Optimal Maintenance Task Generation and Assignment for Rail Infrastructure

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ABSTRACT

A safe and efficient railway operation relies on a well-maintained system. The expenditure on track maintenance often contributes to approximately half of the maintenance expenditure; therefore, how to properly allocate the resources in track maintenance according to safety, comfort, and cost is an important task in the planning process. This study develops an optimization process to deal with the annual maintenance planning problem. Results from case studies demonstrate that the developed process can successfully identify appropriate maintenance tasks and assign them into the annual maintenance plan by minimizing the costs of expected failures (safety), irregularity (comfort), and maintenance. Adopting this developed process can assist planners to identify the necessary maintenance activities with balance in safety, comfort, and cost, and efficiently create a long-term maintenance plan.

Keywords

Rail Transportation, Track Maintenance, Maintenance Planning, Optimization

INTRODUCTION

A safe and efficient railway operation relies on a well-maintained system. This system requires regular inspection and maintenance for infrastructure, rolling stock, and other related subsystems. Among all the important elements in a railway system, track is the foundation of railway operations and is the fundamental support for a safe and smooth ride. To ensure the safety and comfort of the transportation, alignment of the track has to be maintained within millimeters of the design. Better condition of track ensures higher ride quality and service reliability; however, it may also require greater maintenance expenditure. Therefore, a trade-off exists between track maintenance cost and track quality (including safety and comfort).

On the basis of long-term track maintenance planning process, planners and engineers have to identify the types and amount of maintenance tasks to remedy the deficiencies in alignment. Safety, ride comfort, and cost are the three key elements in planning maintenance work. Safety related requirements are usually determined by the regulations. Comfort of the passengers can be estimated by a set of track quality indicators, which are governed by company standards. Available budget is often a difficult constraint for planners to determine the maintenance tasks.

For the conventional railway in Taiwan, the Taiwan Railways Administration (TRA), the track department at TRA needs to create an annual maintenance plan for the following year on the basis of the condition of the infrastructure around the end of the current year. The process is currently manually performed based on the planners' judgment and experiences. Planners are able to create a feasible maintenance plan according to all the safety requirements and constraints on resources. However, optimally allocating resources is extremely difficult because of the complex trade-off among safety, comfort, and cost, especially for a long period of time, such as one year.

Most previous research on maintenance planning look into only a particular type of maintenance task, such as tamping (*1-3*) and rail grinding (*4, 5*). In addition, past studies usually plan maintenance based on given maintenance tasks (*6-9*); hence, they are not able to identify possible maintenance tasks according to the condition of the infrastructure. Lovett et al. (10) developed a process for North American freight railroads to identify necessary maintenance activities and then schedule these tasks within a time horizon. Although safety and maintenance costs were considered in their research, indicators and considerations for passenger railway, such as ride comfort, were not discussed.

To assist the TRA of maintenance planning process, this study develops an optimization process to deal with annual maintenance planning problem including both generation and assignment. The optimization process aims to allocate resources to maintain the track at an acceptable quality by minimizing the cost of expected failures (safety), cost of irregularity (comfort), and the cost of maintenance. Using this process can assist maintenance planners to identify the balance in safety, comfort, and cost, efficiently creating a long-term maintenance plan.

MAINTENANCE PLANNING PROCESS AT TRA

The maintenance planning processes is currently performed by experienced planners in the track department at TRA. On the basis of defects and irregularities, planners have to identify the types and amount of maintenance tasks to remedy the problems. Maintenance planning is an annual planning activity, which determines appropriate maintenance tasks by segment or section, and assigns them into particular month in the decision horizon (usually a year).

Track Maintenance Planning

Figure 1a shows the process of maintenance planning, including task identification and assignment. A number of input data exist, including network and geometry, timetable and traffic, track component, and their quality indicators, deterioration rate, regulation and standards, and budget. On the basis of these input data, planners have to identify appropriate maintenance activities based on the safety, comfort, and cost. Safety is governed by the requirements of the regulations. Necessary maintenance activities have to be implemented to meet the requirements. In addition, safety should also be evaluated by the cost of expected failures, which can be computed based on the expected number of failures and the corresponding cost. Ride comfort is usually denoted by the level of track irregularities against the requirements from the standard. The third important consideration is the maintenance cost from the maintenance activities.

