21

Maintenance in Rail Industry

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21.1 Introduction

This chapter presents two case studies of maintenance optimization in rail industry. The first case study discusses grouping of maintenance activities into maintenance packages. The second case study uses a life cycle cost approach to prioritize between maintenance and renewal projects under budget constraints.

Grouping of maintenance activities into maintenance packages is an important issue in maintenance planning and optimization. This grouping is important both from an economic point of view in terms of minimization of set-up costs, and also with respect to obtaining administratively manageable solutions. If several maintenance activities may be specified as one work-order in the computerized maintenance management system, we would have less work-orders to administer. The maintenance intervals are usually determined by considering the various components or activities separately, and then the activities are grouped into maintenance packages. By executing several activities at the same time, the set-up costs may be shared by several activities. However, this will require that we have to shift the intervals for the individual activities. If we try to put too many activities into the same group, the gain with respect to set-up costs may be dominated by the costs of changing the intervals for the individual activities. The case study we present for maintenance grouping is related to train maintenance, and especially we focus on activities related to components in the bogie.

Another problem most industries are facing is the limited resources available for maintenance and renewal, implying that optimization has to be conducted under budget constraints. Then two main questions should be addressed, first of all whether the budget constraints should be eliminated to some extent by putting more resources into maintenance and renewal in case we have more good projects than we have resources. The other question is how to prioritize, given the budget constraints. In the case study we present an approach to cost-benefit analysis of the various projects. This gives a ranked list of projects to consider for execution. The proposed method has been implemented by the Norwegian National Rail Administration (JBV), responsible for the Norwegian railway net.

Section 21.2 presents some general information about rail maintenance in Norway as a basis for the two case studies. The first case study in Section 21.3 discusses grouping of maintenance activities into maintenance packages. The second case study in Section 21.4 uses a life cycle cost approach to prioritize between maintenance and renewal projects under budget constraints.

21.2 Background information about rail maintenance

During the past decades there has been a dramatic change in the organization of the European railways. The European Union has been an important driving force, and legislation has been introduced to split the former state railways into one national infrastructure manager, and one or more train operators (railway undertakings). The idea has been to allow for many train operators to compete against each other to offer train services on the European network. Further, the maintenance of both the rolling stock (trains) and the infrastructure has to a great deal been outsourced.

The Norwegian State Railways (NSB) is the main Norwegian railway undertaking. NSB has outsourced most of the maintenance to MANTENA, a maintenance contractor. The preventive maintenance is based on activity based contracts where NSB decide type and amount of maintenance, whereas corrective maintenance is compensated for by a lump sum. The potential for the contractor to earn more money is in effective grouping of the maintenance, and in improved work processes for organization and execution of maintenance. NSB has implemented reliability centred maintenance (RCM) as basis for the preventive maintenance program. There is an objective that maintenance should be executed in natural lulls in the timetable. Major revisions of, e.g., the bogies need longer depot stops.

JBV is the infrastructure manager of the Norwegian network. The level of outsourcing of maintenance work is relatively low. Less than 10% of the operations and corrective maintenance work is performed by external contractors, whereas for preventive maintenance contract work represents 10-20%. For renewals the percentage is almost 70, and for investment (new lines) the percentage is more than 80. JBV has also implemented RCM as a basis for the preventive maintenance program. For larger maintenance projects and all renewal projects a prioritization regime supported by life cycle cost considerations has been implemented. The Norwegian network is split into three regions, where each region is responsible for prioritization of the resources that are allocated by the central maintenance administration. For the track and overhead line data from special measuring wagons is important input to the models used to support prioritization between large maintenance and renewal projects such as rail grinding, level tamping, ballast cleaning and rail repair and renewal.

Most European infrastructure managers have introduced more formalized optimization models for maintenance and renewal planning. Some recent references are Carreteroa et al (2003), Zoeteman (2003), Veit and Wogowitsch (2003) , Vatn et al (2003), Zarembski and Palese (2003), Pedregala et al (2004), Meier-Hirmer1 et al (2005), Budai et al (2005) and Reddy et al (2006). Railway research related to maintenance is however, dominated by wear modelling.

Especially wheel-rail wear models and track degradation models are important because the major maintenance and renewal costs of a railway line are due to track components. Some important references are Bing and Gross (1983), Li and Selig (1995), Sato (1995), Bogdaanski et al (1996), Ferreria and Murray (1997), Zhang et al (1997), Kay (1998), Zakharov et al (1998), Salim (2004), Telliskivi and Olofsson (2004), Grassie (2005) and Braghin et al (2006). A complete survey of reported models is beyond the scope of this chapter.

21.3 Case study 1: Grouping of maintenance activities

21.3.1 Introduction

Rolling stock maintenance is characterized by the fact that the trains have to be taken out of service while they are maintained in a maintenance depot. This causes a lot of challenges related to scheduling of the train services taking the need for maintenance into account. The scheduling problem is not considered here, and we only present a rather simple model for grouping of some maintenance activities assuming that we have access to the train whenever we want. Sriskandarajah et al (1998) present a methodology utilizing genetic algorithms on a much more complex situation within train maintenance scheduling. In our example we only consider the following cost elements:

- Man-hour costs and material costs related to preventive maintenance of each component
- Set-up costs to get access to the components to be maintained, and by paying the set-up costs access to several components is obtained
- Costs of taking the train out of service. These costs are included in the set-up costs from a modelling point of view.
- Man-hour costs and material costs related to corrective maintenance. Typically set-up costs can not be shared by other components unless preventive maintenance is advanced (opportunity maintenance).
- Costs related to the effect of a failure, i.e., punctuality, safety and material damage costs.

