematical programming models for section combing in railway maintenance planning and optimization.

This study proposes a maintenance planning and optimization model that can consider the relationship between UTSs and combine surrounding sections into one maintenance activity. Based on detection data, under constraints such as maintenance budget, workforce, and material resources, the UTSs are combined into several maintenance activities at once. The maintenance location, time, and combination strategy are determined to achieve the optimal comprehensive performance of the entire railway network at the time point of the next yearly inspection.

The remaining arrangement of this paper is as follows: Second 2 reviews the domestic and international progress in maintenance planning and optimization. Section 3 introduces the proposed maintenance planning and optimization method. Second 4 verifies this method through practical application by formulating a maintenance plan for a railway network with a total mileage of 100 km. The last section summarizes this paper and proposes prospects for future research.

2. Literature review

China has conducted long-term exploration and practice in railway track maintenance planning and optimization, which are still under continuous development. Based on dynamic and static inspection data, professional technical personnel evaluate and analyze the track status, make a maintenance plan, and execute it after approval. For example, the rule (Ministry of Railway of China, 2012) says that the track is divided into units of 200 m, and dynamic inspection is carried out using track inspection vehicles to obtain the TQI of each unit and its constituent individual indicator values (including vertical irregularities, longitudinal irregularities, gauge irregularity, transverse irregularity, and twist irregularity). When the TQI or individual indicator exceeds the management value, it must be included in the maintenance plan.

The above methods can determine the sections that need to be focused on. However, when to execute the maintenance, which measure should be adopted, and how to organize it mainly depend on the experience of professional technical personnel, which is highly subjective and lacks quantitative evaluation of the maintenance planning quality. Realizing this issue, researchers began to propose some objective methods for maintenance planning and optimization, among which the most classic method is the use of mathematical programming, i.e., the problem of railway network maintenance planning can be transformed into a mathematical programming problem. It can objectively determine the location, measure, and maintenance time under certain constraints and provide quantitative evaluation, the optimal objective value. These studies can be roughly divided into three categories according to the modeling approach (Guo, 2015): equipment-centered, track occupancy-centered, and personnel scheduling centered. The modeling approach of this study is also equipment centered, so this type of research is mainly introduced. This approach primarily focuses on the equipment, i.e., the railway track. The maintenance plans are formulated by analyzing the performance evolution of the equipment, the applicability and advantages of maintenance measures, the impact of maintenance timing on the performance of the equipment during its lifecycle, and comprehensively considering economic benefits and other factors (Miwa, 2002; Oyama and Miwa, 2006).

The maintenance planning considering UTS combinations that this study focuses on is a common measure in railway maintenance practice. However, no reports have been on using mathematical programming models for UTS combinations. However, similar studies are prevalent in the road industry. This measure has several names, such as work zone optimization (Lethanh et al., 2018), project packaging (Qiao, 2019), project bundling or project combination (Xiong et al., 2017). The term "section combination" is used in this paper. The basic idea is to combine multiple nearby sections into a project contract to share the overall cost of the project (Xiong et al., 2017). With this, the efficiency of mechanical operations can be fully utilized, and the maintenance time can be reduced, thereby reducing project organizational costs (Qiao et al., 2019a, 2019b). Commonly used section combination methods include (1) Quantitative analysis of the similarity between different projects and transforming the section combination problem into a permutation and combination problem (Qiao, 2019); (2) Based on the idea of dynamic segmentation, clustering segments with similar conditions, and then matching corresponding maintenance measures according to the characteristics of each category (Lea, 2015; Yang et al., 2009); (3) Network model based optimization method, which will be introduced with details as follows.

In 2006, Hajdin and Adey (2006) first used a mathematical programming method to solve the section combination problem. They designed a network model that can determine a work zone in the road network at one time and combine multiple different types of objects into this work zone. In this network model, arcs represent road sections and their maintenance measures, and nodes represent the starting and ending points of road sections and maintenance measures. This model can consider all facility objects in the road network, considering each object's fixed and dynamic maintenance costs. Based on this model, Lethanh et al. (2014) proposed a new network model that can determine multiple work zones at one time, each of which is a combination. Nodes represent road sections and maintenance measures, and arcs represent changes in traffic organization methods. Their model considered the maximum length constraint, minimum work zone distance constraint, and budget constraint. Eicher et al. (2015) further designed an algorithm that can fully automate the above optimization process.

However, since these models place information such as maintenance costs and benefits at nodes, they cannot consider the connection between adjacent road sections and, therefore, cannot consider the fixed cost of setting up work zones, nor can they consider the cost savings brought by combinations. Realizing this issue, Xu and Burkhalter et al. (2021) proposed an improved hybrid network optimization model. It still uses nodes to represent road sections and maintenance measures and arcs to represent changes in traffic organization methods. However, it adopts arcs being chosen or not as decision variables and places cost-effectiveness on the arcs. This method can obtain multiple work zones at one time, and each work zone can consider the relationship between road sections. When conditions are met, adjacent work zones will be combined into one work zone. However, this model can only determine the maintenance's spatial location and combination plan. It cannot determine the maintenance time since it does not consider time factors. This study is a continuation of the work (Xu, Wu, et al., 2021). The contribution is two-fold: (1) proposing a network optimization model that can consider UTS combination for railway track maintenance; (2) improving the above model by taking into account the time factor so that the optimal temporal and spatial integrated maintenance plan can be obtained at one time.

3. Methodology

3.1. Network model

This section takes a simple railway line composed of 5 UTSs as an example to introduce the network model, as shown in the bottom part of **Figure 1**, where red indicates that the unit is in poor condition. It is assumed that the maintenance department has three maintenance and combination options to choose for each UTS when making decisions, namely, (1) do not execute any maintenance and do not combine the UTS into the project (denoted as no maintenance & no combination), (2) do not execute any maintenance but combine the UTS into the project (denoted as no maintenance & combination), and (3) execute maintenance and combine the UTS into the project (denoted as maintenance & combination), represented by 1, 2, and 3 respectively. Two times for maintenance within a year is considered, one scheduled for the first half of the year and the other scheduled for the second half, denoted by 1 and 2, respectively. The network model of this example railway line is shown in the top part of **Figure 1**. The node represents the UTS and the maintenance measure, combination scheme, and maintenance time applied to it. One UTS may have multiple nodes because it may have various maintenance and combination options to choose from, and the option can be executed at different maintenance periods. Therefore, nodes are used to represent these possible situations. The node is represented as (A, B, C), where A represents the UTS number, B represents the maintenance and combination option used, and C represents the maintenance time. Virtual starting points (s) and ending points (e) are added to complete the network model.