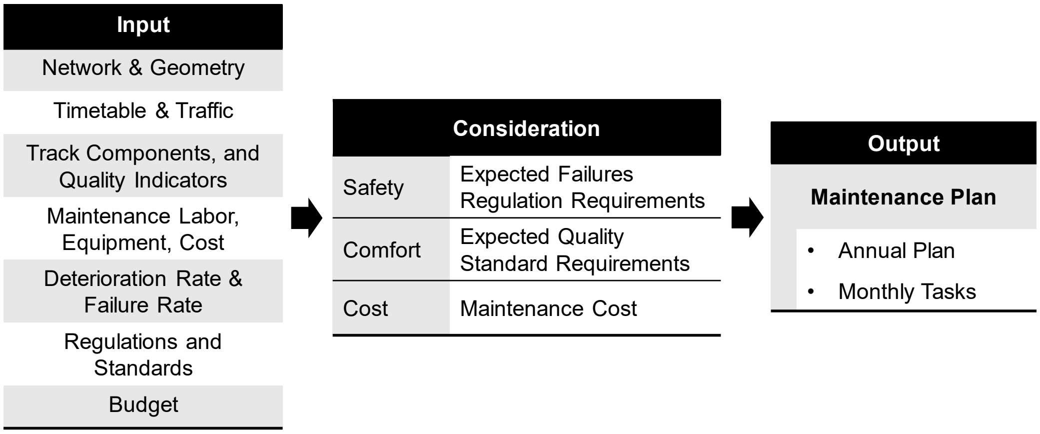


Figure 1. Input, consideration and output of maintenance planning problem.

Table 1 demonstrates the thresholds of a list of track quality indicators, such as the five indicators of irregularities, railhead area loss, and rail wear with their requirements from regulations and standards. The emergency thresholds are governed by the regulations, as are the upper limit for the track irregularity. The maintenance thresholds are governed by the standards of TRA, which is the threshold for considering corresponding maintenance activities. In other words, maintenance thresholds can be violated if necessary but not the emergency thresholds. However, planners usually would like to keep the irregularity around the maintenance values if possible because these values can be seen as the lower bound of the ride comfort. Aside from the indicators in Table 1, another important indicator is the accumulative load passing through the section, which contributes to conditions of rail surface, interior, and weld. This attribute and the corresponding failure rate should also be monitored over time.

Table 1. Maintenance and emergency thresholds of track quality indicators for TRA

Track Quality Indicator		Maintenance Threshold	Emergency Threshold
Irregularity	Gauge	10 mm	20 mm
	Level	11 mm	-
	Vertical	13 mm	23 mm
	Horizontal	13 mm	23 mm
	Torsion	-	23 mm
Railhead Area Loss			22%
Rail Wear			15 mm

Maintenance activities can also be separated into section-type maintenance or segment-type maintenance. A track section is the link between adjacent stations and a segment is a basic unit of track considered in railroad asset management, which is usually 200 m for TRA. Hence, different types of maintenance have different requirement on labor and equipment resources. All these factors have to be considered in the process to identify necessary maintenance activities. After identifying necessary maintenance activities, planners can then assign these tasks to each month of the year by considering the constraints on labor and equipment. The annual maintenance plan including monthly activities will then be passed to the maintenance scheduling process for creating detailed schedules.

METHODOLODGY

This study develops an optimization process to deal with annual maintenance planning problem. The following sections present the optimization models of this module.