In classical maintenance optimization the objective is to find the optimum frequency of maintenance of one component at a time. However, in the multi-component situation there exist dependencies between the components, e.g., they may share a common set-up costs (economy of scope), the costs may be reduced if the contract to a maintenance contractor is huge (economy of scale), etc. This will complicate the modelling from the single component approach, e.g., see Dekker et al (1997) for a survey of models used in the multi-component situation. In this chapter we only consider the situation where we can save some set-up costs by executing several maintenance activities at the same time.

We often distinguish between the static and the dynamic planning regimes. In the static regime the grouping is fixed during the entire system lifetime, whereas in the dynamic regime the groups are re-established over and over again. The static grouping situation may be easier to implement than the dynamic, and the maintenance effort is constant, or at least predictable. The advantage of the dynamic grouping is that new information, unforeseen events, etc., may require a new grouping and changing of plans. For an introduction to maintenance grouping we refer to Wildeman (1996) who discusses these different regimes in detail. In the example that follows we illustrate some aspects of dynamic grouping related to maintenance activities on a train bogie.

21.3.2 Modelling framework

The trains are regularly taken out of service and sent to the maintenance depot for execution of maintenance. Several subsystems are maintained at the same time, and this makes the definition of set-up costs rather complicated when we develop grouping strategies. In principle, some of the set-up costs are related to the fact that the train is sent to the depot for maintenance, whereas some other parts of the set-up costs are specific for one subsystem. In the following, we will simplify and only consider costs related to the bogie, i.e., we assume one fixed set-up costs related to the bogie. We also assume that the train is available at the maintenance depot at any time. This is also a simplification, since each train follows a schedule, and can only enter the maintenance depot at some of the end stations for the different services. In order to get access to the various components in the bogie some disassembling is required before maintenance can be executed, and also some re-assembling is required after execution of maintenance. The costs of disassembling and re-assembling are here included in the set-up cost. In the model presented we also assume that the set-up costs are the same for all activities. It is further assumed that there is one and only one maintenance activity related to each component. This simplifies notation because we then may alternate between failure of component *i* and executing maintenance activity *i* where there is a unique relation between component and activity. The basic notation to be used is as follows.

Notation

c_i^P	Planned maintenance cost, exclusive set-up cost. Typically the costs of replacing one unit periodically.
c_i^U	Unplanned costs upon a failure. These costs include the corrective maintenance costs, safety costs, punctuality costs, and costs due to material damage.
S	Set-up costs, i.e., the costs of preparing the preventive maintenance of a group of components maintained at the same time. We assume the same set-up costs for all activities.
$\lambda_{E,i}(x)$	Effective failure rate for component *i* when maintained at intervals of length *x*
$M_i(x)$	$M_i(x) = x \cdot c_i^U \cdot \lambda_{E,i}(x)$ = expected costs due to failures in a period $[0,x)$ for a component maintained at time 0, exclusive planned maintenance

	cost
$\Phi_i(x,k)$	$\Phi_i(x,k) = [c_i^P + S/k + M_i(x)]/x$ = average costs per unit time if x is the length of the interval between planned maintenance, and the set-up costs are shared by totally k activities
$\Phi^*_{i,k}$	The minimum value of $\Phi_i(x,k)$, i.e., minimization over x
$x^*_{i,k}$	The x-value that minimizes $\Phi_i(x,k)$
$k_{i,\mathrm{Av}}$	Average number of components sharing the set-up costs for the i-th component, i.e., the i-th component is in average maintained together with $k_{i,\mathrm{Av}}$ -1 other components
$\Phi^*_{i,\mathrm{Av}}$	Average minimum costs per unit time over all k-values
$x^*_{i,\mathrm{Av}}$	Optimum value of x_i over all k-values. $x^*_{i,\mathrm{Av}}$ is measured in million kilometres since last maintenance on component i
t_0	Point of time when we are planning the next group of activities. Initially $t_0 = 0$. t_0 is measured in running (million) kilometres since t=0.
x_i	Age of component i at time t_0, i.e., time since preventive maintenance
$t^*_{i,\mathrm{Av}}$	$t^*_{i,\mathrm{Av}} = t_0 + x^*_{i,\mathrm{Av}} - x_i$ = optimum time in running (million) kilometres
K_k	Candidate group, i.e., the set of the first k components to be maintained according to individual schedule with $t^*_{i,\mathrm{Av}}$ as the basis for due time
N	Number of activities/components
T	End of planning horizon, i.e., we are planning from $t_0 = 0$ to T.

The optimization problem is basically a question of balancing planned costs against unplanned costs. The planned costs are incurred when the train is taken out of service for preventive maintenance, whereas the unplanned costs arise upon failures, i.e., corrective maintenance costs (repairs), costs related to accidents, delays, etc.

