Train-set Assignment Optimization with Predictive Maintenance

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Abstract
The efficiency of rolling stock utilization is an important objective pursued in practice. Rolling stock assignment plan including the assignment of utilization paths and maintenance tasks. Previous studies have adopted the fixed periodic maintenance (PM) strategy; however, the difference in the reliability of rolling stock is not considered. Maintenance planners have to manually adjust utilization and maintenance tasks on the basis of experience. Consequently, this study proposes an optimization process for assigning rolling stock to utilization paths and maintenance tasks in accordance with the predictive maintenance strategy (PdM) with trainset-specific reliability models. Results of the empirical study demonstrate that the developed process with PdM can assign utilization paths and schedule maintenance tasks to each trainset efficiently and reduce the total cost by over 14% compared with the PM-only strategy. Adopting this process can help planners improve the efficiency and reliability of rolling stock utilization.

Keywords
Train-set assignment, maintenance scheduling, and predictive maintenance

1 Introduction

Train-set is an expensive asset of a railway system (Caprara et al. (2007); Cheng (2010)). Taiwan Railways Administration (TRA), manages and maintains a number of train-sets through train-set assignment, which includes the assignment of utilization paths and schedule of maintenance tasks. In practice, maintenance scheduling is performed with periodic maintenance (PM) strategy. For train-set of the same type, a fixed set of rules is applied to all of them because their quality and performance are supposed to be similar. However, the reliability of each train-set is actually unique and may differ. Previous studies have adopted the fixed PM strategy for the train-set assignment problem (Yun et al. (2012); Li et al. (2016)) but maintenance intervals cannot be flexibly adjusted according to the difference in train-sets. Although a few studies have considered the reliability of train-sets, maintenance thresholds remain fixed without any flexibility (Moghaddam and Usher (2011); Asekun (2014)). To perform effective train-set maintenance scheduling, researchers proposed the predictive maintenance (PdM) strategy, such as wheelset maintenance (Li et al. (2014)). Other studies have adopted PdM in train-set maintenance by assuming a fixed degradation rate (Herr et al. (2017)). These studies resulted in a local optimum rather than the global optimum.

With the rise of big data analysis and artificial intelligence (AI) techniques, a train-set specific reliability model can now be obtained from reliability and maintenance data over time. We propose an optimization process for assigning train-set to utilization paths and scheduling maintenance tasks in accordance with the PdM strategy with train-set specific reliability models. Using this process can help planners evaluate the trade-off between reliability and cost.

2 Train-set Assignment and Maintenance Problem

The train-set assignment plan of TRA includes the assignment of utilization paths and maintenance schedules in accordance with utilization schedule (demand) and maintenance requirements. A utilization schedule contains a set of utilization paths created based on a timetable. Each utilization path identifies the ideal type and amount of train-set to meet the demand. However, if a particular type of train-set is unavailable, an alternative type of train-set can be used subject to a penalty cost (i.e., replacement cost) due to the difference in seat arrangements.

Table 1 presents the maintenance rules of commuter train-sets at TRA. The rules include four levels, namely, daily maintenance (DM), monthly maintenance (MM), bogie maintenance (BM), and general maintenance (GM). Fixed thresholds by accumulative operating days are adopted by these PM rules. High maintenance levels (BM and GM) are scheduled in advance for each train-set. These levels require longer maintenance times and consider the limited workshop capacity. By contrast, low maintenance levels (DM and MM) must be considered during the assignment at the operational level along with restrictions on maintenance location and capacity. The DM process takes approximately an hour whereas MM requires a day and thus cannot be performed during the connection or an overnight period in a utilization path. The maintenance tasks of high maintenance levels include all maintenance tasks in low maintenance levels; therefore, after one class of maintenance process, all accumulative operating days of the executed maintenance level and the corresponding low maintenance level return to zero. Previous studies have improved the efficiency of train-set usage. Their processes do not consider train-set specific reliability. Hence, this research examines the possibility of PdM strategy in this process and its potential benefit.

Table 1: Maintenance regulations in TRA

Maintenance level	**Accumulative operating days**	**Maintenance location**
DM	3 days	Train-set depot
MM	3 months	Train-set depot
BM	3 years	Workshop
GM	6 years	Workshop

3 Methodology

According to literature (Kaczor and Szkoda (2016); Yin et al. (2017)), a two-parameter Weibull distribution is suitable for describing the degradation of a train-set. Figure 1 lists the input, output, and consideration of train-set assignment planning. With the input regarding train-set and maintenance, this process assigns train-set to utilization paths and maintenance tasks by considering the costs, reliability, and efficiency of the utilization.