Maintenance Generation and Assignment Module

The maintenance generation and assignment module generates and assigns appropriate maintenance tasks to each track section or segment within a year based on a number of input listed in Figure 1. This model is formulated as a mixed-integer programming (MIP) model by minimizing the cost of maintenance and passenger comfort. The notations in this module are as follows: i is the index for track section between two adjacent stations, where I is the set of all track sections in network, i.e., $i \in I$. j is the index for track segment, where J is the set of all track segments, i.e., $j \in J$; J_i is the subset in J for track segments j that belong to track section i. p, q are the indices for types of maintenance tasks, where P is the set of all types of maintenance tasks, i.e., $p, q \in P$. P^O and P^A are the subsets in P, where P^O represents segment-type maintenance tasks and P^A represents section-type maintenance tasks. g is the index of track quality indicators including five types of track irregularities, railhead area loss and rail wear of track profile and accumulated train loads of track components, *i.e.,* $g \in G$. G^{TI}, G^{RW} and G^{FT} are the subsets in G, which G^{TI} represents five types of track irregularities, G^{RW}represents rail wear and railhead area loss and G^{FT} represents the failure types of the track components. P_g^{RC} and P_g^{RP} are the subsets in P which P_g^{RC} represents replacement-type maintenance that can affect track quality indicators g and P_g^{RP} represents repair-type maintenance that can affect values of track quality indicators g. n is the index of different type of trains, which will be used to estimate the impact of track irregularities, where N is the set of train types, i.e., $n \in N$. k is the index of time interval (i.e., month in this formulation), where K is the set of planning period, i.e., $k \in K$; K_p is the subset in K for the months in which task p can be assigned.

C_p^O is the unit cost for segment-type maintenance tasks. C_p^A is unit cost of section-type maintenance task. C_{njk}^C is the comfort cost computed by estimated passenger number and accumulated train loads of train type n on track segment j in month k. L_j^O and L_i^A denotes the length of each track segment j and track section i respectively. δ_g is the deterioration rate of track quality indicator g due to the accumulated train loads can be obtained from historical data and literatures *(11-14)*, and γ_{gp} is the recovery values of track quality indicator g due to maintenance task p. R_g^{EM} is the emergency threshold of track quality indicator g set by the regulations; whereas R_g^{NM} is the maintenance threshold of track quality indicator g set by the standard (Table 1). Ω is an arbitrarily large value.

This model has two types of decision variables, namely, assignment of maintenance tasks and values of track quality indicators.

1. Assignment of maintenance tasks:

   (a) y_{jpk}^O is a binary variable that denotes maintenance task assignment to track segment, where

$$y_{jpk}^O = \begin{cases} 1, & \text{if the maintenance task } p \text{ is assigned } to \text{ track segment } j \text{ in month } k \\ 0, & \text{otherwise} \end{cases}$$

   (b) y_{ipk}^A is a binary variable that denotes maintenance task assignment to track section, where

$$y^A_{ipk} = \begin{cases} 1, & \text{if the maintenance task } p \text{ is assigned on track section } i \text{ in month } k \\ 0, & \text{otherwise} \end{cases}$$

2. Values of track quality indicators:

   b_{jgk} is a positive variable that denotes the value of each track quality indicator g on track segment j in month k, which is affected by the maintenance tasks related to g and the daily operation of trains on track segment j.

The following is the MIP model for maintenance generation and assignment module:

$$Min\ \ C = \sum_{k\in K}\sum_{p\in P^D}\sum_{j\in J} C^O_p L^O_j y^O_{jpk} + \sum_{k\in K}\sum_{p\in P^C}\sum_{i\in I} C^A_p L^A_i y^A_{ipk} + \sum_{k\in K}\sum_{g\in G^{TI}}\sum_{j\in J}\sum_{n\in N} C^C_{njk}\, b_{jgk}/R^{NM}_g \tag{1}$$