For each component there is an expected time dependent cost which is a function of the time since the last preventive maintenance activity, i.e., $M_i(x)$. In order to establish $M_i(x)$ we need to (i) establish the accumulated expected number of failures in the period $[0,x)$, (ii) specify the expected corrective maintenance costs for the repair of each failure, and (iii) specify the impact of the failure on safety, punctuality, etc., and quantify these into cost figures. In the model presented here we assume that the effective failure rate, $\lambda_{E,i}(x)$ may be established for the different failure characteristic, and maintenance strategies (e.g., periodic replacement and condition monitoring). Next the costs associated with a failure of component i can in principle be found by risk modelling, punctuality modelling, etc. (see Chapter 4). The result of such modelling is one figure for the expected costs, i.e., c_i^U. Thus, $M_i(x) = x \cdot c_i^U \cdot \lambda_{E,i}(x)$.

The planned costs comprise the costs of executing the maintenance on component i (c_i^P) and set-up costs (S) of getting access to the component. The set-up costs may in general be shared with k-1 other activities.

The average contribution to the total costs for component i per unit time is given by:

$$\Phi_i(x,k) = [c_i^P + S/k + M_i(x)]/x \tag{21.1}$$

If the grouping was fixed, i.e. static grouping, the optimization problem would just be to minimize $\Sigma_i\Phi_i(x,k)$ for all k components maintained at the same time. Static grouping will not be discussed, but we present an approach for dynamic grouping. Mathematically, the challenge now is to establish the grouping either in a finite or infinite time horizon. In addition to the grouping, we also have to schedule the execution time for each group (maintenance package). The grouping and the scheduling can not be done separately. Generally, such optimization problems are NP hard (see Garey and Johnson, 1977, for a definition), and heuristics are required. Before we propose our heuristic we present some motivating results.

Let $\Phi^*_{i,k}$ be the minimum average costs when one component is considered individually, and let $x^*_{i,k}$ be the corresponding optimum x value. It is then easy to prove that $m_i(x^*_{i,k}) = M'_i(x^*_{i,k}) = \Phi^*_{i,k}$ meaning that when the instantaneous expected unplanned costs per unit time, $m_i(x)$, exceeds the average costs per unit time, maintenance should be carried out. The way to use the result is now the following. Assume we are going to determine the first point of time to execute the maintenance, i.e., to find $t = x^*_{i,k}$ starting at $t = 0$. Further, assume that we know the average costs per unit time ($\Phi^*_{i,k}$) but that we have for some reason “lost” or “forgotten” the value of $x^*_{i,k}$. What we then can do is to find t such that $m_i(t) = M'_i(t) = \Phi^*_{i,k}$ yielding the first point of time for maintenance. Then from time t and the remaining planning horizon we can pay $\Phi^*_{i,k}$ as the minimum average costs per unit time. This is the traditional marginal costs approach to the problem, and brings the same result as minimizing (21.1). The advantage of the marginal thinking is that we now are able to cope with the dynamic grouping. Assume that the time now is t_0, and x_i is the age (time since last maintenance) for component i in the group we are considering for the next execution of maintenance. Further assume that the planning horizon is $[t_0,T)$. The problem now is to determine the point of time t ($\geq t_0$) when the next maintenance is to be executed. The total costs of executing the maintenance activities in a group is $S + \Sigma_i c_i^P$ which we pay at time t. Further, the expected unplanned costs in the period $[t_0\ , t)$ is $\Sigma_i M_i(t\text{-}t_0\text{+}x_i)\ \text{-}\Sigma_i M_i(x_i)$. For the remaining time of the planning horizon the total costs are $(T\text{-}t)\Sigma_i\Phi^*_{i,k}$ provided that each component i can be maintained at “perfect match” with k-1 activities the rest of the period. Since $\Phi^*_{i,k}$ depends on how many components that share the set-up cost, which we do not know at this time, we use some average value $\Phi^*_{i,\text{Av}}$. We assume that we know this average value at the first planning. To determine the next point of time for maintaining a given group of components we thus minimize:

$$c_1(t;k) = S + \sum_{i\in K_k}\left[c_i^P + M_i(t-t_0+x_i) - M_i(x_i) + (T-t)\Phi^*_{i,\text{Av}}\right] \tag{21.2}$$

The costs in (21.2) depend on which components to include in the group of activities to be executed next. The more activities we include, the higher the costs will be. For some activities it might thus be cheaper to include them in groups to be executed later. For activities we do not include in this first group we assume that they will be maintained at their “optimum” time $t^*_{i,\text{Av}} > t$. The total contribution to the costs related to these activities in $[t_0,T)$ is:

$$c_2(t;k) = \sum_{i \notin K_k} \left[c_i^P + S / k_{i,\mathrm{Av}} + M_i(x_{i,\mathrm{Av}}^*) - M_i(x_i) + (T - t_{i,\mathrm{Av}}^*)\Phi_{i,\mathrm{Av}}^* \right] \tag{21.3}$$

provided they can be maintained at "perfect match" with other activities, i.e., the set-up costs are shared with $k_{i,\mathrm{av}} - 1$ activities, and executed at time $t_{i,\mathrm{Av}}^*$. The total optimization problem related to the next group of activities is therefore to minimize:

$$c(t;k) = S + \sum_{i \in K_k} \left[c_i^P + M_i(t - t_0 + x_i) - M_i(x_i) + (T - t)\Phi_{i,\mathrm{Av}}^* \right]$$
$$+ \sum_{i \notin K_k} \left[c_i^P + S / k_{i,\mathrm{Av}} + M_i(x_{i,\mathrm{Av}}^*) - M_i(x_i) + (T - t_{i,\mathrm{Av}}^*)\Phi_{i,\mathrm{Av}}^* \right] \tag{21.4}$$