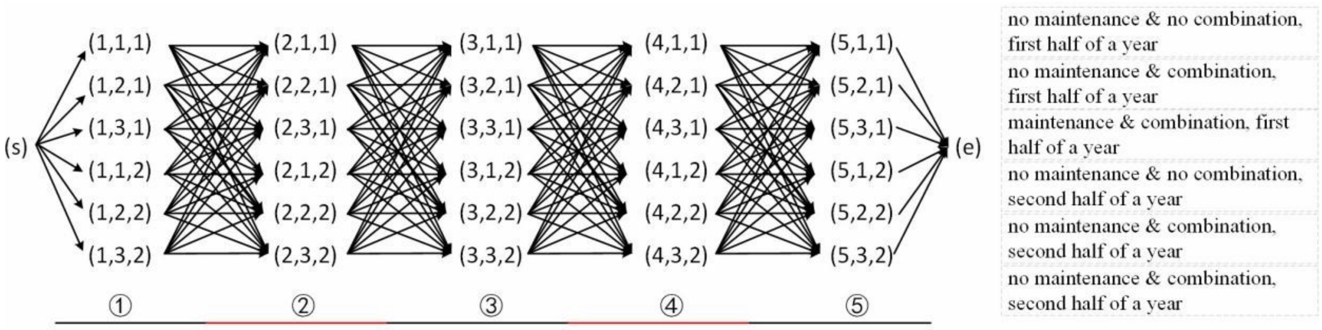


Figure 1. Network optimization model.

An arc is a line connecting nodes. The arc is represented as (A, B, C) − (D, E, F). A and D represent the UTS numbers of the arc's starting and ending nodes, respectively. B represents the maintenance and combination option of the arc's starting UTS; E represents the maintenance and combination option of the arc's ending UTS; C represents the execution time of the arc's starting UTS using option B, and F represents the execution time of the arc's ending UTS using option E. The arc can present the connection relationship between the two adjacent UTSs. For example, the arc (2, 3, 1) − (3, 1, 1) indicates that UTS 2 adopts maintenance and combination option 3 in the first half of the year, which is "execute maintenance and combine the UTS into the project". In contrast, UTS 3 adopts maintenance and combination option 1 in the first half of the year: "Do not execute any maintenance and do not combine the UTS into the project". An arc has multiple attributes, such as maintenance cost and benefit. In this model, they all refer to the ones of the UTS where the arc's ending node is located, taking into account the maintenance and combination option of the UTS where the arc's starting node is located. For example, assuming the cost of arc (2, 3, 1) − (3, 3, 1) is 1000 RMB, it means that in the first half of the year, when UTS 2 adopts the maintenance and combination option 3, the cost of UTS 3 adopting the maintenance and combination option 3 at the same time is 1000 RMB.

3.2. Optimization model

The integer linear programming is adopted to optimize the maintenance plan. The optimization goal is to maximize benefits under certain constraints. Many studies have used TQI as the decision-making basis (Qu, 2010; Shi et al., 2022; Xu, Zhao, et al., 2019). TQI is a comprehensive index that can present the condition of the track line. When TQI increases to the management value, it needs to be taken seriously and included in the maintenance plan, and the goal of maintenance is to control TQI within a certain range. From the perspective of the entire railway network, controlling the overall TQI at an ideal level is the maintenance goal. Therefore, it can be used as an optimization objective.

TQI is the sum of seven individual indicators, including vertical irregularities of the left and right wheels, longitudinal irregularities of the left and right wheels, gauge irregularity, transverse irregularity, and twist irregularity. The TQI calculation formula is as follows:

$$TQI = \sum_{i=1}^{7} \sigma_i \tag{1}$$

$$\sigma_i = \sqrt{\frac{1}{n}\sum_{j=1}^{n}(x_{ij} - \bar{x}_i)^2} \tag{2}$$

$$\bar{x}_i = \frac{1}{n}\sum_{j=1}^{n} x_{ij} \tag{3}$$

where σ_i is the standard deviation of the i-th geometry irregularity, $\bar{x}_i$ is the average of the amplitude values of the sampling points of the i-th geometry irregularity, and n is the number of sampling points (when the length of the UTS is 200 m, n equals 800).

TQI management values of various levels of railways can be found in the maintenance rules. **Table 1** shows the management value of high-speed railway ballastless tracks (Ministry of Railway of China, 2012).

Table 1. Mean management values of the geometry irregularity of the ballastless track of high-speed railway.

Speed (km/h)	Vertical	Longitudinal	Gauge	Transverse	Twist	TQI
200~250	1.4 × 2	1.0 × 2	0.9	1.1	1.2	8.0
250~350	0.8 × 2	0.7 × 2	0.6	0.7	0.7	5.0

This rule states that the track condition is good when TQI and the individual constituent indicators are within the management value range. It should be taken seriously and included in the maintenance plan when it exceeds the management value. However, due to the small management value range, it cannot significantly evaluate the relative level of performance between track sections, which is not conducive to maintenance decisions. If a certain UTS performs exceptionally poorly, it should gain more attention. In response to this issue, this research draws on the results of Xu, Zhao, et al. (2021) to amplify TQI. The main steps are as follows, and the detailed process can be referred to (Xu and Wu et al., 2021).

Their research divides the management values of each irregularity standard deviation into three levels, i.e., "≤st_i/2", "st_i/2~st_i", and ">st_i", and amplifies them using different factors. The formula for calculating the amplified individual indicator is as follows:

$$s_i = \begin{cases} k_1\sigma_i \sigma_i \leq st_i/2 \\ k_2(\sigma_i - st_i/2) + st_i/2 st_i/2 < \sigma_i \leq st_i \\ k_3(\sigma_i - st_i) + k_2(st_i - st_i/2) + k_1 st_i/2 \sigma_i \geq st_i \end{cases} \tag{4}$$

where s_i is the amplified individual indicator, st_i is the management value of i-th individual indicator shown in **Table 1**, and k_1, k_2, and k_3 are amplification coefficients (It is suggested to take the values as 1, 2, and 4, respectively).

Then, the amplified TQI' can be calculated as:

$$TQI' = 1000 - C\sum_{i=1}^{7} \alpha_i s_i \tag{5}$$

where α_i is the weight of each indicator (see **Table 2**), and C is the empirical constant (It is suggested to take the value as 700). The value of *TQI'* varies between 0 and 1000, and the larger the value, the better the track condition.

Table 2. Values of α (%)

	Vertical		Longitudinal				
Item	**Left wheel**	**Right wheel**	**Left wheel**	**Right wheel**	**Gauge**	**Transverse**	**Twist**
α	14.43	13.43	12.64	12.98	16.73	15.57	14.22

The optimization objective can be proposed based on the above methods, as shown in Equation (6).