Subject to

$$b_{jgk} - b_{jg(k-1)} \tag{2}$$

$$\geq \begin{cases} \alpha_{jk}\delta_g - \sum\limits_{p\in P^A\cap P^{RP}_g} \gamma_{gp} y^A_{ipk} - \sum\limits_{p\in P^O\cap P^{RP}_g} \gamma_{gp} y^O_{jpk} - \Omega \sum\limits_{p\in P^{RC}_g} y^O_{jpk}, \forall i \in I, j \in J_i, g \in G^{TI}, k \in K \\ \alpha_{jk}\delta_g + \sum\limits_{p\in P^A\cap P^{RP}_g} \gamma_{gp} y^A_{ipk} + \sum\limits_{p\in P^O\cap P^{RP}_g} \gamma_{gp} y^O_{jgk} - \Omega \sum\limits_{p\in P^{RC}_g} y^O_{jpk}, \forall i \in I, j \in J_i, g \in G^{RW}, k \in K \\ \alpha_{jk} - \Omega \sum\limits_{p\in P^{RC}_g} y^O_{jpk}, \quad \forall j \in J, g \in G^{FT}, k \in K \end{cases}$$

$$b_{jgk} \leq R^{EM}_g,\ \forall j \in J, g \in G, k \in K \tag{3}$$

$$y^O_{jpk} + y^A_{ipk} = 0,\ \forall i \in I, j \in J_i, p \in P, k \notin K_p \tag{4}$$

And

$$y^O_{jpk}, y^A_{ipk} \in \{0,1\}, \quad \forall i \in I, j \in J_i, p \in P, k \in K \tag{5}$$

$$b_{jgk} \in R^+, \quad \forall j \in J, g \in G, k \in K$$

The objective function [Equation (1)] minimizes the summation of costs: (1) cost of maintenance (section and segment), computed by unit maintenance cost of type p multiplied by the length of maintenance; (2) cost of passenger comfort, estimated by product of the ticket fare and the ratio of irregularities, representing the loss in passengers' comfort. The ticket fare that a passenger pays should guarantee a certain level of comfort from the transportation; therefore, if any deviation exists between the actual values and the ideal values, then it can be transformed to the benefits loss of passengers.

Equation (2) calculates values of the track quality indicator with deterioration and recovery due to operation and maintenance over time. For the five types of irregularities, $g \in G^{TI}$, the values of track quality indicators can be recovered after repair-type maintenance or the value will be reset to zero once a replacement-type task is assigned on that track segment j. For rail wear and railhead area loss, $g \in G^{RW}$, the values of track quality indicator will be conversely increased after rail grinding or the values will be reset to zero once a replacement-type is assigned on that track segment j. For the accumulated train loads, $g \in G^{FT}$, the values of track quality indicator, the load, changes according to the operating plan or returns to zero after replacement-type of maintenances. Equation (3) ensures that the track quality should be below the emergency thresholds (R_g^{EM}). Equation (4) ensures that maintenance tasks cannot be assigned on months forbidden according to the standards. Equation (5) describes the properties of the variables.

EMPIRICAL STUDY

To demonstrate the applicability of the proposed model, one case study based on the TRA network was selected and analyzed. The selected corridor is 64.35 km in length along the west corridor of Taiwan near Taichung area with 14 stations, 13 sections and 315 track segments (Figure 2). The case involves comparing the solution quality of the annual maintenance plan between the manual process and the optimal solution at a given budget.