The idea is simple, we first determine the best group to execute next, and the best time to execute it. Further we assume that subsequent activities can be executed at their local optimum. It is expected to do better by taking the second *grouping* into account when planning the first group, and not only treat the activities individually. See e.g., Buday et al (2005) for more advanced heuristics in similar situations to those presented here. The heuristic is as follows:

Step 0 – Initialization. This means to find initial estimates of $k_{i,\mathrm{Av}}$, and use these k-values as basis for minimization of (21.1). This will give initial estimates for $x_{i,\mathrm{Av}}^*$ and $\Phi_{i,\mathrm{Av}}^*$. Finally the time horizon for the scheduling is specified, i.e., we set $t_0 = 0$ and choose an appropriate end of the planning horizon (T).

Step 1 – Prepare for defining the group of activities to execute next. First calculate $t_i^* = x_{i,\mathrm{Av}}^* + t_0 - x_i$ and sort in increasing order.

Step 2 – Establish the candidate groups, i.e., for $k = 1$ to N we use the ordered t_i^*'s to find a candidate group of size k to be executed next. If $t_k^* > \min_{i<k} (t_i^* + x_{i,\mathrm{Av}}^*)$ this means that at least one activity in the candidate group needs to be executed twice before the last one is scheduled which does not make sense. Hence, in this situation the last candidate group is dropped and we are not searching for more candidate groups at the time being.

Step 3 – For each candidate group K_k, minimize $c(t,k)$ in (21.4) with respect to execution time t. Next choose the candidate group K_k that gives the minimum cost. This group should then be executed at the corresponding optimum time t.

Step 4 – Prepare for the next group, i.e., we assume that all activities in the chosen candidate group are executed at time t. This corresponds to setting $x_i = 0$ for $i \in K_k$, $x_i = x_i + t - t_0$ for $i \notin K_k$ and then update the current time, i.e., $t_0 = t$. If $t_0 < T$ GoTo Step 1, else we are done.

There are several ways to improve the algorithm. One intuitive improvement is to improve the estimates of $k_{i,\mathrm{Av}}$ and corresponding $x_{i,\mathrm{Av}}^*$ and $\Phi_{i,\mathrm{Av}}^*$ to be specified in Step 0. This is easy, since we in Step 4 get a new value of k for those activities included in the candidate group, and when the algorithm terminates we simply set

Table 21.1 Snapshop of FMECA for bogie components

#	**Component**	**Function**	**Failure type**	**Failure effect**
1	Torsions bar and Lever, Motor Bogie	Anti roll device	Crack	Potential reduction of anti tilting
2	ZF-Ecomat 5HP600	Transmission between motor and axle gear	Wear and tear	Defect of gear
3	Flexible coupling bearing (CENTA)	Coupling between diesel engine / gear	Wear and tear	Worn out bearing -> vibrations
4	Deep Groove Ball Bearing	Power transfer	Wear and tear	Worn out bearing
5	Aeration Valve	Pressure balance	Locked	Problems with fuel oil filling
6	Torque Reaction Arm	Torque reaction link	Wear and tear	Fissure and demaged rubber of silent blocks
7	Diesel Engine Cummins N14-R	Actuation of half train set	Wear and tear	Functional failure or lower compression of engine
8	Engine attachment (bearing NS3.59)	Engine seat	Wear and tear	Worn out bearing
9	Plant frame bearing (NS3.61)	Damping of vibrations	Wear and tear	Worn out bearing
10	Primary Damper	Absorbing the vibration between axle box and bogie	Functional failure	Reduced dynamic characteristics
11	Horizontal Damper, Motor Bogie	Absorbing the vibration between bogie and car body	Functional failure	Reduced dynamic characteristics

Table 21.1 Continued

#	**Component**	**Function**	**Failure type**	**Failure effect**
12	Horizontal Damper, Motor Bogie	Absorbing the vibration between bogie and car body	Functional failure	Reduced dynamic characteristics
13	Vertical Damper, Motor Bogie	Absorbing the vibration between bogie and car body	Functional failure	Reduced dynamic characteristics
14	Vertical Damper, Motor Bogie	Absorbing the vibration between bogie and car body	Functional failure	Reduced dynamic characteristics
15	Longitudinal Car Body Damper	Absorbing vibrations between car bodies	Functional failure	Reduced dynamic characteristics
16	Break Beam Support Bush	Fixing pin for break beam	Wear and tear	Increased gap between pin and bush
17	Bush for Brake Pad Link	Reduction of wear between bolts brake support	Wear and tear	Increased gap between pin and bush
18	Bush for Brake Unit	Reduction of wear between bolts and brake unit support	Wear and tear	Increased gap between pin and bush
19	Cylindrical roller bearing actuation side	Bearing rotor of generator	Wear and tear	Rotor of generator blocks
20	Cardan Shaft	Power transmission from gear box to bogie	Wear and tear	Fracture joint bearing

$k_{i,\mathrm{Av}}$ as the average for each activity i in the period $[0,T)$. We may then start over again at Step 0 with these new values of $k_{i,\mathrm{Av}}$.

The procedure is demonstrated by analyzing components in a train bogie. A snapshot of the corresponding FMECA is presented in Table 21.1.

