

Optimal Maintenance Clustering for Rail Track Components Subject to Possession Capacity Constraints

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Abstract—This paper studies the optimal maintenance planning of preventive maintenance and renewal activities for components in a single railway track when the available time for maintenance is limited. The rail-track system consists of several types of components, such as rail, ballast, and switches with different preventive maintenance and renewal intervals. To perform maintenance or renewal on the track, a train free period for maintenance, called a possession, is required. Since a major possession directly affects the regular train schedule, maintenance and renewal activities are clustered as much as possible. In a highly dense and utilized railway network, the possession time on the track is critical since the demand for train operations is very high and a long possession has a severe impact on the regular train schedule. We present an optimization model and investigate the maintenance schedules with and without the possession capacity constraint. In addition, we also integrate the social-economic cost related to the effects of the maintenance time to the variable possession cost into the optimization model. A numerical example is provided to illustrate the model.

Keywords—Rail-track components, maintenance, optimal clustering, possession capacity.

I. INTRODUCTION

IN European countries, railway infrastructure maintenance is performed in a possession, i.e. a train free period that the track is available for maintenance but not for operation. The railway maintenance activities can be classified into two types: *i.* routine maintenance such as regular inspections, cleaning, and minor repairs, and *ii.* major maintenance activities such as major repairs and renewal projects. Routine maintenance requires minimal amount of time and is often scheduled in a minor possession, e.g. few hours at night. Major repairs and large renewal projects require a longer period and need a major possession. Planning of minor possessions is not difficult since routine maintenance can be done at night and it does not affect the train paths operation [1]. However, scheduling major possessions affects the train paths timetable and it can involve train operating companies, traffic control, and maintenance executing contractors.

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A track possession involves a high cost related to the train paths' disruptions and, thus, maintenance jobs are often clustered to reduce the total cost. In addition, a track possession requires several setting up activities and it may be more economical to maintain several components at the same time to utilize the benefit of spending this set-up cost only once. In railway maintenance planning, as described in Budai-Balke [2], the maintenance interval or the number of periods between two consecutive preventive maintenance or renewal activities and the execution costs for performing these activities are given. We need to determine the time to perform maintenance and renewal activities so that the objective, e.g. the total cost or the disruptions, is minimized.

There has been some research related to the maintenance scheduling problems for rail track components. Higgins [3] investigated the job-allocation problem of assigning maintenance activities to crews so that the expected disruption to the train operation is minimized. Cheung et al. [4] considered the railway maintenance as a time-allocation problem, that is, assigning the maintenance jobs as much as possible in the available time slot for maintenance. Budai et al. [5] formulated the preventive maintenance scheduling problem for a single track with repetitive routine works and renewal projects to minimize the total maintenance and possession cost. Zhao et al. [6] and Pargar [7] considered the maintenance scheduling with minimization of maintenance and renewal cost and studied several types of cost savings due to the joint renewal and maintenance activities. The types of saving depend on the number of adjacent segments and the share of special machinery for maintenance. Peng and Ouyang [8] presented a special approach for modelling the railway maintenance clustering problem. It was modelled as a vehicle routing problem, where a maintenance crew was considered as a "vehicle" and there was a set of projects with several jobs in each project being considered as "routes". A vehicle, i.e. maintenance crew, needs to travel to several jobs, i.e. routes, in the projects in the way that all the routes are covered and the total travelling cost is minimized.

One of the shortcomings in the literature is that the existing papers did not consider the total time for doing maintenance in each possession and its affect to the overall maintenance planning. In a highly dense railway transportation network, the conflict of assigning the track for maintenance and for train operation is a critical issue [9]. Due to this conflict, maintenance and renewal activities are often scheduled in the time slot with less impact to the customers and the time for

maintenance is tightened up to a specified window. For example, in the Netherlands, the routine maintenance activities are strictly done at night with a 4-hour window of maintenance time. Major maintenance and renewal projects are often combined and the maintenance time is often limited to two days (a weekend) when the impacts to train operation are not severe. In this paper, we study the maintenance scheduling problem with a possession capacity constraint to address this practical situation. In addition, the existing maintenance planning models assume that possession cost is incurred when at least one activity is performed in a period and this cost is fixed regardless of the number of activities to be clustered in that period. In fact, the possession cost is varying depending on the possession time as well as the social-economic impacts related to the track location and train operation schedule such as the expected number of customers and the cost per customer per hour.