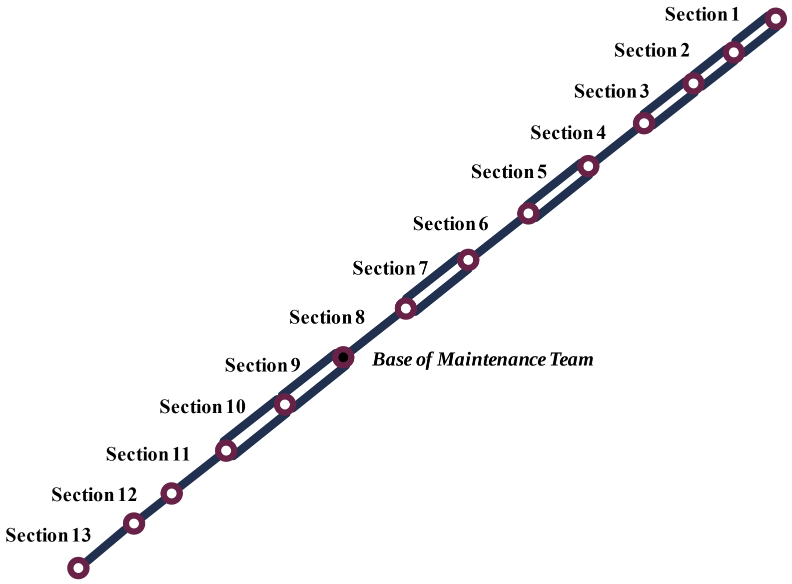


FIGURE 2. Network structure for empirical cases.

Case Study: Maintenance Planning

The input data are the inspection values of track quality indicators. In Table 2, the five values of irregularities denote the initial condition of each track section, which means the deviation in millimeter of track section from its ideal situation; the values of rail profiles are the initial amounts of railhead loss (mm^2) and rail wear (mm); and the values of failure types mean the accumulated train loads in MGT at the beginning of the planning horizon. Three maintenance teams exist on this corridor, which contain a total of 21 employees. Therefore, the amount of tasks in each month is restricted by the labor resource, which is equal to the number of workers multiplied by work days per month and work hours per day, resulting in 3,780 labor-hours per month. The annual maintenance budget is 110 million new Taiwan dollar (NTD).

TABLE 2. The initial values of track quality indicators

	Irregularity					**Rail Profile**		**Accumulated Train Load**			
	Horizontal (mm)	Vertical (mm)	Torsion (mm)	Gauge (mm)	Level (mm)	Surface (mm)	Area (mm^2)	Interior (MGT)	Surface (MGT)	Weld (MGT)	Sleeper (MGT)
Section 1	11.48	9.25	9.22	13.69	11.22	4.16	114.07	31.97	30.76	28.86	217.09
Section 2	11.76	11.91	11.52	10.58	10.30	3.43	142.79	32.42	25.37	29.54	173.66
Section 3	10.75	10.43	10.94	11.22	10.15	4.09	132.84	30.27	30.19	31.74	238.76
Section 4	12.43	11.18	10.08	9.41	9.60	4.01	147.88	31.87	28.66	29.31	193.60
Section 5	10.26	12.14	11.61	9.04	9.95	3.93	154.87	33.07	29.85	31.03	219.01
Section 6	12.20	11.76	10.39	9.90	8.99	3.29	118.65	33.75	22.69	31.76	266.65
Section 7	11.03	11.85	11.83	8.80	10.02	4.10	127.08	34.90	28.77	32.92	233.55
Section 8	10.00	10.51	10.77	9.13	10.68	2.76	148.75	28.01	33.91	31.04	299.08
Section 9	13.59	10.39	11.49	11.56	10.82	3.81	127.19	26.71	29.06	28.53	285.68
Section 10	11.74	12.23	11.23	9.61	8.80	4.70	148.03	29.28	32.90	35.00	230.11
Section 11	12.07	12.47	12.84	13.09	10.38	4.93	141.09	32.63	31.16	29.77	313.55
Section 12	9.88	10.55	9.46	8.70	10.04	4.13	130.63	31.64	30.37	34.06	290.44
Section 13	9.98	10.47	10.20	8.96	12.04	4.65	114.07	33.22	24.73	22.84	306.77

The MIP model developed in our model is solved by using CPLEX. Table 3 shows the results of the manual plan and the optimal plan. This table displays a number of maintenance tasks identified through the process and assigned to each month in the year. The optimal plan identified more number of large scale maintenance tasks, such as ballast replacement and machine tamping, than the manual plan. Both types of maintenance activities require higher maintenance resources but can also better recover the problems in the infrastructure. This finding shows that manual decisions are usually nearsighted, thereby resulting in more minor maintenances, while the optimal process will take long-term effect into consideration to optimize the total cost and benefits.