Table 21.2 gives cost figures for the bogie components. All failure times are assumed to be Weibull distributed, where we specify the mean time to failure (MTTF, given in million kilometres), and the aging (shape) parameter α. The parameter values have been established in cooperation with NSB experts. However, some of the parameters have been modified by intention to meet competitive considerations. The example is thus realistic, but no single figure should be regarded as approved by NSB. The format and quality of the available data within the maintenance organization of NSB is currently not compatible with requirements for estimating aging parameters or fitting parametric distributions. The shape parameters have therefore been established on a very qualitative understanding of failure mechanisms, and the Weibull distribution has been chosen due to convenience considerations. Set-up costs are assumed to be 3 000 € for all activities. We assume a standard age replacement model, but it is easy to adopt to more complex situations where we, for example, combine inspection and replacement upon condition rather than age (see e.g., Podofollini 2006 for an example model).

In step 0 of the algorithm we first assess $k_{i,\mathrm{Av}} = 13$ for all activities, meaning that we initially believe that in average more than half of the activities are included in each execution of a maintenance group. For all activities we have set $k_{i,\mathrm{Av}} = 13$, and we use (21.1) to find $x^*_{i,\mathrm{Av}}$ for each activity. The result is shown in Table 21.2. The values of $\Phi^*_{i,\mathrm{Av}}$ are not presented here. The time horizon is set to $T = 15$ million kilometres.

In Step 1 we calculate the optimum of each individual activity, $t^*_i = x^*_{i,\mathrm{Av}} + t_0 - x_i$. In the example we have assumed that initially all x_i's are zero (a new train), and since t_0 also is zero initially, we simply have $t^*_i = x^*_{i,\mathrm{Av}}$. These values are sorted in Table 21.3 (values given in million kilometres).

In Step 2 we establish candidate groups. For $k = 12$ we note that $t^*_{12} > t^*_1 + x^*_{1,\mathrm{Av}}$ which means that we only process candidate groups with $k < 12$.

In Step 3 we calculate $c(t,k)$, and the minimum values are shown in Table 21.3. The minimum is found for $k = 10$. Further $c(t,10)$ has it's minimum for $t^* = 0.829$ million kilometres. We observe that for those activities included in the first group, the t^*_i-values are rather close to 0.829 million kilometres.

In Step 4 we now proceed, and set x_i to 0 for those activities which are executed (i.e., $i \leq 10$), whereas $\mathrm{x}_i = \mathrm{x}_i + 0.829$ million kilometres for $i > 10$. Finally we set $t_0 = 0.829$ million kilometre before we go to Step 1 again. The next group of activities is similarly found to be executed at $t^* = 1.606$ million kilometres. This next group comprises some activities not included in the first group, but also some activities that was executed in the first group and are now executed for the second time. We proceed until $t_0 > 15$.

When the procedure terminates, we have a total cost of 1.2 million €. We have also recorded the average values of $k_{i,\mathrm{Av}}$ which in this example ranges from 13.5 to 17 which is slightly higher than the initial assessment of $k_{i,\mathrm{Av}} = 13$. By repeating the entire procedure with the new values for $k_{i,\mathrm{Av}}$ a small reduction in costs of 1% is obtained.

Table 21.2 Cost figures and reliability parameters

#	C^P (€)	C^U(€)	**MTTF (10^6 kilometres)**	**Aging, α**	$x^*_{i,\text{Av}}$ **(10^6 kilometres)**
1	960	6 740	2.56	3.5	1.38
2	9 600	22 400	3.33	3	2.48
3	680	6 230	33.33	3.5	0.67
4	632	5 960	40.40	3.5	1.12
5	720	6 320	10.00	2	4.76
6	400	5 720	2.11	3.5	0.98
7	37 000	72 500	2.00	3.5	7.90
8	520	5 960	4.17	3.5	2.01
9	780	6 440	12.50	3.5	6.46
10	664	6 236	1.60	3.5	0.80
11	424	5 786	1.61	3.5	0.75
12	384	5 711	1.61	3.5	0.74
13	384	5 711	1.78	3.5	0.82
14	184	5 336	1.78	3.5	0.74
15	600	6 116	1.78	3.5	0.88
16	1 440	7 580	2.67	3.5	1.53
17	4 060	12 590	2.67	3.5	1.77
18	1 160	7 130	2.67	3.5	1.48
19	6 080	16 220	1.61	2.5	1.22
20	6 400	16 700	1.33	3.5	0.93

21.3.3 Opportunity based maintenance

The dynamic scheduling regime presented above is a good basis for opportunity based maintenance. The scheduling we have proposed may be used to set up an explicit maintenance plan for the time horizon $[0,T\,)$. But even though the plan exists, we may consider changing it as new information becomes available, either in terms of new reliability parameter estimates, or if unforeseen failures occur. In operation, for any time t_0 we may update the scheduling of preventive maintenance.

Table 21.3 Results for the first maintenance group

#	Activity	t_i^* (10^6 kilometres)	*k*	$c(t^*,k)$ (10^6 €)	t^* (10^6 kilometres)
3	PM	0.674	1	1.2009	0.659
6	PM	0.740	2	1.2007	0.682
10	PM	0.742	3	1.2005	0.690
11	PM	0.751	4	1.2002	0.700
12	PM	0.805	5	1.2000	0.718
13	PM	0.819	6	1.1998	0.728
14	PM	0.879	7	1.1996	0.743
15	PM	0.932	8	1.1995	0.814
20	PM	0.979	9	1.1993	0.820
1	PM	1.120	10	1.1991	0.829
9	Wait	1.221	11	1.1993	0.872
18	Wait	1.375	12	.	.
2	Wait	1.475	13	.	.
16	Wait	1.534	14	.	.
5	Wait	1.769	15	.	.
17	Wait	2.013	16	.	.
7	Wait	2.483	17	.	.
8	Wait	4.760	18	.	
19	Wait	6.461	19	.	
4	Wait	7.904	20	.	