There are four constraints:

1) Maximum length constraint

During actual maintenance, due to the limited efficiency of machines and the length of time window, there is a limitation on the length of track that can be maintained, which can be formulated as Equation (7).

2) Continuity constraint

Continuity constraint refers to that a UTS can only adopt one maintenance and combination option, either no maintenance & no combination, no maintenance & combination, or maintenance & combination. For each UTS m, it should meet the continuity constraint of Equation (8). If it is the starting point (s) of the network model, it should satisfy Equation (9), and if it is the endpoint (e), it should satisfy Equation (10). In addition, for the same maintenance, the maintenance and combination option chosen for nearby UTSs should be completed simultaneously, so it also needs to meet the constraints of Equation (11). In the equations, t_i^w is the execution period of UTS i of the *w*-th maintenance activity, and $t_{a_n^w}$ is the execution period of the first UTS of *w*-th maintenance activity. The meanings of other parameters are the same as before.

3) Budget constraint

Budget constraint is pervasive, which means that the total maintenance cost cannot exceed the budget. Maintenance costs include fixed costs and variable costs. Fixed cost refers to the one incurred as long as maintenance is carried out, such as the working-day cost of machines and labor cost of workers, etc., which is only related to the number of maintenance. Some studies also consider track occupancy costs as fixed costs (An, 2021). Variable costs occur during the maintenance process, including costs of materials, fuel, and power consumption, and are related to the length of the maintenance. The budget constraint can be formulated as Equation (12), where $Cost_{owner}$ is the maintenance cost, and Ω is the budget.

4) Number of maintenance per period constraint

Due to a limited workforce and resources, there is a limitation on the number of maintenance activities per period in the entire railway network. The total number of maintenance activities in each period cannot exceed the maximum number of activities executed in that period. This constraint can be represented by Equation (13), where Θ_t^{MAX} is the maximum number of maintenance that can be performed in period *t*.

$$MaxZ = \sum_{n=1}^{N}\sum_{m=1}^{N}\sum_{j=1}^{M}\sum_{k=1}^{M}\sum_{x=1}^{T}\sum_{y=1}^{T} \delta_{(n,j,x)-(m,k,y)} \times TQI'_{(n,j,x)-(m,k,y)} \quad (6)$$

where $\delta_{(n, j, x)-(m, k, y)}$ is a binary variable. If the optimized path passes through arcs $(n, j, x) - (m, k, y)$, the value is 1. Otherwise, it is 0. N is the total number of UTSs, M is the total number of maintenance and combination options, and T is the total number of periods. $TQI'_{(n, j, x)-(m, k, y)}$ is the amplified TQI of arc $(n, j, x) - (m, k, y)$.

$$\sum_{n=a_n^w}^{e_n^w} \lambda_n \leq \Lambda^{MAX}\ \forall w \quad (7)$$

where λ_n is the length of UTS n, a_n^w is the first UTS of the w-th (w = 1, …, W) maintenance activity, e_n^w is the last UTS of the w-th activity, and Λ^{MAX} is the maximum allowable length of an activity.

$$\sum_{n=1}^{N}\sum_{j=1}^{M}\sum_{x=1}^{T} \delta_{(n,j,x)-(m,k,y)} = \sum_{n=1}^{N}\sum_{j=1}^{M}\sum_{x=1}^{T} \delta_{(m,k,y)-(n,j,x)}\ \forall (m,k,y) \quad (8)$$

$$\sum_{n=1}^{N}\sum_{j=1}^{M}\sum_{x=1}^{T} \delta_{(s)-(n,j,x)} = 1 \forall (s) \quad (9)$$

$$\sum_{n=1}^{N}\sum_{j=1}^{M}\sum_{x=1}^{T} \delta_{(n,j,x)-(e)} = 1 \forall (e) \quad (10)$$

$$t_i^w = t_{a_n^w}, a_n^w \leq i \leq e_n^w, \forall w \quad (11)$$

$$\sum_{n=1}^{N}\sum_{m=1}^{N}\sum_{j=1}^{M}\sum_{k=1}^{M}\sum_{x=1}^{T}\sum_{y=1}^{T} \delta_{(n,j,x)-(m,k,y)} \times Cost_{owner,(n,j,x)-(m,k,y)} \leq \Omega \quad (12)$$

$$\sum_{n=1}^{N}\sum_{m=1}^{N}\sum_{j=1}^{M}\sum_{k=1}^{M} \delta_{(n,j,1)-(m,k,t)} \leq \Theta_t^{MAX}, k > 1, \forall t \quad (13)$$

4. Case study

4.1. Description

This section demonstrates the method of this paper in the form of a case study. As shown in **Figure 2**, it is a high-speed railway network with six stations connected by five lines, represented by Link 1–5, with lengths of 22 km, 20 km, 18 km, 25 km, and 15 km, respectively. Taking 200 m as the length of a UTS, the entire track network can be divided into 500 units. Number these units, and mark each Link's starting and ending UTS numbers on the figure. For example, the starting UTS number of Link 1 is 1, and the ending UTS number is 110. **Table 3** provides a detailed interpretation of **Figure 2** in the form of a list.

The geometry irregularity data of the railway network was inspected using a track inspection car. The TQI and individual indicators were obtained. Part of the data is shown in **Table 4**. According to the rules (Ministry of Railway of China, 2012), a total of 292 UTSs should be included in the maintenance plan, since their TQI or individual indicator exceeds the management value.

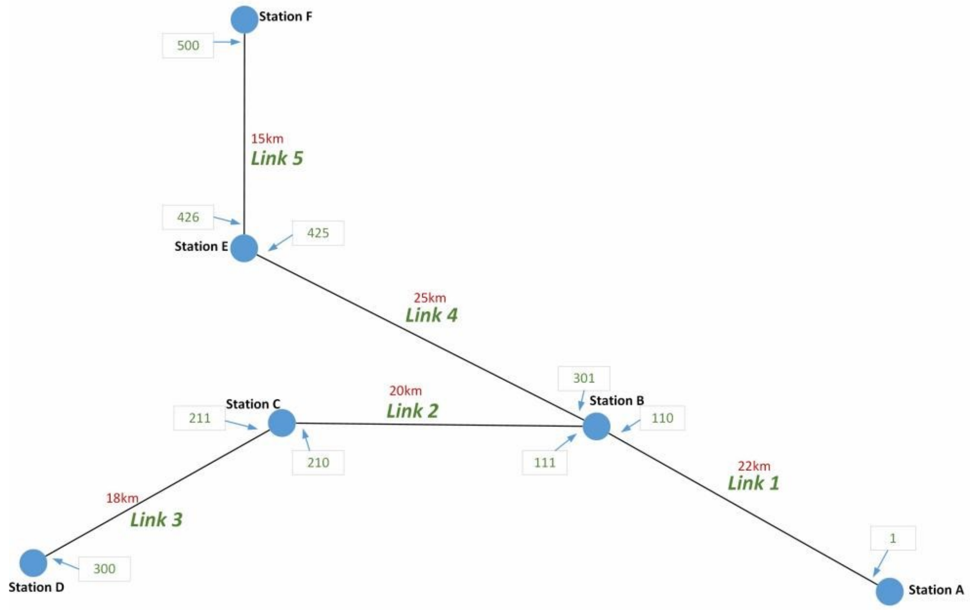


Figure 2. High-speed railway network of the case study.