TABLE 3. Maintenance plan based on (a) manual process (b) optimization process

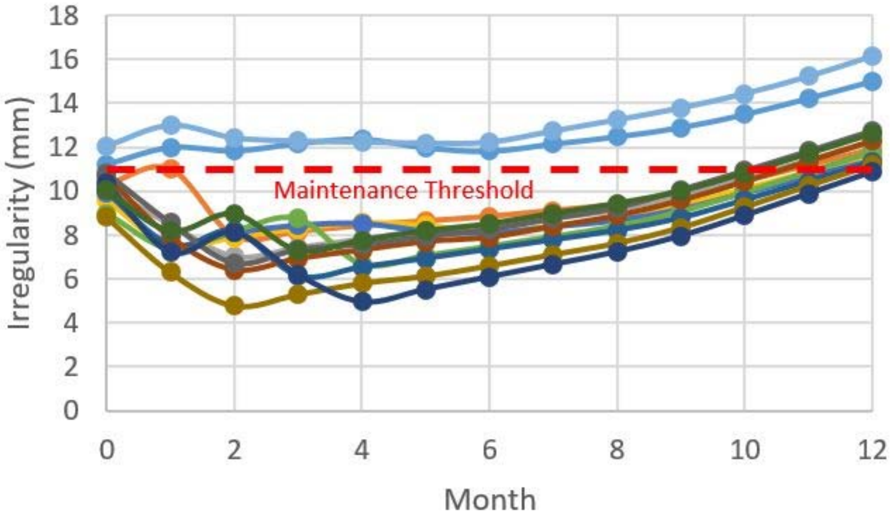
(a)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
Ballast Replacement	0	0	0	0	0	0	0	0	0	0	0	0	0
Machine Tamping	10	5	3	2	0	0	0	0	0	0	0	0	20
Manual Tamping	254	141	89	62	185	164	0	0	150	0	85	0	1,130
Ballast Injection	0	98	68	46	48	49	0	0	6	0	0	0	315
Ballast Stabilization	274	156	92	69	75	106	20	92	93	66	92	0	1,135
Ballast Marshal	284	175	129	108	185	84	315	235	108	49	60	13	1,745
Rail Replacement	0	0	0	0	0	0	0	0	0	0	0	0	0
Rail Grinding	0	0	0	0	0	0	2	1	0	1	9	0	13
Weld Repair	0	0	0	0	0	0	0	0	0	0	0	0	0
Irregularity Correction	55	196	234	292	313	313	315	315	181	47	87	30	2,378
Sleeper Replacement	29	6	2	2	0	0	0	0	0	0	0	0	39
Fastening Repair	0	0	0	0	0	0	0	0	0	0	0	0	0
Subgrade Work	1	1	1	1	1	1	1	1	1	1	2	1	13
Environmental Work	40	40	40	40	40	40	40	50	90	80	40	90	630
Labor-hours	3,779	3,779	3,777	3,778	3,779	3,779	3,645	3,598	2,960	2,753	3,235	2,338	

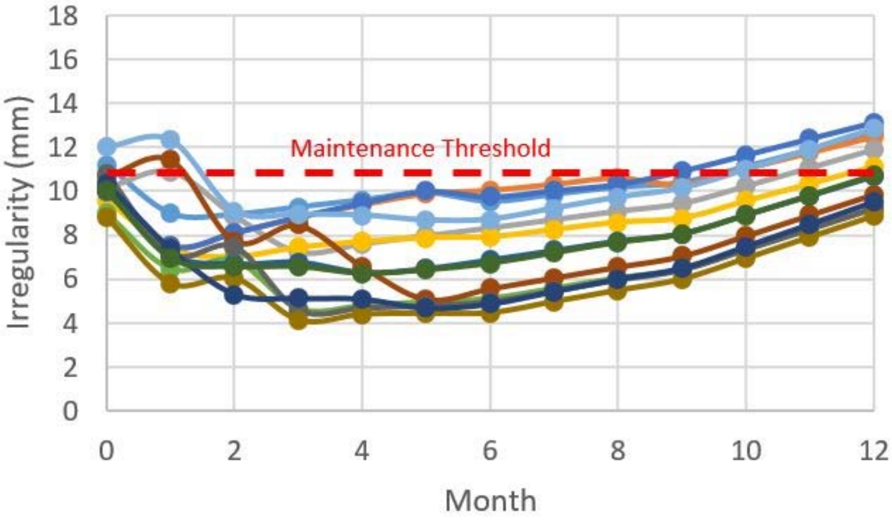
(b)