Upon a failure requiring the set-up costs to be paid, it is rather obvious that activities that already were due if they were treated individually according to (21.1) should be executed upon this opportunity. Further, activities not scheduled in the next group (maintenance package) should not be executed since they were not even included in a group to be executed later than the time of this opportunity. The basic question is thus which of the remaining activities in the next due group that should be executed at this opportunity. Let K_k be the set of k activities in this group. Assume that we have found that it is favourable to execute the first i-1 < k activities on this opportunity. The procedure to test whether or not activity i also should be executed is as follows:

- First perform a scheduling by starting at Step 1 in Section 21.3.2. First we assume that all activities up to i are executed on this opportunity , i.e., $x_j = 0$, $j \le i$, and x_j is set to the time since activity j were executed for $j > i$.

- Let C_1 be the minimum value of $c(t,k)$ obtained in Step 3 plus the marginal cost, c_i^P of executing activity *i*.
- Next, we assume that only activities up to *i*-1 is executed, i.e., $x_j = 0, j \leq i$-1, and x_j is set to the time since activity *j* was executed for $j \geq i$.
- Let C_2 be the minimum value of $c(t,k)$ obtained in Step 3 this second time.
- If $C_1 > C_2$ is it not beneficial to do activity *i*.

If it was beneficial to do activity *i* at t_0 we should test for i=i+1 as long as $i \leq k$. The procedure is demonstrated by the following example.

We assume that a failure occurs at time t = 0.8 million kilometres. From Table 21.3 we observe that the first 10 activities were scheduled for execution at time 0.829 million kilometres. Since the schedule costs already is paid by the corrective activity, it is obvious that the first four activities, i.e., those with individual optimum less than t = 0.8 million kilometres should be done. Then we test whether activity 5 (t_5^* = 0.805) should be done at this opportunity. We calculate C_1 = 1.188267 million € and C_2 = 1.188274 million €, hence activity 5 should be done. Then we proceed similarly, and find that also activity 6 should be executed. For activity 7 (t_7^* = 0.879) we find that it is not cost effective to executed this activity. Since the first six activities have been executed upon this opportunity, the next planned maintenance can be postponed from the original t = 0.829 million kilometres to t = 0.985 million kilometres.

21.4 Case study 2: Prioritization of major maintenance and renewal projects

21.4.1 Introduction

The infrastructure manager usually has a limited budget for maintenance and renewal of the railway network. This calls for a structured approach to prioritization of possible projects. In this section we discuss a portfolio approach to greater projects, in contrast to the situation in Section 21.3 where the scheduling of periodical activities were discussed. Examples of such greater projects are:

- Ballast cleaning when the ballast is polluted and stones are crushed
- Rail grinding when the rail surface is rough
- Tamping and leveling when track geometry is degraded
- Sandblasting of bridges exposed to corrosion
- Renewal of overgrown ditches
- Point replacement of rails, e.g., in curvatures with high wear factor

The challenge is to schedule the candidate projects proposed by the local railway departments. Scheduling here means to decide which projects to include in the renewal plan for the next 10 years, and the order of executing the proposed projects. JBV requires that all candidate projects are subject to a cost-benefit analysis (CBA). For such projects we need to consider a time span of several decades, hence it is natural to calculate the net present value (NPV) as a basis for CBA. The CBA figures will only be used as input to the decision process, since it might be other considerations than the pure CBA figures that are taken into account when projects are selected.

Notation

$\rho_{\mathrm{C/B}}$	Cost-benefit ratio, i.e. the net present value of the benefits divided by the net present value of the costs of the project.
$\{\mathrm{RC}(t)\}$	Portfolio costs of renewals without the project.
$\{\mathrm{RC}^*(t)\}$	Portfolio costs of renewals with the project.
$\{T^*\}$	Set of renewal times with the project.
$\{T\}$	Set of renewal times without the project.
$c(t)$	Time dependent cost as at point of time t (from now).
$c^*(t)$	Time dependent cost when a maintenance or renewal project is executed.
d	Factor to describe increase in time dependent cost due to degradation, i.e., the increase from one year to another is $d \cdot 100\%$.
LCC	Life cycle cost.
N	Calculation period for net present value calculations.
r	Discount rate.
RIF	Risk influencing factor, i.e. a factor that influences the risk level.
RLT	Residual life time without the project.
RLT*	Residual life time with the project.

21.4.2 Model formulation

The basic situation is that the railway infrastructure is deteriorating as a function of time and operational load. This deterioration may be transformed into cost functions, and when the costs become very large it may be beneficial to maintain or renew the infrastructure. In the following we introduce the notation $c(t)$ for the time dependent costs as a function of time. In $c(t)$ we include costs related to (i) punctuality loss, (ii) accidents, and (iii) extra maintenance and operation due to reduced track quality. By executing a maintenance or renewal project we typically reset the time dependent cost function $c(t)$, either to zero, or at least a level significantly below the current value. Thus, the operating costs will be reduced in the future if we execute the maintenance or renewal project.