The remainder of this paper is organized as follows. Section II provides a detailed description of the railway maintenance scheduling problem (RMSP) with possession capacity constraint. A mathematical optimization model for the maintenance planning problem is proposed in Section III. An illustrative example and important results to highlight the differences and effects when considering possession capacity constraint are presented and discussed in Section IV. Finally, Section V draws conclusions and suggests a future research direction from this study.

II. PROBLEM DESCRIPTION AND FORMULATION

Assume that we have to schedule maintenance and renewal activities for a track system with a set of n components in a discrete planning horizon from the first period to T_{max} , i.e. $t=1, 2, \dots, T_{max}$. It is assumed that the planning horizon is long enough so that at least one preventive maintenance (PM) activity will be performed on each component i , $i=1, 2, \dots, n$. A renewal is required after a maximum number of PM activities has been performed on component i . In each time period, if there is at least one maintenance or renewal action, the whole track system needs to be possessed for maintenance. During a possession, different cost factors are considered such as the fixed possession cost - the set-up cost related to the preparation for maintenance, maintenance and renewal cost - actual cost of doing maintenance and renewal activities on the track system, and the variable social-economic cost - the cost related to the disruptions of the regular train operation. With the input data on time, cost, interval of doing maintenance and renewal, the RMSP is to find the best schedule to perform maintenance and renewal activities to minimize the total cost in the planning horizon.

In this paper, we assume that the maximum number of time periods, i.e. the maximum interval of doing two consecutive PM activities, $\tau_{p,i}$, and the maximum number of PM activities before a renewal, $N_{p,i}$, are given. Other available data include the time and cost of doing each activity, the current number of periods elapsed since the last PM, and number of PM activities from the last renewal. After a PM, component is in a good

condition but the wear stock of the component decreases, that is, the number of remaining PM activities to the next renewal decreases. After a renewal, component is assumed to be "as good as new" and the same life-cycle is repeated.

We define the following decision variables to represent the maintenance, renewal, and possession in each planning period.

$$x_{i,t}^m = \begin{cases} 1 & \text{if component is maintained in period } t \\ 0, & \text{otherwise} \end{cases}$$

$$x_{i,t}^r = \begin{cases} 1 & \text{if component is renewed in period } t \\ 0, & \text{otherwise} \end{cases}$$

$$x_t^p = \begin{cases} 1 & \text{if a possession is required in period } t \\ 0, & \text{otherwise} \end{cases}$$

Denote $c_{i,t}^m$ and $c_{i,t}^r$ as the maintenance and renewal cost of component i in period t , respectively. The total cost of maintenance and renewal for n components in T_{max} time periods is shown in (1) and (2).

$$C_M = \sum_{i=1}^n \sum_{t=1}^{T_{max}} x_{i,t}^m c_{i,t}^m \quad (1)$$

$$C_R = \sum_{i=1}^n \sum_{t=1}^{T_{max}} x_{i,t}^r c_{i,t}^r \quad (2)$$

Similarly, let t_i^m and t_i^r be the maintenance and renewal time of component i respectively. We assume that the maintenance of components is performed consecutively. The total time for maintenance and renewal of all components in period t is shown in (3).

$$T_t = \sum_{i=1}^n (t_i^m x_{i,t}^m + t_i^r x_{i,t}^r) \quad (3)$$

Since a possession is required when there is at least one maintenance or renewal activity, we have:

$$x_t^p = \max(x_{i,t}^m, x_{i,t}^r) \quad (4)$$

In each period t , the possession cost consists of a fixed setup cost, c_{p0} , incurred only one time regardless of the number of maintenance and renewal activities in that period and a variable social-economic cost, C_p^{var} . The variable social-economic cost in period t is a product of the possession time - T_t , the expected number of customers in period t - N_t^C , and the cost per customer per unit time - c_{pe} . The total possession cost in the whole planning horizon is calculated as in (5).