Table 3. Basic data of the railway network of the case study.

Link	Name	Length (km)	Number of units	Start unit	End unit
1	Station A-Station B	22	110	1	110
2	Station B-Station C	20	100	111	210
3	Station C-Station D	18	90	211	300
4	Station B-Station E	25	125	301	425
5	Station E-Station F	15	75	426	500

Table 4. Geometry irregularity data of some track units of the case study.

UTS	Length (m)	Longitudinal		Vertical		Transverse	Gauge	Twist	TQI
Number		Left wheel	Right wheel	Left wheel	Right wheel				
1	0.3	0.4	0.5	0.5	0.4	0.2	0.6	2.8	0.3
2	0.4	0.5	0.7	0.7	0.6	0.2	0.8	4.1	0.4
3	0.4	0.5	0.7	0.6	0.6	0.2	0.7	3.6	0.4
4	0.4	0.5	0.7	0.6	0.6	0.2	0.7	3.6	0.4
5	0.4	0.5	0.6	0.6	0.6	0.2	0.7	3.5	0.4

The maintenance is executed using machinery. Considering whether to combine and whether to conduct maintenance, there are three maintenance and combination options, namely 1-no maintenance & no combination, 2-no maintenance & combination, and 3-maintenance & combination. According to the maintenance rules (Ministry of Railway of China, 2012), when the TQI is greater than 5mm, it should be taken seriously and included in the maintenance plan. Therefore, for units with TQI > 5 mm, there is only one maintenance and combination option in the next maintenance plan, namely 3-maintenance & combination, whereas other units have three options. The task of this case is to make a yearly maintenance plan. Maintenance can be arranged monthly, i.e., the number of maintenance periods is 12.

Then a network model can be constructed, as shown in **Figure 3**.

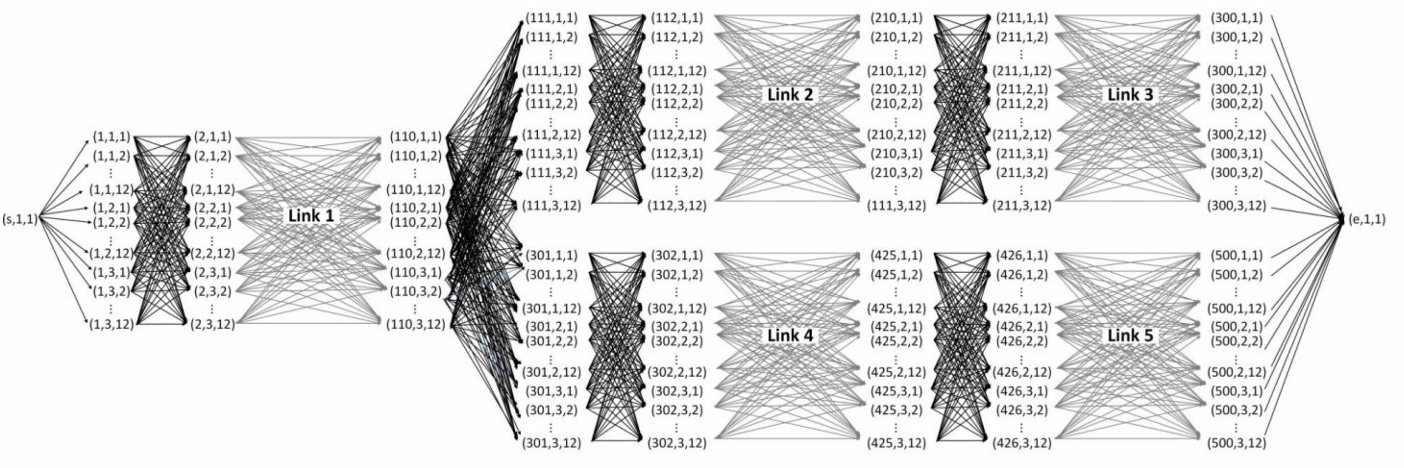


Figure 3. Network model of the case study.

4.2. Cost and benefit calculation

In this case, fixed cost is considered as 20,000 RMB per time (An, 2021), only related to whether maintenance is carried out. As long as there is a maintenance activity, the fixed cost is incurred, usually including expenses such as the working-day cost of machines and fixed losses. The variable cost is 10,000 RMB/km, which is related to the maintenance length and usually includes expenses such as materials, fuel, and power (Xu, Zhao, et al., 2019).

The calculation method of the optimization objective, i.e., the benefits, is introduced in Section 1.2, which refers to the total TQI' of the railway network at the time of the next yearly inspection. For each UTS's TQI', this value is related to whether it is maintained this year and the maintenance time. Typically, as time goes by, the geometry regularity of the track will deteriorate, resulting in an increase in TQI and the individual indicators. Suppose the initial state is good and the deterioration rate is slow. In that case, the irregularity index may still be within the management value range till the time point of the next yearly inspection. Otherwise, the irregularity index may exceed the management value, resulting in poor TQI' value and affecting the total TQI' of the railway network. Suppose maintenance is scheduled for a certain period this year. In that case, the regularity will be recovered to a certain extent after the maintenance, thereby delaying the deterioration of regularity and ultimately affecting the total TQI' of the network. Therefore, it can be seen that the calculation of benefits is closely related to the regularity decay function and the regularity recovery function after maintenance.

In the past few decades, researchers have extensively researched the decay and recovery of regularity and proposed various linear and nonlinear models (Chaolong et al., 2013; Gao et al., 2020; Quiroga and Schnieder, 2012; Xu and Wu, 2005). Since the focus of this paper is on the network optimization model, it is not intended to dive into the exploration of regularity decay and recovery. Instead, a linear model is chosen as the regularity decay prediction model (Xu and Wu, 2005). In terms of recovery, it is assumed that after each maintenance, the regularity can be improved by 20% (Mu et al., 2018), but it cannot exceed the initial value of the track. The decay rate remains consistent before and after maintenance. As shown in **Figure 4**, the initial TQI or individual indicator of a specific unit is σ_0. If maintenance is not carried out, it will decay and follow the trend of Line 1 until it reaches the management value σ_{limit}. Suppose the maintenance is carried out at t_0. Theoretically, the indicator will decrease by 20%, but since the condition cannot be more ideal than the initial value, it can only be reduced to σ_0. After maintenance, it will be developed according to Line 2. Similarly, when maintenance is executed at t_1 and t_2, the condition can only be recovered to σ_0. After maintenance, it will develop according to Line 3 and Line 4, respectively. When maintenance is executed at t_3 and t_4, the performance will improve by 20%. After maintenance, it will be developed according to Line 4.