These objectives can be attained by minimizing the maintenance costs and expected costs of failure. Efficiency of utilization can also be ensured by the minimization of the MM cost because the less frequent MM is, the better the train-set availability is.

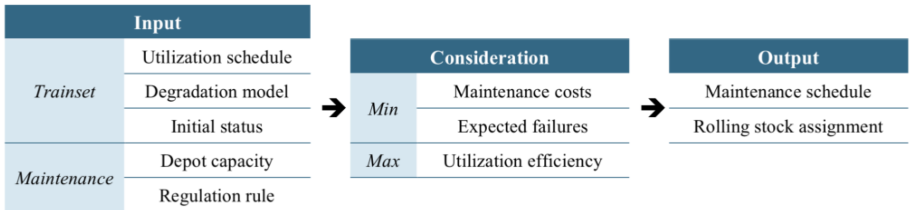

Figure 1: Input and output of train-set assignment planning

To identify and assign appropriate maintenance tasks to each tension section for a year according to reliability evaluation, a mixed-integer programming (MIP) model is formulated by minimizing expected cost of failures, expected cost of operation loss, and expenditure on maintenance. Inspection tasks are ignored in this model because they are not scheduled in the annual maintenance planning process.

I denote the set of all partial utilization paths; I^A, I^B, I^O and I^I are the subset in J that represents DM paths, MM paths, operational paths and starting partial paths; K denote the set of all time intervals and K^I is the subset of all starting time intervals for partial path I^I; S denotes the set of all stages that discretize accumulative days; U denotes the set of types of train-set; V denotes the set of all available train-sets.

C^D, C^M and C^H represent the cost for DM, MM, and train-set replacement; D^A denotes the accumulative operating days upper bound for DM; F denotes the expected cost of failures; $F_{v,s}$ denotes the discretized expected number of failures on train-set v in each stage s; G denotes the MM capacity in the depot; $N_{u,i}$ denotes number of train-sets of type u required in partial path i; P denotes number of discrete stages in each period; P_i denotes operation time of partial path i; Q denotes minimum number of times of MMs need per week; S_i denotes mileages of partial path i; M denotes the relatively large positive number; W denotes the relatively small positive number ensuring that all accumulative values return to zero.

$d^A_{v,k}$ and $d^B_{v,k}$ are non-negative integer indicates the DM and MM accumulative operating days of train-set v at the end of time interval k; $f_{v,k}$ is non-negative integer denotes the expected number of failures on train-set v of time interval k; $q_{u,i,k}$ is binary integer that indicates whether the partial path i in time interval k is operated by type u or not; $x_{i,v,k}$ is binary integer that expresses whether train-set v operates partial path i in time interval k or not; $z_{v,k}$ and $r_{v,k}$ are binary variables that denote whether train-set v executes DM or MM in time interval k or not; $\theta^+_{v,k,s}$ and $\theta^-_{v,k,s}$ are auxiliary binary variables that linearize the nonlinear function.

The MIP model is as follows:

Objective function

Min

$$C^D \sum_{v\in V}\sum_{k\in K} z_{v,k} + C^M \sum_{v\in V}\sum_{k\in K} r_{v,k} + C^H \sum_{u\notin U^i}\sum_{i\in I}\sum_{k\in K} q_{u,i,k}$$
$$+F\sum_{v\in V}\sum_{k\in K} f_{v,k} + W\sum_{v\in V}\sum_{k\in K}(d^A_{v,k} + d^B_{v,k}). \quad (1)$$

Equation (1) minimizes the total cost of train-set assignment, including the DM cost, MM cost, replacement cost (due to undesired train-set), expected cost of failures, and accumulative duration variable of the utilization path that returns to zero when the corresponding maintenance tasks are executed. The reliability of the utilization is governed by the minimization of the expected cost of failures, which is computed as the sum of ticket refund loss and emergency maintenance cost (= expected number of failures × cost of minimum repair).

Assignment Constraints

To satisfy the demand train-set (utilization paths), train-set assignment constraints are presented in the following equations.