$$C_p = C_p^{fix} + C_p^{var} = c_{p0} \sum_{t=1}^{T_{max}} x_t^p + c_{pe} \sum_{t=1}^{T_{max}} N_t^C T_t \quad (5)$$

In summary, the total cost in the whole planning horizon, i.e. the objective function to be minimized, is presented as in (6).

$$C = C_p^{fix} + C_p^{var} + C_M + C_R. \quad (6)$$

III. MAINTENANCE SCHEDULING OPTIMIZATION MODEL

The RMSP with possession capacity constraint can be

formulated as a binary integer programming model as follows:

Minimize:

$$C = c_{p0} \sum_{t=1}^{T_{max}} x_t^p + c_{pe} \sum_{t=1}^{T_{max}} N_t^c \sum_{i=1}^n (t_i^m x_{i,t}^m + t_i^r x_{i,t}^r) + \sum_{i=1}^n \sum_{t=1}^{T_{max}} c_{i,t}^m x_{i,t}^m + \sum_{i=1}^n \sum_{t=1}^{T_{max}} c_{i,t}^r x_{i,t}^r \quad (7)$$

S.t.

$$\sum_{t=1}^{\tau_{p,i}^1} x_{i,t}^m \geq 1, \forall i = 1, 2, \dots, n; \tau_{p,i}^1 = \tau_{p,i} - \tau_{p,i}^0 \quad (8)$$

$$\sum_{t=1+k}^{\tau_{p,i}^1+k} x_{i,t}^m \geq 1, \forall i = 1, 2, \dots, n; \forall k = 1, 2, \dots, T_{max} - \tau_{p,i} \quad (9)$$

$$\sum_{t=1}^{\tau_{r,i}^1} x_{i,t}^r \geq 1, \forall i = 1, 2, \dots, n; \tau_{r,i}^1 = \tau_{p,i} (N_{p,i} - N_{p,i}^0) - \tau_{p,i}^0 \quad (10)$$

$$\sum_{t=1+k}^{\tau_{r,i}^1+k} x_{i,t}^r \geq 1, \forall i = 1, 2, \dots, n; \forall k = 1, 2, \dots, T_{max} - \tau_{r,i}; \tau_{r,i} = \tau_{p,i} N_{p,i} \quad (11)$$

$$\sum_{i=1}^n t_i^m x_{i,t}^m + t_i^r x_{i,t}^r \leq T_t^0, \forall t = 1, 2, \dots, T_{max} \quad (12)$$

$$x_t^p \geq x_{i,t}^m, \forall i = 1, 2, \dots, n, \forall t = 1, 2, \dots, T_{max} \quad (13)$$

$$x_t^p \geq x_{i,t}^r, \forall i = 1, 2, \dots, n, \forall t = 1, 2, \dots, T_{max} \quad (14)$$

$$x_t^p, x_{i,t}^m, x_{i,t}^r \in \{0, 1\}, \forall i = 1, 2, \dots, n, \forall t = 1, 2, \dots, T_{max} \quad (15)$$

The objective of our RMSP is to minimize the total cost incurred in the planning horizon. The first term in the objective function is the fixed set-up cost occurred only once in each period if at least one maintenance or renewal activity is performed. The second term is the variable social-economic cost, and the last two terms are the maintenance and renewal costs, respectively.

Constraints (8) and (9) guarantee that the preventive maintenance activities are performed within the allowed PM interval, i.e. at least one PM action has to be performed in each component's PM interval. Similarly, constraints (10) and (11) ensure that the renewal activities are performed on component i when the number of PM reaches its limit $N_{p,i}$. In constraints (8) and (10), $\tau_{p,i}^0$ and $N_{p,i}^0$ are the number of periods and the number of PM activities elapsed since the last PM/renewal of component i . These two takes the current ages of components into consideration for the first maintenance and renewal. Constraint (12) is the possession capacity constraint, which implies that the total time for maintenance and renewal of all components must be less than or equal to the available

possession time in each period t , T_t^0 .

The set of variable constraints includes three constraints, of which constraints (13) and (14) make sure that a possession is required whenever a maintenance or renewal activity takes place and constraint (15) simply shows the binary conditions of decision variables.