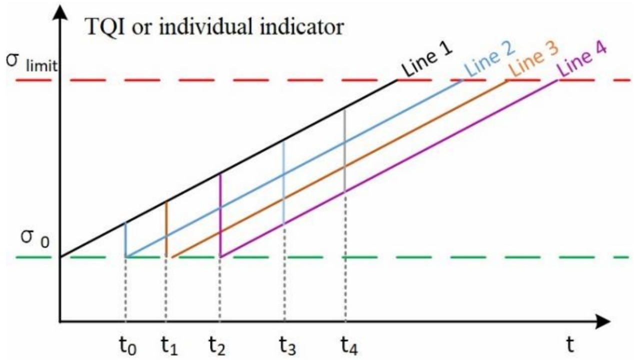


Figure 4. Prediction model of the decay and recovery of the track geometry data.

Therefore, the latest inspected value can be used for each UTS as the current geometry irregularity indicator. A performance decay curve can be fitted based on the previous inspected values. Therefore, for any arc $(n, j, x) - (m, k, y)$, the related costs and benefits can be calculated based on the values of j, x, k, and y.

Case 1: When j is 1 and k is 1, it indicates that for UTS m, it does not execute any maintenance and does not combine the UTS into the project. The cost is 0. The regularity will be developed according to the initial curve. Calculate the indicator value for the time point of the next yearly inspection, which is 365 days later, and calculate the corresponding TQI' as the benefit of this UTS.

Case 2: When j is 1 and k is 2, it indicates that for UTS m, it does not execute any maintenance but combines the UTS into the project. UTS m is the first UTS in this work zone. Therefore, the cost includes only a fixed cost of 20,000 RMB. The benefit calculation is the same as Case 1.

Case 3: When j is 1 and k is 3, it indicates that for UTS m, it executes maintenance and combines the UTS into the project. UTS m is the first UTS in this work zone. The cost includes fixed and variable costs, which is 10,000 RMB/km × 0.2 km + 20,000 RMB = 22,000 RMB. The benefit can be calculated as follows: (1) calculate the irregularity at the moment before maintenance, (2) calculate the irregularity after maintenance, and (3) use the new curve to calculate the indicator value for the time point of next yearly inspection, and convert it into TQI'.

Case 4: When $j > 1$ and k is 1, it indicates that for UTS m, it does not execute any maintenance and does not combine the UTS into the project. The cost is 0. The benefit calculation is the same as Case 1.

Case 5: When $j > 1$ and k is 2, it indicates that for UTS m, it does not execute any maintenance but combines the UTS into the project. UTS m is not the first UTS in this combination, so the cost is 0. The benefit calculation is the same as Case 1.

Case 6: When $j > 1$ and k is 3, it indicates that for UTS m, it executes maintenance and combines the UTS into the project. UTS m is not the first UTS in this combination. Therefore, the cost only includes variable costs, which is 10,000 RMB/km × 0.2 km = 2000 RMB. The benefit calculation is the same as Case 3.

4.3. Optimization analysis

Using the four scenarios in **Table 5** as examples, the impact of different parameter settings on the optimization results is studied. Scenario 1 is the basic scenario with no budget constraint. However, considering the machinery's efficiency and the maintenance time window limitation, the maximum length of each maintenance activity is 7500 m. Considering the constraints of human and material resources, only 10 maintenance activities can be processed per period. For other scenarios, only one parameter changes based on Scenario 1.

Table 5. Scenarios investigated of the case study.

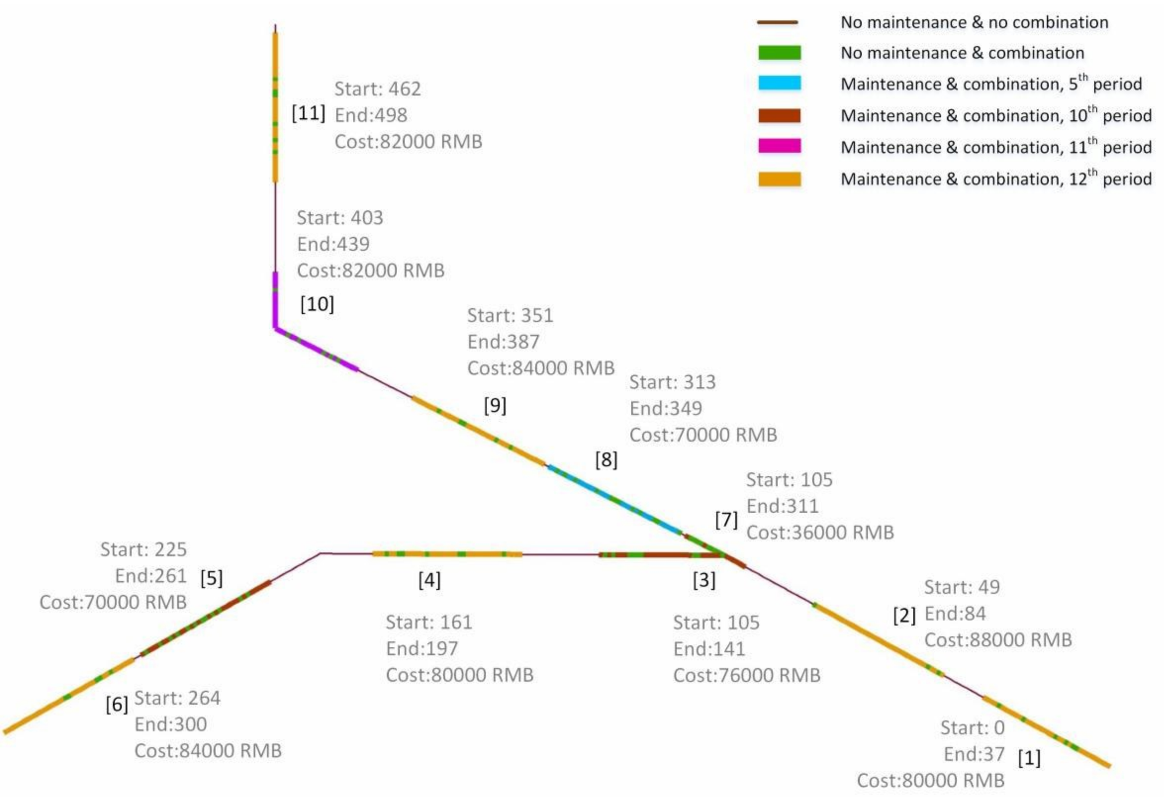
Scenario	Budget (RMB)	Maximum length (m)	Number of maintenance/period
1	800,000	7500	10
2	Unlimited	7500	10
3	800,000	5000	10
4	800,000	7500	5