Subject to

$$\sum_{u\in U} q_{u,i,k} = 1. \qquad \forall i \in I^I, k \in K^I \qquad (2)$$

$$\sum_{v\in V^u} x_{i,v,k} = N_{u,i} q_{u,i,k}. \qquad \forall u \in U, i \in I^I, k \in K \qquad (3)$$

$$\sum_{i\in I} x_{i,v,k} \le 1. \qquad \forall v \in V, k \in K^I \qquad (4)$$

$$(n-1)x_{i,v,k} = \sum_{h=1}^{n-1} x_{i+h,v,k+h}. \qquad \forall i \in I^O, v \in V, k \in K \qquad (5)$$

$$x_{i,v,k} = x_{i+1,v,k+1}. \qquad \forall i \in I^O, v \in V, k \in K \qquad (6)$$

Equations (2) and (3) ensure that every starting operational partial path satisfies the required type and amount of train-set. Equation (4) guarantees that each train-set can only be assigned to one path at most. The starting partial paths of utilization paths are considered in Equation (5) due to the multiple-day paths in TRA. Equation (5) ensures that all partial paths of incomplete utilization paths are correctly connected, and it works with Equations (2) and (3) to complete the complicated multiple-day path assignment. For example, when a one-day path with two-time intervals (either morning–evening or evening–morning) is encountered, Equation (5) can be expanded as Equation (6), as shown in Figure 2.

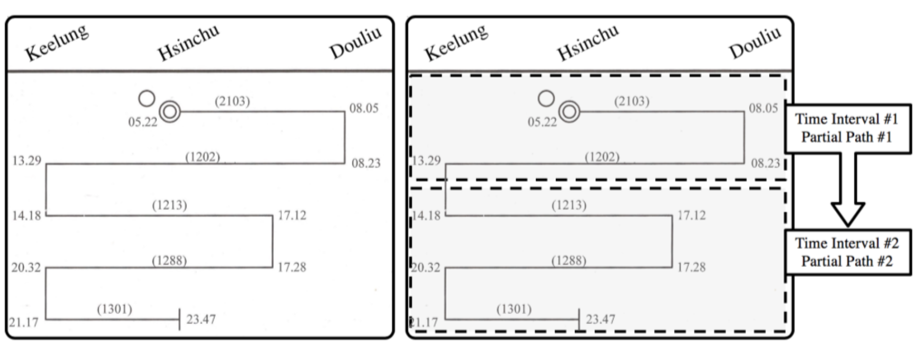

Figure 2: Time interval and partial path
(left, origin; right, divided into time intervals)

Maintenance-related Constraints

Equations (7) and (8) deal with the accumulative times of train-set that should return to zero after executing the maintenance tasks. Equation (9) ensures the DM regulation of train-set in accordance with the PM requirement. Equation (10) ensures that the train-set executing the DM task cannot be assigned to the operational paths, and Equation (11) is for the MM task. Equation (12) ensures that the amount of MM does not exceed the depot capacity. Equation (13) guarantees the minimum number of MM tasks to avoid over-concentrating the train-set executing the MM task or wasting the human resource of the maintenance crew. The MM task requires a full day. Thus, Equation (14) ensures that the MM task starts off the day.

$$d_{v,k}^{A} \geq d_{v,k-1}^{A} + \sum_{i \in I} P_i x_{i,v,k} - M r_{v,k} - M z_{v,k}. \qquad \forall v \in V, k \in K \tag{7}$$

$$d_{v,k}^{B} \geq d_{v,k-1}^{B} + \sum_{i \in I} P_i x_{i,v,k} - M r_{v,k}. \qquad \forall v \in V, k \in K \tag{8}$$

$$d_{v,k}^{A} \leq D^{A}. \qquad \forall v \in V, k \in K \tag{9}$$

$$\sum_{i \in I^A} x_{i,v,k} \geq z_{v,k}. \qquad \forall v \in V, k \in K \tag{10}$$

$$\sum_{i \in I^B} x_{i,v,k} \geq r_{v,k}. \qquad \forall v \in V, k \in K \tag{11}$$

