Rule-based heuristic algorithm for trainset assignment under predictive maintenance scheme

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A rule-based heuristic algorithm adopting predictive maintenance strategy is developed in this research to assign trainsets. Applying this algorithm can assist planners improve the efficiency and reliability of trainset utilization.

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１．INTRODUCTION

The efficiency of trainset utilization is an important objective pursued in practice(1)(2)(3). The conventional railway operator in Taiwan, namely, the Taiwan Railways Administration (TRA), manages and maintains a number of trainsets through trainset assignment, which includes the assignment of utilization paths and schedule of maintenance tasks(4). Previous studies have adopted the fixed PM strategy for the trainset assignment problem(4)(5). However, maintenance intervals cannot be flexibly adjusted according to the difference in trainsets with the PM strategy. In addition, few studies used the historical maintenance data to adapt the degradation model of trainset. Cheng and Yeh(6) collected the historical failure data of TRA EMU500 and E1000 trains to discuss the relationship between the main failure components and the risks management. However, this research did not further analyze the deterioration rate of these trainsets. Though these researches determined degradation models for trainsets, the resulting model is still the same for the same types of train-sets (not a trainset-specific model) nor a comprehensive train-set assignment problem under PdM strategy has been proposed.

Data generated from reliability and maintenance data over time can now be used to develop a trainset-specific degradation model thanks to advances in big data analysis and artificial intelligence (AI). Consequently, this study proposes a rule-based heuristic algorithm based on the MIP model of the previous study(7) for assigning trainsets to utilization paths and maintenance tasks according to a predictive maintenance strategy (PdM) with trainset-specific degradation models.

２．ROLLING STOCK ASSIGNMENT AND MAINTENANCE PROBLEM

The trainset assignment plan of TRA includes the assignment of utilization paths and maintenance schedules to each trainset for a period in accordance with demand (utilization schedule) and maintenance requirements. Each utilization path identifies the ideal type and amount of trainset to meet the demand.

Table 1 shows TRA's maintenance rules for commuter trainsets. Maintenance is divided into four levels, such as daily maintenance (DM), monthly maintenance (MM), bogie maintenance (BM), and general maintenance (GM). This PM rule adopts thresholds based on cumulative operating days. BM and GM levels of maintenance are scheduled in advance for each trainset. As a result, they require longer maintenance times than DM and MM do, and are subject to limited workshop capacity. The operational level must also consider restrictions on maintenance location and capacity when assigning trainsets at low maintenance levels, namely, DM and MM. For multi-day utilization paths, the DM process is typically performed during the overnight period or at the time of connecting follow-up paths. However, MM is not feasible for a connection or overnight period in a utilization path since it takes a day to complete. Consequently, all maintenance tasks in low maintenance levels are included in the maintenance tasks of high maintenance levels; therefore, all operating days associated with the executed maintenance level and the corresponding low maintenance level return to zero after each class of maintenance process. The efficiency of trainset usage has already been improved in previous studies(4)(5) In spite of this, their processes do not consider trainset-specific reliability; therefore, this research examines the possibility of integrating PdM into this process in order to determine its potential benefits.

Table 1 Maintenance Regulations in TRA

Maintenance level	Accumulative operating time	Maintenance location
DM	3 days	Trainset depot
MM	3 months or 90,000 km	Trainset depot
BM	3 years or 1,000,000 km	Workshop
GM	6 years or 2,000,000 km	Workshop

３．METHODOLOGY

This study proposes a short-term assignment model to assign rolling stock to DM and MM paths based on a set of given utilization paths. The optimization model introduced in previous study(7) can guarantee the optimal results. However, it takes a large amount of time to solve the problem, especially for the scenario with a long decision horizon or that with a long analysis corridor. For such large-scale problems, optimization method has to face the exponential growth in solution time as the number of decision variables increases. As a result, for the purpose of achieving the solution efficiency and maintaining the solution quality, this research develops a rule-based heuristic algorithm on a basis of practical considerations in current maintenance planning process. Table 2 lists the notations used in the Rule-based Heuristic Algorithm.