The optimization algorithm of this study is implemented on Matlab. Considering that the number of UTSs is large, and Matlab's native solver intlinprog does not support parallel computing, to avoid unacceptable high computational costs, this study adopts a mature parallel computing solver Gurobi (Ralphs et al., 2018), which has a Matlab interface and can achieve seamless integration with Matlab. The above task was run on a server with 32 CPU cores and 256 Gb of memory, with an average running time of less than 1 hour for each experiment, which meets practical needs.

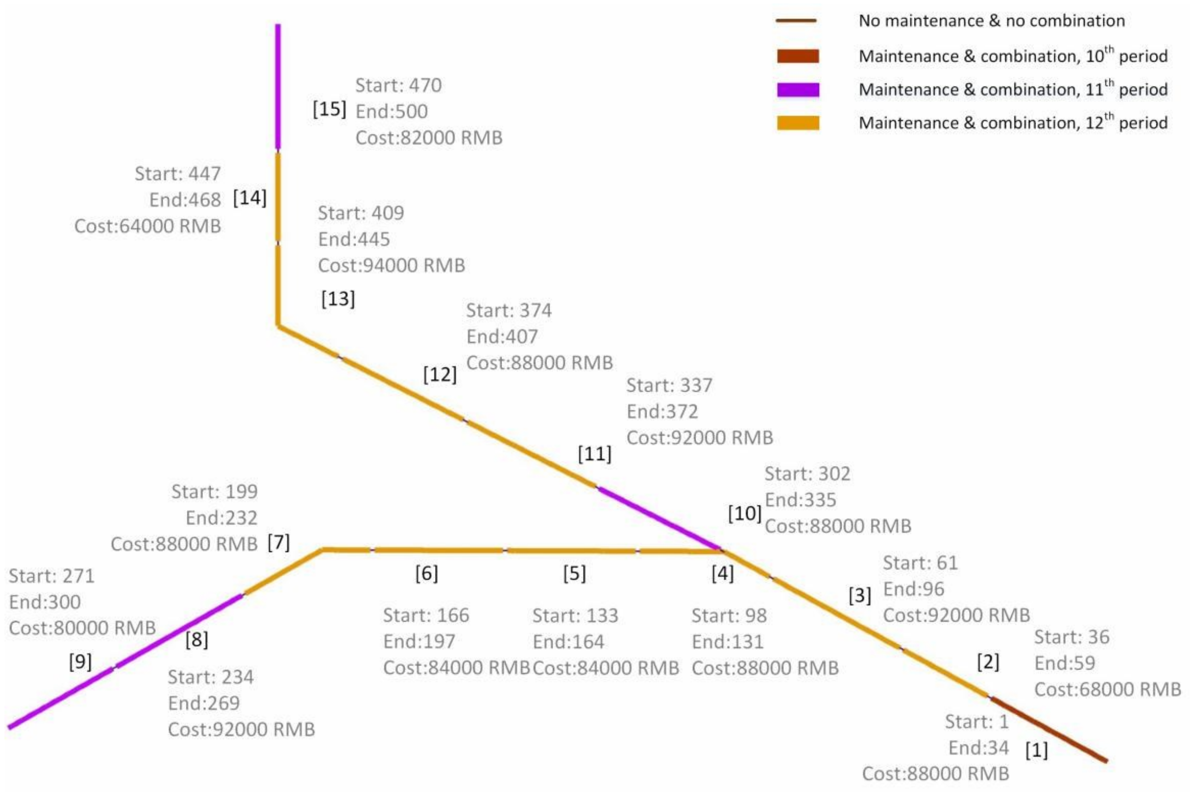
The calculation results for each scenario are shown in **Table 6** and **Figure 5**. **Table 6** lists the number of maintenance activities divided by the optimal solution for each scenario, the number of UTSs selected in each activity, the number of UTSs actually maintained, the total cost, and the total benefit information. Taking Scenario 3 as an example, it is divided into 13 maintenance activities in total. 312 out of 500 UTSs are selected for the activities, of which 280 require maintenance. The total maintenance cost is 800,000 RMB. At the time of the next inspection, the total TQI' of the entire railway network is 310,225.0 mm, which is 98.8% of Scenario 1. **Figure 5** presents the specific maintenance activities for each plan in the form of a map, where the location and time of each activity can be clearly seen. Taking Scenario 1 as an example, a total of 11 maintenance activities were divided. One maintenance activity is planned in the 5th period, three in the 10th period, one in the 11th period, and six in the 12th period. The number of each maintenance is marked with square brackets, and the starting UTS number, ending UTS number, and maintenance cost are listed next to it.

Table 6. Comparison of the maintenance planning schemes of the network of the case study.