IV. COMPUTATIONAL EXAMPLE AND RESULTS

In this section, we create a problem with $n = 4$ components to illustrate the planning problem and analyze the effects of the possession capacity constraint. The input data on PM intervals, maximum number of PMs in each life-cycle, cost and time to do a PM and renewal for each component and other information on the planning horizon, costs, and available possession time are given in Tables I and II.

Fig. 1 shows an original schedule which is obtained by directly assigning the latest possible time to do a maintenance/renewal activity as the planned time to do it. In this figure, M is maintenance and R is renewal. This schedule includes seven possessions, two maintenance activities for each component 1, 2, and 3, one maintenance activity for component 4, and three renewal activities for components 1, 2, and 4. The cost for this schedule is presented in Table III.

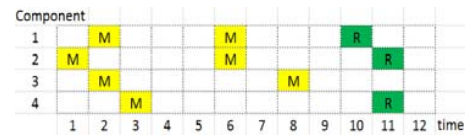


Fig. 1 Original schedule

We investigate two maintenance schedules: A - without possession capacity constraint and B - with possession capacity constraint. Schedule B can be obtained with the given optimization model. The optimization model to obtain schedule A is formulated by removing constraint (14) out of the model in Section III. The details of maintenance schedules A and B are shown in Figs. 2 and 3, respectively.

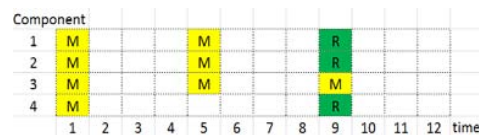


Fig. 2 Maintenance schedule without possession capacity constraint (A)

TABLE I
COMPONENTS' MAINTENANCE DATA

Component (i)	$\tau_{p,i}$ (periods)	$N_{p,i}$	$c_{i,t}^m$ (cost units)	$c_{i,t}^r$ (cost units)	t_i^m (hrs)	t_i^r (hrs)	$\tau_{p,i}^0$	$N_{p,i}^0$
1	4	3	2	8	6	12	2	1
2	5	5	3	20	8	15	4	3
3	6	4	4	18	8	18	4	0
4	8	6	5	16	9	16	5	5

Without the possession capacity constraint, the maintenance and renewal activities are clustered as much as possible and

there are only three possessions needed in the planning horizon (Schedule A). Interestingly, an extra maintenance

activity for component 3 is required in comparison with the original schedule. When considering the possession capacity constraint, maintenance activities are also combined but not as much as in schedule A. In total, five possessions are needed and exactly the same number of maintenance and renewal activities as the original schedule is required in schedule B. However, due to the possession capacity constraint, all four maintenance activities for four components cannot be implemented simultaneously in period 1. Also, three renewal activities for components 1, 2, and 4 cannot be done together in period 9, and they are separated in two periods (8, 9) due to the same reason. A cost comparison of three maintenance schedules, i.e. the original schedule, schedule A, and B, is included in Table III.

TABLE II
OTHER INPUT DATA

T_{max}	c_p (cost units)	C_{pe} (cost units)	N_c (# of customers)	T_t^0 (hrs)
12	10	0.0005	200	30

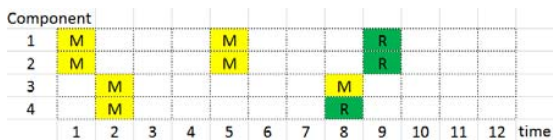


Fig. 3 Maintenance schedule with possession capacity constraint (B)

TABLE III
COST COMPARISON OF THREE MAINTENANCE SCHEDULES

Schedule	Maintenance cost (C_M)	Renewal cost (C_R)	Fixed pos. cost (C_p^{fix})	Variable pos. cost (C_p^{var})	Total cost (C)
Original schedule	23	44	70	9.6	146.6
Schedule A	27	44	30	10.4	111.4
Schedule B	23	44	50	9.6	126.6

From Table III, we see that the original schedule has the highest total cost in comparison with the other two schedules. The biggest difference of the three schedules is the fixed possession cost caused by the number of possessions required. There is a slight discrepancy in the maintenance and variable possession cost while the renewal costs in all three schedules are identical. Schedule A - without the possession capacity constraint results in the least total cost of 111.4 cost units, i.e. 24% less than the original schedule. Schedule B - with possession capacity constraint also reduces the total cost to 126.6 cost units, i.e. 14% less than the original schedule.