Table 2 Notations of Rule-based Heuristic Algorithm

Notation	Description
$\boldsymbol{I^K}$	Set of utilization path in time interval k
$\boldsymbol{V}$	Set of all available trainsets
$\boldsymbol{V^R}$	Set of all remaining trainsets
$\boldsymbol{K}$	Set of all time intervals within the planning period
C^F	Expected cost of failures
D^A	Accumulative operating days upper bound for DM
D^B	Maximum accumulative days between two MM tasks for rolling stock depot to perform
Si	Distance of utilization path *i*
$d^A_{v,k}$	Cumulative days of trainset v from the last DM till the end of time interval k
$d^B_{v,k}$	Cumulative days of trainset v from the last MM till the end of time interval k
$f_{v,k}$	The expected number of failures on trainset *v* of time interval *k*
U	The accumulative MM times
E_k	Expected number of MM times

Phase 1: Identifying MM tasks with PdM strategy

Trainset assignment plan including the assignment of utilization paths and maintenance tasks. However, a safe and efficient railway operation relies on a well-maintained system so that we first assign the maintenance tasks. With the trainset-specific degradation models, since predictive maintenance (PdM) strategy is applied, the MM interval is flexible. Because of the wider solution space, the problem is also much more intractable compared to the plan under PM strategy. Hence, we identify MM tasks by several iterations based on the tradeoff between the maintenance cost and failure cost (trainset reliability). In each iteration, the algorithm first check which trainset is available in the time interval and which are not. Second, evaluate the reliability of all available trainset with, and conduct reliability analysis to decide whether the trainset perform the MM in this iteration. Finally, identify it and then update.

Input: initial value.

Output: identified MM tasks for $v \in \boldsymbol{V}$.

For trainset v, $v \in \boldsymbol{V}$:
｜｜For time interval k, $k \in \boldsymbol{K}$:
｜｜｜Calculate $f_{v,k}$ sequentially.
｜｜｜｜If $C^F \times f_{v,k} \geq C^M$:
｜｜｜｜｜Let $r_{v,k} = 1$, $d^B_{v,k} = 0$, $U = U+1$.
｜｜｜｜Else v is placed in set $\boldsymbol{V^R}$.
For time interval k, $k \in \boldsymbol{K}$:
｜If: $\sum_{v \in V} r_{v,k} \geq 1$
｜｜Then $d^A_{v,k} = 0$, $d^B_{v,k} = 0$.
｜Else $d^A_{v,k} = d^A_{v,k} + 1$, $d^B_{v,k} = d^B_{v,k} + 1$.
Obtain $r_{v,k}$.

Phase 2: Assigning the trainset to the utilization path

Trainsets could be out for several days without returning back to the original depot. Hence, the longer operating mileages utilization path has, the higher reliability trainset need. That is, the assignment of utilization path is iteratively conducted based on the trainset reliability. Failure possibility and failure cost resulting from different trainsets with different utilization paths should be evaluated before assignment. First, sort unassigned utilization paths according to the longest operating mileage. Second, possible assignment plan is listed in consideration of constraints on the requirement of each utilization path including required type and amount of trainset. Next, assign the utilization path with the highest reliability trainset until all utilization path assigned. By comparing the reliability, trainsets are assigned according to their failure cost with the assistance of train-specific degradation model.

Input: $x_{i,v,k}$ for $v \in \boldsymbol{V}$, $k \in \boldsymbol{K}$.

Output: identified utilization paths for $v \in \boldsymbol{V^R}$.