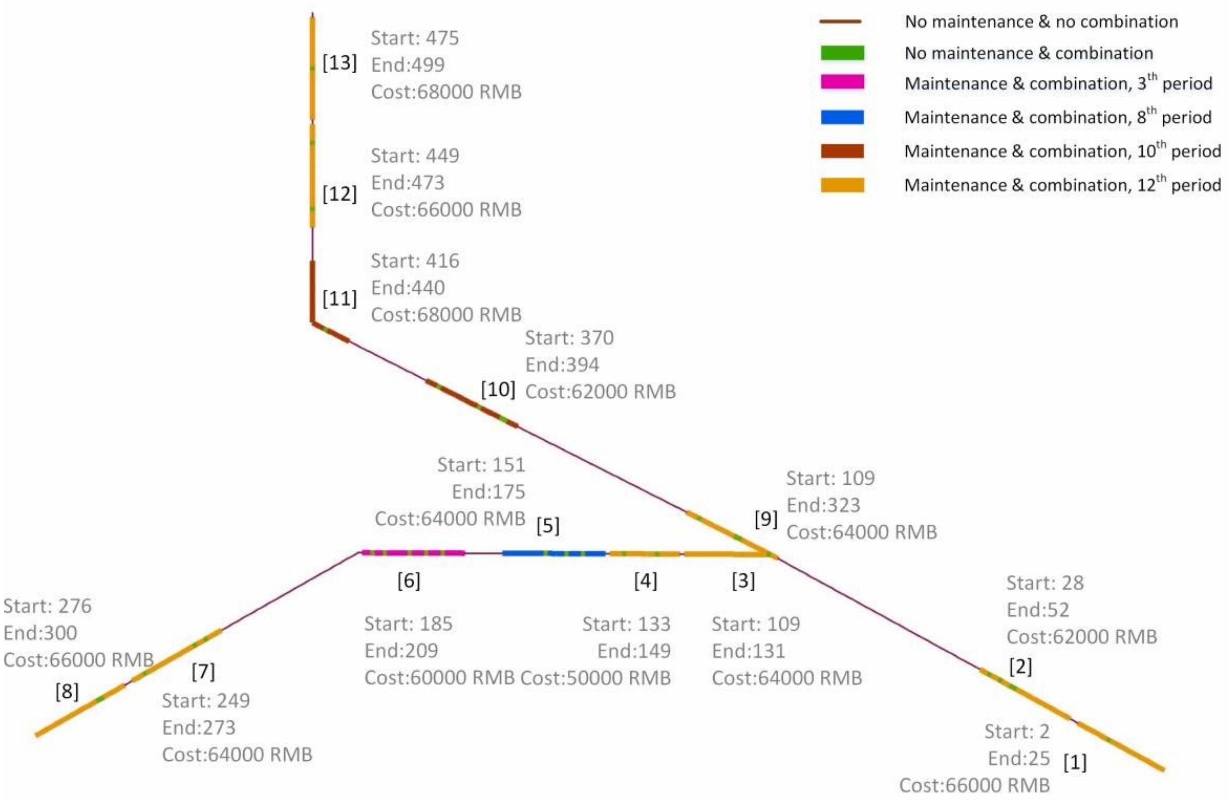
	Number of activities	Number of UTS selected		Total	Total benefit	
Scenario		**For combination**	**For maintenance**	**Cost (RMB)**	**Value (mm)**	**Percentage of Scenario 1**
1	11	380	300	80	313,802.0	-
2	15	486	486	127.2	336,578.4	107.3%
3	13	312	280	80	310,225.0	98.8%
4	13	427	280	80	312,006.4	99.4%



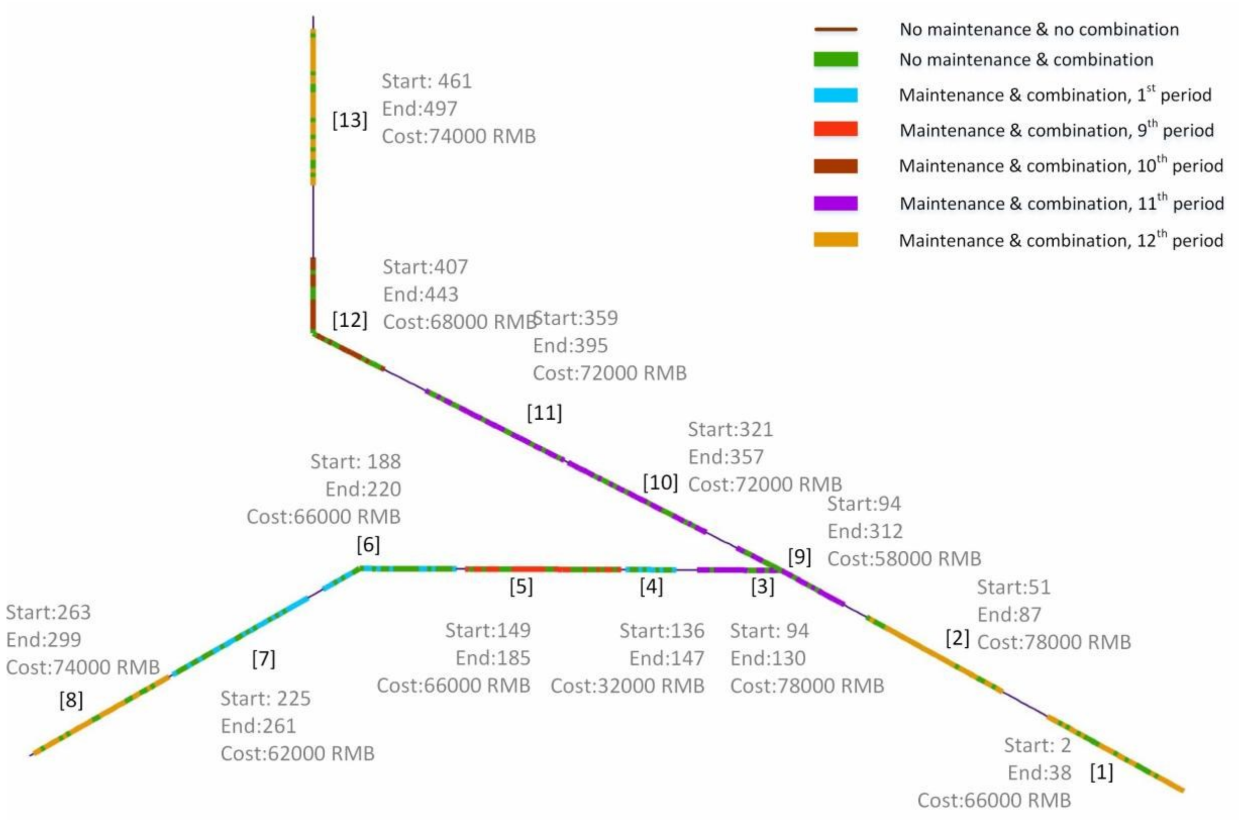
(a) Scenario 1.



(b) Scenario 2.



(c) Scenario 3.



(d) Scenario 4.

Figure 5. Maintenance planning and optimization result of the network of the case study.

Analyzing the data of Scenario 1, it can be seen that this model can: (1) consider constraints such as budget (the actual total cost of Scenario 1 is less than or equal to the budget, which is 800,000 RMB), workforce and material resources (the number of maintenance in each period of Scenario 1 is less than the work capacity, which is 10 maintenance activities per period), and task efficiency (the length of each maintenance activity in Scenario 1 is less than 7.5 km), to obtain the yearly maintenance plan that maximizes the performance of the entire railway network for the time point of next yearly inspection at once; (2) determine the exact location and maintenance and combination option for each maintenance. This model can consider the relationship between UTSs and combine UTSs within a certain distance into one activity, which is beneficial for expanding the scope of maintenance, fully utilizing the efficiency of machinery, and saving costs. The green sections in the figure are the ones that do not execute any maintenance but are combined into the project, which are used to connect and combine the surrounding UTSs into one maintenance activity.