It is noted that the cost comparison in Table III ignores the fact that a too long possession may not be possible due to the limitation of the available possession time. Thus, schedule A is not applicable or there will be a huge penalty when implementing it. We assume that a penalty of c_{pen} is associated with the track system in each hour that the possession is extended beyond the available time for maintenance T_0 . Table IV shows the costs of three schedules when the penalty is 1 cost unit per an extra hour of maintenance time.

When the penalty cost per hour is high, maintenance

schedule A may not be the cost optimal schedule. In this case, if the penalty cost per hour, c_{pen} , is greater than 0.691 cost units, schedule A will be no longer the best maintenance plan. Meanwhile, by considering the possession capacity constraint, schedule B is always applicable and will be the one with the least total cost if c_{pen} is greater than 0.691.

TABLE IV
PENALTY COST AND ADJUSTED TOTAL COSTS

Schedule	Cost (with no penalty)	Penalty cost	Adjusted cost (with penalty)
Original schedule	146.6	1	147.6
Schedule A	111.4	22	133.4
Schedule B	126.6	-	126.6

V. CONCLUSION

This paper proposes a maintenance planning model for several components in a railway track considering the possession capacity constraint. This model is useful for highly dense and utilized railway networks, where a long possession is not possible due to a high demand of track for train operation. An optimization model to minimize the total cost in the planning horizon including the maintenance and renewal costs, fixed possession cost, and the social economic cost is presented. We incorporate the durations of maintenance and renewal activities into the model and analyze maintenance strategies with and without the possession capacity constraint. The illustrative example shows that maintenance and renewal activities should be clustered in the schedule to reduce the possession cost, but more maintenance possessions may be required when taking the possession capacity constraint into consideration.

This study only focuses on different components in a single track system. It is recommended that the model is extended for the whole railway network with several track links.

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REFERENCES

- [1] T. Lidén, "Railway Infrastructure Maintenance - A Survey of Planning Problems and Conducted Research," *Transp. Res. Procedia*, vol. 10, pp. 574-583, 2015.
- [2] G. Budai-Balke, *Operations Research Models for Scheduling Railway Infrastructure Maintenance*. Tinbergen Institute. Retrieved from <http://hdl.handle.net/1765/16008>, 2009.
- [3] A. Higgins, "Scheduling of railway track maintenance activities and crews," *J. Oper. Res. Soc.*, vol. 49, no. 10, pp. 1026-1033, 1998.
- [4] B. S. N. Cheung, K. P. Chow, L. C. K. Hui, and A. M. K. Yong, "Railway track possession assignment using constraint satisfaction," *Eng. Appl. Artif. Intell.*, vol. 12, no. 5, pp. 599-611, 1999.
- [5] G. Budai, D. Huisman, and R. Dekker, "Scheduling preventive railway maintenance activities," *J. Oper. Res. Soc.*, vol. 57, no. 9, pp. 1035-1044, 2006.
- [6] J. Zhao, A. H. C. Chan, and M. P. N. Burrow, "A genetic-algorithm-based approach for scheduling the renewal of railway track components," *Inst. Mech. Eng. Proc. Part F J. Rail Rapid Transit*, vol.

- 223, no. 6, pp. 533–541, 2009.
- [7] F Pargar, “A mathematical model for scheduling preventive maintenance and renewal projects of infrastructures,” in *Safety and Reliability of Complex Engineered Systems*, 0 vols., CRC Press, 2015, pp. 993–1000.
 - [8] F. Peng and Y. Ouyang, “Optimal Clustering of Railroad Track Maintenance Jobs,” *Comput.-Aided Civ. Infrastruct. Eng.*, vol. 29, no. 4, pp. 235–247, 2014.
 - [9] T. Lidén and M. Joborn, “Dimensioning windows for railway infrastructure maintenance: Cost efficiency versus traffic impact,” *J. Rail Transp. Plan. Manag.*, vol. 6, no. 1, pp. 32–47, 2016.