Rank the mileages of utilization path S_i, $i \in \boldsymbol{I^K}$ from long to short.
For utilization path i, $i \in \boldsymbol{I^K}$:
｜For trainset v, $v \in \boldsymbol{V^R}$:
｜｜If trainset v have minimum failure cost ($\min C^F \sum_{v \in V} \sum_{k \in K} f_{v,k}$).
｜｜｜Let $x_{i,v,k} = 1$, remove the utilization path i, v is removed from V^R.
｜｜Else :
｜｜｜v is still in set $\boldsymbol{V^R}$.
Obtain $d^A_{v,k}$, $d^B_{v,k}$, $x_{i,v,k}$.

Phase 3: Ensure the MM tasks evenly assign

In order to avoid over-concentration of maintenance time for all trainsets, this phase reserves workload of trainset depot in advance. The number of reserved maintenance trainset is estimated by the predetermined the average maintenance intervals of all trainsets divided by the number of all trainset fleet. If the trainset depot does not maintain any trainset on day k, and the accumulative MM times also smaller than the expected number of MM times, this phase will assign the trainset with the lowest reliability to perform the MM task.

Input: $f_{v,k}$ for $v \in \boldsymbol{V^R}$, $k \in \boldsymbol{K}$.

Output: identified additional MM tasks for $v \in \boldsymbol{V}$.

1. For trainset v, $v \in \boldsymbol{V^R}$:
2. │ │ For time interval k, $k \in \boldsymbol{K}$:
3. │ │ │ Sort the failure rate $f_{v,k}$ sequentially.
4. │ │ │ │ If $d^B_{v,k} > D^B$ and $U < E_k$:
5. │ │ │ │ │ Choose the trainset v with maximum $f_{v,k}$ and let $r_{v,k} = 1$.
6. Obtain $r_{v,k}$.

Phase 4: Identifying DM tasks with PM strategy

Due to the flexibility of the PM strategy, these DM tasks have to be identified after those MM tasks. The operation process is to calculate the time intervals after the last DM first. Then, identify the tasks from the intervals near the PM regulations and update new values of trainsets. Finally, repeat and stop if the PM regulation is not violated.

Input: $d^A_{v,k}$ for $v \in \boldsymbol{V^R}$, $k \in \boldsymbol{K}$.

Output: identified DM tasks for $v \in \boldsymbol{V}$.

1. For trainset v, $v \in \boldsymbol{V^R}$:
2. │ │ For time interval k, $k \in \boldsymbol{K}$:
3. │ │ │ If $d^A_{v,k} \geq D^A$:
4. │ │ │ │ Let $z_{v,k} = 1$ and $d^A_{v,k} = 0$
5. Obtain $z_{v,k}$
6. Return to ***Phase 1***

4. CASE STUDY

To demonstrate the practical use of the proposed trainset assignment model, this study applies the developed optimization process[7] to empirical trainset assignment tasks in the Hsinchu depot of TRA. The planning horizon is 90 days (which cannot be solved by the exact optimization model) to demonstrate the applicability of the heuristic method. Eleven multi-day utilization paths are present in the utilization schedule in a week (Table 3), and they have to be fulfilled by six sets of EMU500 and 40 sets of EMU700 trains. Each path has its required train type. That is, several paths can only be operated by EMU500 trains, EMU700 trains, or by any of the two types (i.e., E12 and E12_1). In terms of the trainsets, EMU500 can operate as single or double trainsets depending on the demand of the utilization path, and EMU700 trainsets often operate as a pair of two trainsets. In addition, the operating frequency of each utilization path is different due to the utilization of some train only operate at specified day.

Table 3 Utilization Paths at Hsinchu Depot

Path No.	Required type	Required quantity	Operating days (day)	Operating frequency (days of occurrences)
E5	EMU500	1	2	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	3	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

The planning horizon in this research is 90 days, equal to the MM threshold. In this case, the exact optimization model is not able to tackle this problem. In order to examine the possibility of PdM strategy in the trainset assignment process and the potential benefit, we implement the heuristic model with PM strategy, developed by Lai et al.[4], and the proposed heuristic model with PdM strategy, developed in this study.