$$\sum_{v \in V} r_{v,k} \leq G. \qquad \forall v \in V, k \in K \tag{12}$$

$$\sum_{v \in V} \sum_{k \in K} r_{v,k} \geq Q. \tag{13}$$

$$r_{v,k} = r_{v,k+1}. \qquad \forall v \in V, k \in K^{I} \tag{14}$$

Reliability-related Constraints

Train-set specific degradation models are presented in the form of reliability functions. To transform the nonlinear Weibull distribution to linear parameters, the nonlinear relationship is discretized into stages. Equation (15) indicates that for all stages, only one stage can make $\theta_{v,k,s}^{+}$ equal to 1 only when the MM accumulative days of train-set fall within *s* and*s-1*. Then, $\theta_{v,k,s}^{+}$ and $\theta_{v,k,s}^{-}$ are equal to 1 and 0, respectively. Equation (16) ensures that at every stage, only one stage can make $\theta_{v,k,s}^{+}$ equal to 1. Equation (17) sets up $\theta_{v,k,s}^{-}$ to control the invalid situations in Equation (15) with a large *M*. Equation (18) obtains the expected number of failures from the different stages. Equations (19) and (20) describe the properties of the variables. Three positive and five binary variables are available in the proposed optimization model.

$$-M\theta_{v,k,s}^{-} + \frac{s-1}{P}\theta_{v,k,s}^{+} \leq d_{v,k}^{B} \leq M\theta_{v,k,s}^{-} + \frac{s}{P}\theta_{v,k,s}^{+}. \qquad \forall v \in V, k \in K, s \in S \tag{15}$$

$$\sum_{s \in S} \theta_{v,k,s}^{+} = 1. \qquad \forall v \in V, k \in K \tag{16}$$

$$\theta_{v,k,s}^{+} + \theta_{v,k,s}^{-} = 1. \qquad \forall v \in V, k \in K, s \in S \tag{17}$$

$$f_{v,k} = \sum_{s \in S} \theta^{+}_{v,k,s} F_{v,s}. \qquad \forall v \in V, k \in K \tag{18}$$

Variable Domain

Equations (19) and (20) describe the properties of the variables. Three positive and five binary variables are available in the proposed optimization model.

$$d^{A}_{v,k}, d^{B}_{v,k}, f_{v,k} \geq 0. \tag{19}$$

$$r_{v,k}, x_{i,v,k}, z_{v,k}, \theta^{+}_{v,k,s}, \theta^{-}_{v,k,s} \in \{0,1\}. \tag{20}$$

In practice, a train-set assignment plan is determined daily for the following seven days. Therefore, a rolling horizon process is also developed to implement the proposed train-set assignment optimization model. The lengths of the decision and implementation horizons are two decisions that should be decided for the process. The first decision (the length of the decision horizon) should consider solution quality and computational time. The other decision (implementation horizon) is based on the degree of uncertainty in train-set availability. A short implementation horizon is usually better than a long one due to the increase in flexibility.

4 Case study

This study applies the process in Hsinchu depot of TRA. The MIP model is coded in Python environment with Gurobi solver. Hsinchu depot mainly manages commuter trains. 11 multi-day utilization paths are present in the utilization schedule, and they have to be fulfilled by 6 sets of EMU500 and 40 sets of EMU700 trains. EMU500 can operate as single or double train-sets depending on the utilization path, and EMU700 often operate as a pair of two train-sets. Table 2 shows detailed information on the utilization paths in Hsinchu depot. To demonstrate the benefit of adopting PdM in MM, we set the planning horizon to 180 days. Parameters are obtained or estimated from Railway Reconstruction Bureau and TRA.

Table 2: Utilization paths for EMU500 and EMU700 train-sets at Hsinchu depot

Path No.	Required type	Required quantity	Accumulative operating days	Operating frequency
E5	EMU500	1	1	Every day
E6	EMU700	2	3	Every day
E7	EMU700	2	3	Every day
E8	EMU700	2	2	Every day
E9	EMU700	2	4	Every day
E10	EMU700	2	3	Mon, Tue, Fri, Sat, Sun
E10_1	EMU700	2	2	Wed, Thu
E11	EMU700	2	2	Every day
E12	500/700	2	2	Mon, Tue, Wed, Thu, Sun
E12_1	500/700	2	1	Fri, Sat
E13	EMU500	1	1	Every day

Table 3 presents the results with the "PM-only" strategy (DM and MM are scheduled based on a fixed threshold) and with the "PM + PdM" strategy (DM via a fixed threshold/MM via a PdM strategy). Train-set assignment under the PM + PdM strategy provides a lower total cost than that under the current PM-only strategy. Especially the outcomes in the expected cost of failure are different because the PM + PdM strategy considers the degradation model of each train-set and failure cost as opposed to treating all train-sets with a fixed set of maintenance thresholds. These degradation models provide additional information regarding the reliability of each train-set. As a result, the maintenance cost under the PM + PdM strategy is reduced by 4.59%, a saving from the increase of the MM interval mainly for the EMU700 train-sets due to their better reliability performance. The expected cost of failures from the PM+PdM strategy also outperforms the PM only strategy because reliability and their expected cost of failures were considered in the proposed model.