Fig. 21.2 shows the savings in operational costs, $c(t)$ - $c^*(t)$, if we perform maintenance or renewal at time T. In addition to the savings in operational costs, we will also often achieve savings due to an increased “residual lifetime”.

Special attention will be paid to projects that aim at extending the lifelength of a railway system. A typical example is rail grinding for lifelength extension of the rail, but also the fastenings, sleepers and the ballast will take advantages of the rail grinding. Fig. 21.2 shows how a smart activity (💡) may suppress the increase in $c(t)$ and thereby extend the point of time before the costs explode and a renewal is necessary.

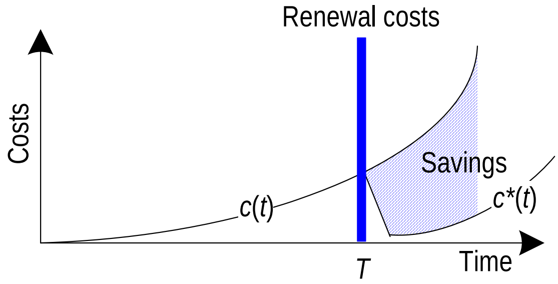

Fig. 21.1 Costs savings

From a modelling point of view the situation is rather complex because different projects are interconnected. For example, by executing a ballast cleaning project the track quality is increased, reducing the need for tamping and leveling. On the other hand, by tamping and point-wise supplement of ballast in pumping areas (surface water) we may postpone the much more expensive ballast cleaning. A third factor to take into account is the fact that for each tamping cycle there is some stone crushing, and hence we should also be reluctant to do too much tamping. Despite the fact that railways have existed for over 160 years there is a lack of documented mathematical models describing the interaction between different components in the railway, and the effect of the various maintenance activities. When developing a tool for prioritization it has therefore been necessary to base the model on model parameters specified by the maintenance planners and their experts. In the future, it is planned to improve the models based on the findings from a joint research project between Norway and Austria.

In the following we describe the basic input for performing the cost benefit analysis. The numerical calculations are supported by a computerized tool (PriFo).

Qualitative information

The situation leading up to each proposed project is described. This is typically information from measurements and analysis of track quality, trends etc. It is important to describe the situation qualitatively before any quantitative parameters are assessed. It is, however, a great challenge to transform the qualitative problem description to quantitative numbers. In the future this can be supported by the expected results from various research projects on deterioration models.

Safety related information

A general risk model has been derived where important risk influencing factors (RIFs) have been identified. The RIFs relate both to the accident frequency such as number of cracks in the rails, but also to the accident consequences such as speed, terrain description etc. Table 21.4 shows an example related to the derailment frequency. In the modelling, f_0 corresponds to the “average” derailment frequency related to rail problems. The value of f_0 is found by analysing statistics over derailments in Norway, where we find $f_0 = 3 \times 10^{-4}$ per kilometre per year.

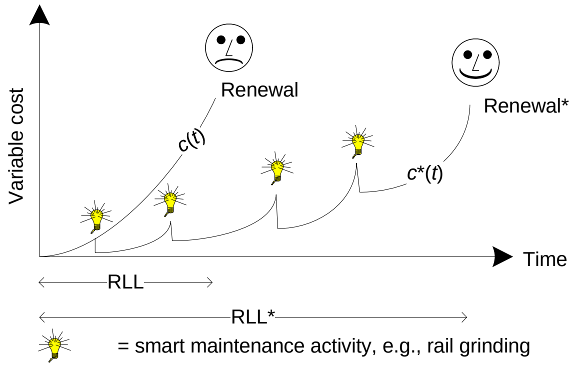

Fig. 21.2 Lifelength extension

The variation width (w) in Table 21.4 shows the maximum negative or positive effect of each RIF. In this model the values of the various RIFs are standardised, which means that -1 represents the “worst value” of the RIF, 0 represent the “base case”, and +1 represents the “best value” of the RIF. The interpretation of w is as follows: If one RIF equals -1, then the derailment frequency is w times higher than for the base case, and if the RIF equals 1 then the derailment frequency is w times lower than the base case. Assuming that the various RIFs act independently of each other an influence model for the derailment frequency may be written:

$$f = f_0 \Pi_i w_i^{-\mathrm{RIF}_i} \tag{21.5}$$

where w_i is the variation width of RIF number i, and RIF_i is the value of RIF number i. By using equation (21.5) with the generic weights from Table 21.4, we may easily assess the derailment frequency only by assessing the values of the RIFs for a given railway line or section.

In addition to the current value of the risk, also the future increase has to be described corresponding to the two cost curves $c(t)$ and $c^*(t)$ in Fig. 21.2. For example, we might use an exponential growth of the form $c(t) = f\,(1+d)^{t-1}$, where d is the degradation from one year to the next. The rational behind an exponential growth is that the forces driving the track deterioration often is assumed proportional to the deviation from an ideal track. A simple differential equation argument would then show an exponential growth.

Punctuality information

The basic punctuality information to be specified is the ordinary speed for the line, and any speed reductions due to the degradation the project is intended to fight against. Based on the amount of speed restrictions it is rather easy to calculate the corresponding train delay minutes. Very often such delays cause cascading effects in a tight network.