Table 4 presents the results of the optimization process 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). Both strategies require similar numbers of DMs and MMs, but the outcomes in the expected cost of failure are different. Trainset assignment under the PM + PdM strategy provides a better rolling stock assignment plan with a lower total cost than that under the current PM-only strategy. The PM + PdM strategy considers the degradation model of each trainset and failure cost as opposed to treating all trainsets with a fixed set of maintenance thresholds. These degradation models provide additional information regarding the reliability of each trainset. Therefore, the resulting assignment and maintenance plan can cope well with the actual characteristics of the rolling stock. As a result, an efficient and reliable assignment plan can be determined through the proposed process.

Table 4 Comparison of Assignment Result

Models	PM	PdM	Difference (%)
Number of DMs	607	611	
Number of MMs	24	21	
Number of MMs before PM	4	5	
Number of MMs at PM	20	1	
Number of MMs after PM	0	15	
Maintenance Cost (NTD)	180,700	166,100	
Failure Cost (NTD)	5,149,542	4,860,162	
Expected Number of Failures	4.648	4.386	
Total cost	**5,330,242**	**5,026,262**	**-5.7%**

Figure 1 demonstrates the accumulative operating days before MM for trainsets which have executed MM task in the 90-day assignment period on the basis of PM and PdM strategies. The accumulative operating days under PM strategy are generally near the MM threshold of 90 days. On the contrary, the accumulative operating days under PdM strategy vary in accordance with the actual reliability of the trainset. In terms of the EMU700 trains, the accumulative operating days before entering the MM under PdM strategy is about

97 days on average, an extension from the 90-day threshold adopted PM strategy. However, the accumulative operating days of the EMU500 trains (i.e., EMU542, EMU544, and EMU546) are considerably lower than the maintenance regulation. This is because, the EMU500 trains has much lower reliability than that of the EMU700 trains. Introducing PdM strategy provides flexibility in the maintenance schedule by trainset-specific degradation models. As a result, even if higher reliability trainsets execute the MM tasks after the current regulations of 90 days, the expected number of failures is still lower than under PM strategy which performs more maintenance tasks.

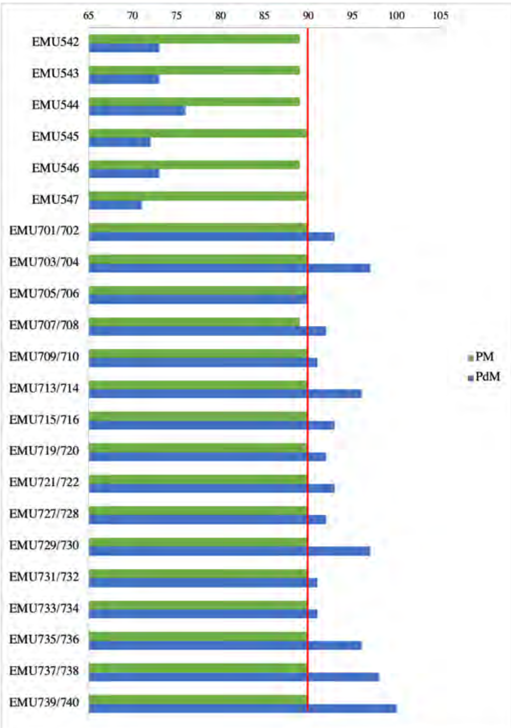

Figure 1 Accumulative Days of MM

6. CONCLUSIONS

This study developed a rule-based heuristic algorithm to increase solving efficiency and also keep the solution quality. The results of the empirical study demonstrate that the developed process can assign utilization paths and schedule maintenance tasks to each trainset efficiently according to the degradation model simultaneously. The total cost can also reduce compared with the PM strategy. Adopting this process can help planners improve the efficiency and reliability of trainset utilization.

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