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	Total
Ballast Replacement	0	0	0	0	0	0	0	0	0	10	3	0	13
Machine Tamping	10	4	4	1	1	0	0	0	0	12	2	0	34
Manual Tamping	196	161	154	104	91	70	0	0	25	0	0	0	801
Ballast Injection	19	12	50	55	87	68	0	0	24	0	0	0	315
Ballast Stabilization	247	179	166	106	91	71	0	0	25	0	0	0	885
Ballast Marshal	285	251	244	258	246	271	315	315	137	10	5	3	2,340
Rail Replacement	0	0	0	0	0	0	0	0	0	0	0	0	0
Rail Grinding	0	0	0	0	0	0	0	1	2	5	13	0	21
Weld Repair	0	0	0	0	0	0	0	0	0	0	0	0	0
Irregularity Correction	52	186	176	268	265	307	315	315	288	18	5	0	2,195
Sleeper Replacement	54	25	9	1	0	0	0	0	0	0	0	0	89
Fastening Repair	4	0	0	0	0	0	0	0	0	0	0	0	4
Subgrade Work	0	0	0	0	0	0	1	1	1	2	5	3	13
Environmental Work	0	0	0	0	0	0	60	131	99	126	105	109	630
Labor-hours	3,779	3,778	3,778	3,776	3,780	3,779	3,780	3,569	3,699	2,943	3,333	2,697	

Figure 3 shows the level irregularity of 13 track sections over time for the entire year. The irregularities are all below the emergency threshold set by the regulations and are close to the maintenance threshold by the standard. Compared with the manual plan, the optimal plan tends to maintain the irregularity among all sections within a smaller range and below the maintenance threshold for most of the time due to the consideration of passenger comfort. In addition, the quality of the sections from the optimal plan are consistent with the level of the traffic volume and ridership. More resources are allocated to sections with more ridership, thereby contributing to higher passenger satisfaction than the sections with less passengers.



(a)



(b)

FIGURE 3. Sectional level irregularities in Case I: (a) manual plan; (b) optimal plan

Table 4 shows the results of the objective values from manual and optimal plans. With the given budget at 110 million NTD, both plans require similar amount of maintenance cost but the outcome in cost of expected failures and passenger comfort are different. As mentioned before, the optimization module takes the whole decision horizon into consideration resulting in more number of large scale maintenance tasks and lower costs on expected failure and passenger comfort than the myopic decisions from manual process. Compared to the manual plan, the savings from the optimal plan in total cost is about 10%. Results from this case study demonstrate clear advantages of using the developed module.

TABLE 4. The cost values of manual plan and optimal plan

	Manual Plan	Optimal Plan
Maintenance Cost (NTD)	110,000,000	109,999,457
Failure Cost (NTD)	47,236,274	16,050,962
Passenger Comfort Cost (NTD)	428,865,417	402,627,128
Total Cost (NTD)	586,101,691	528,677,548

CONCLUSIONS

This study develops an optimization process to deal with the annual maintenance planning problem. Results from the case studies demonstrate the developed process can successfully identify appropriate maintenance tasks and assign them into the annual maintenance plan by minimizing the costs of expected failures, irregularities, and maintenance. Using this process can assist maintenance planners to identify the balance in safety, rider comfort, and cost, and efficiently create a long-term plan maintenance plan.

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