When the budget is not limited (Scenario 2), it is evident that the optimal solution will repair all UTSs (the number of UTSs combined in activities is equal to the number of maintained ones). However, under the constraints of maximum length, workforce, and material resources, these maintenance UTSs were finally divided into 15 maintenance activities assigned to different maintenance periods. The final total maintenance cost is 1.272 million RMB. It shows a certain improvement in performance compared to Scenario 1 and reaches a total benefit, i.e., the total TQI’ of the railway network of 336,578.4 mm, which is 107.3% of Scenario 1.

When the maximum length constraint is reduced to 5 km (Scenario 3), the optimal solution undergoes significant changes compared to Scenario 1. On the one hand, to meet the new maximum length constraint, the combinations in Scenario 1 were decomposed and reconstructed. As an example, the maintenance [11] in scenario 1 is split into two maintenance activities in scenario 3. On the other hand, the number of activities has changed from 11 in Scenario 1 to 13. Due to same budget constraints, as the number of maintenance increases, fixed costs increase, resulting in a decrease in the actual number of UTSs that can be repaired, from 300 in Scenario 1 to 280. The above changes finally affect the overall benefits. The total TQI' of the railway network in Scenario 3 at the time of the next yearly inspection is lower than Scenario 1, accounting for 98.8%.

When the constraint on the number of maintenance per period is reduced to 5 (Scenario 4), the optimal solution changes due to some UTSs being unable to be maintained at the optimal time. The number of activities in Scenario 4 has increased to 13 compared to Scenario 1, with 427 UTSs selected in the combinations and 280 units that can be maintained. The total benefit obtained is 31,206.4 mm, 99.4% of Scenario 1.

Additionally, a distinct advantage of this optimization method is evident from the results of the four scenarios, namely, that through the combination of UTSs, the number of maintenance activities can be significantly reduced. As the original data in section 4.1 indicate, a total of 292 UTSs have TQI or individual indicators exceeding the management value and need to be included in the maintenance plan. In an extreme scenario, assuming that only one UTS can be repaired at a time, a maximum of 292 maintenance activities would need to be scheduled, requiring 292 maintenance windows. Generally, through manual experience, some UTSs can be grouped together to reduce the number of maintenance activities. Since the solutions obtained by this model represent the theoretically global optimal results, even the most experienced engineers' plans would not generate fewer maintenance activities than our solution. The reduction in the number of maintenance activities implies a decrease in the number of maintenance windows required and an expansion of construction scale, which can enhance operational efficiency to a certain extent. This enhancement is of significant importance to the improvement of transportation efficiency.

4.4. Discussion

This case study demonstrates the making of a yearly maintenance plan for a high- speed railway network, considering 12 maintenance periods per year. In fact, this model is applicable to maintenance planning of different scales and time granularity. For larger railway network scales, there are specific requirements for computer performance. It is a solution to use computers with more substantial processing power and larger memory. One can also try clustering, networking, cloud computing, and other methods to achieve large-scale parallel processing. For different time granularity, parameters such as the planning cycle and the number of maintenance periods can be modified. For example, a five-year maintenance plan needs to change the planning cycle to five years. For an annual maintenance plan, if the number of periods is 12, maintenance arrangements can be made monthly; if the number of periods is 4, maintenance arrangements can be made quarterly; if the number of periods is 36, maintenance arrangements can be made ten- day. It is noteworthy that long-term planning tends to be more intricate, necessitating potential adjustments when calculating costs and benefits. For instance, there might be a need to integrate the relationships between maintenance and renewal operations, as well as to incorporate a preference factor for the present (Gaudry et al., 2016). These refinements can enhance the reliability of the outcomes without necessitating substantial modifications to the framework proposed in this paper.

An important factor affecting the optimization results of this model is the selection of the performance decay prediction model and performance recovery model after maintenance. This case study is simplified to a certain extent, and linear function is used to predict the geometry regularity decay, while the recovery model assumes that the performance recovery ratio after maintenance is fixed. The direct consequence of this simplification is that optimization plans tend to prioritize maintenance in the later periods. As shown in **Figure 4**, due to the limited degree of degradation of regularity within a year, if calculated at a fixed proportion after maintenance, the regularity after maintenance will be better than the initial condition. However, in this case, it assumes that the regularity after maintenance will at most return to its initial state (i.e., between 0–t_2), so that the later the maintenance time, the better the regularity at the time point of the next yearly inspection. It also explains why the maintenance plans for each scenario in **Figure 5** are concentrated in periods 10, 11, and 12. To restore the actual situation more realistically, other nonlinear or nonparametric prediction models can be used, such as grayscale prediction, neural networks, etc., to avoid the above problems.

This study uses the geometry regularity index TQI to evaluate track performance and support the making of maintenance plans, mainly considering that there are many existing studies on this index, and it can comprehensively reflect the track status. In fact, it can be substituted by other indicators. Correspondingly, by proposing a new benefit calculation method, a new decay prediction model of the indicators, and a new recovery model after maintenance, a new maintenance plan based on other indicators can be achieved without changing the network optimization model architecture. Therefore, the applicability of this network model is broad.

5. Conclusion and outlook

This paper proposes a network optimization model that can consider the combination of UTSs for planning railway track maintenance. Based on the measured data of track geometry regularity, the maintenance planning problem is transformed into a 0–1 integer linear programming problem through the network model establishment. This model takes the maximization of the total TQI’ of the railway network as the optimization objective, taking into account budget constraint, maximum length constraint, maximum number of maintenance in each period constraint, and continuity constraints. Taking a high-speed railway network with a total length of 100 km as an example, the effectiveness of this method in different scenarios is demonstrated. The following conclusions are drawn:

1) Compared with the method recommended by maintenance rules, this method can objectively make maintenance plans. Compared with existing maintenance planning methods that use mathematical programming, this method can consider the connection between sections and combine the surrounding sections that need maintenance into one maintenance activity, which can expand the scope of operations, fully utilize the efficiency of machinery, and further alleviate the contradiction between railway transportation and maintenance. Compared with previous research (Xu, Wu, et al., 2021), this method can not only determine the location of maintenance but also determine the specific time, achieving spatial-temporal integration of maintenance planning and optimization.
2) This model is suitable for maintenance planning of various scales and granularities. Based on high-performance computers and using a solver that supports parallel processing, the optimal solution can be obtained quickly to meet practical needs. Though this paper takes railway track lines as the research object, it can actually be applied to other infrastructure of railway networks, such as traction power supply, signal facilities, etc. It only requires adjustments to basic data, evaluation indicators, and cost-benefit calculations without modifying the network model. Therefore, future research will attempt to apply the method proposed in this paper to other railway infrastructures to achieve cross-disciplinary comprehensive maintenance planning and optimization.

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