Table 3: Comparison of assignment result

Model	**PM only**	**PM + PdM**	**% difference**
Number of DMs	1,433	1,431	
Number of MMs before PM	18	12	
Number of MMs at PM	32	2	
Number of MMs after PM	0	32	
Expenditure on maintenance	311,750	298,070	-4.59%
Expected cost of failures	1,152,011	977,283	-17.87%
Total cost	1,463,761	1,275,353	-14.77%

Figure 3 shows the cumulative days before MM for all train-sets on the basis of PM-only and PM + PdM strategies. The accumulative operating days under the PM-only strategy are generally near the MM threshold of 90 days. On the contrary, the accumulative operating days under the PM + PdM strategy vary in accordance with the actual reliability of the train-set. In terms of the EMU700 train-sets, the accumulative operating days before entering the MM under the PM-PdM strategy is about 95 days on average, an extension from the 90-day threshold adopted by the PM strategy. However, the accumulative operating days of the EMU500 train-sets (i.e., EMU542, EMU544, and EMU546) are considerably lower than the maintenance regulation. This is because, the EMU500 train-sets, as the oldest types of existing train-sets for commuter trains, has much lower reliability than that of the EMU700 train-sets. Introducing the PdM strategy provides flexibility in the maintenance schedule by train-set specific reliability models. As a result, an efficient and reliable assignment plan can be determined through the proposed process.

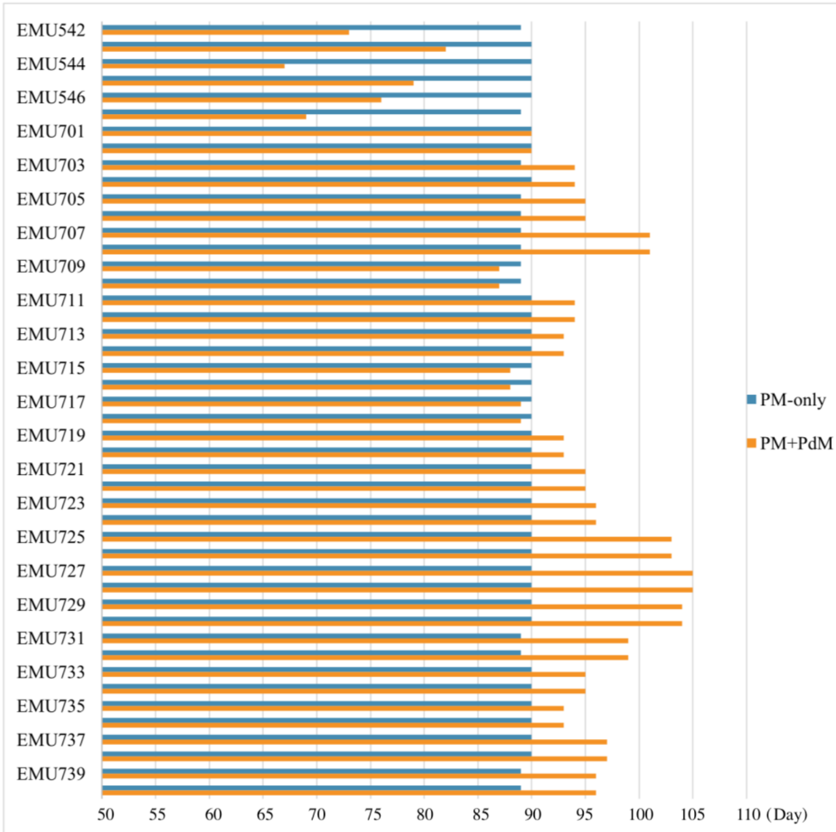

Figure 3: Accumulative days of MM

5 Conclusions

This study proposes an optimization process for assigning train-set to utilization paths and maintenance tasks in accordance with the PdM strategy with train-set specific reliability models. The results of the empirical study demonstrate that the developed process can assign utilization paths and schedule maintenance tasks to each train-set efficiently and reduce the total cost by over 14% compared with the PM-only strategy. Adopting this process can help planners improve the efficiency and reliability of train-set utilization.

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