Table 21.4 Example of effect of risk influencing factors

Risk influencing factor, RIF	**Variation width, *w***
Number of failures/cracks	4
Rail quality (age, type, rail profile)	2
Gradient	2
Quality of sleepers, ballast and fastening	2
Number of fixed points with narrow filling	1.5
Horizontal geometry	1.5

Such effects can not be assessed unless we have a good understanding of the network capacity, and the possibilities for change of crossings, etc. In Norway, where most lines are single track lines, change of crossing may cause large disturbances in the network. It may also be possible to catch up with a delay if there is slack in the schedule.

Maintenance and operating information

The degradation of the permanent way will very often require extra maintenance and operating costs. Examples of such costs are extra runs of the measurement car, extra line inspections, use of alternative transportation such as busses, shorter lifetime of influenced components, etc. These costs need to be quantified in the model. Describing the change in maintenance and operating costs are very challenging because short term and long term activities interact. It is possible to perform explicit modelling of such interactions if we have a good understanding of the physical deterioration. Welte et al (2006) has, e.g., used a Markov state model to model degradation, and the effect of different inspection and renewal strategies.

Residual lifelength

To be able to calculate the economic gain due to increased lifelengths it is required to describe the residual lifelength both if the proposed project is executed, e.g., RLL*, and if the project is not executed, RLL.

Project costs

The project costs are specified for each year in the project period.

Cost parameters

A set of general cost parameters are common for all projects. For JBV these are:

- The discount rate is r = 4%. Note that we here introduce the discount factor as the difference between the interest rate and the inflation rate.
- Monetary values for safety consequence classes as given in Table 21.5.
- Costs per kiloton freight delayed one minute =160 €.

Table 21.5 Monetary values in € for each safety consequence class

Safety consequence		**Monetary value (€)**
C_1	Minor injury	2 000
C_2	Medical treatment	33 000
C_3	Serious injury	330 000
C_4	1 fatality	1.7 millions
C_5	2-10 fatalities	11 millions
C_6	> 10 fatalities	175 millions

- Costs per passenger delayed one minute = 0.4 €. A train with 250 passengers then gives 100 € per minute delayed.

21.4.3 LCC calculations

A life cycle cost (LCC) perspective will be taken with respect to calculating the cost benefit ratio for the different projects. This includes a net present value analysis, taking the following aspects into consideration:

- Change in variable costs, $c(t)$
- The effect of extending the lifelength
- The project costs

Change in variable costs

The variable cost contribution from the dimension safety, punctuality, and maintenance and operation can be treated similarly from a methodical point of view. Let $c(t)$ denote the variable costs in year t (from now) if the project is not executed, and similarly $c^*(t)$ is the cost if the project is run. See Fig. 21.2 for an illustration. For example, for the safety dimension we have:

$$\Delta \mathrm{LCC}_\mathrm{S} = \sum_{t=1}^{N} \left[c(t) - c^*(t) \right] (1+r)^{-t} \tag{21.6}$$

where r is the discount rate, and N is the calculation period. N is here the residual lifelength (RLL) if nothing is done. This means that we compare the situation with and without the project in the period from now till we in any case have to do something. Similarly we obtain the change in punctuality costs, $\Delta\mathrm{LCC}_P$ and the change in maintenance and operational costs, $\Delta\mathrm{LCC}_{\mathrm{M\&O}}$.

To calculate (21.6) we may in some special situations find closed formulas. For example, if $c(t)$ is constant, i.e., $c(t) = c$, the formula for the sum of a geometric series yields:

$$\sum_{t=1}^{N} c(1+r)^{-t} = c\left[\frac{1-(1+r)^{-N}}{r}\right] \tag{21.7}$$

Further if $c(t)$ the first year is c_1 and $c(t)$ increases by a factor $(1+d)$ each year we have:

$$\sum_{t=1}^{N} c_1(1+d)^{t-1}(1+r)^{-t} = c_1\left[\frac{1-\left(\frac{1+d}{1+r}\right)^{N}}{r-d}\right] \tag{21.8}$$

The effect of extending the lifelength
To motivate for the calculation we show a sketch of the need for renewal both if and if not the proposed project is executed in Fig. 21.3.
We now let:

{RC(t)} = Portfolio costs of renewals without the project
{RC*(t)} = Portfolio costs of renewals with the project
{T} = Set of renewal times without the project
{T*} = Set of renewal times with the project.

The cost contribution related to increased residual lifetime may now be found by:

$$\Delta\mathrm{LCC}_{\mathrm{RLT}} = \sum_{t\in\{T\}} \mathrm{RC}(t)\cdot(1+r)^{-t} - \sum_{t\in\{T^*\}} \mathrm{RC}^*(t)\cdot(1+r)^{-t} \tag{21.9}$$

The project costs
The LCC contribution from the project cost, LCC_I, is the net present value of the project costs in the project period. The project costs may be spread over some years, and hence we have to calculate the NPV of the project cost profile.

Total LCC contribution
The total gain in terms of life cycle costs are:

$$\Delta\mathrm{LCC} = \mathrm{LCC}_I + \Delta\mathrm{LCC}_S + \Delta\mathrm{LCC}_P + \Delta\mathrm{LCC}_{\mathrm{M\&O}} + \Delta\mathrm{LCC}_I \tag{21.10}$$

The cost benefit ratio, or more precisely the benefit cost ratio is given by:

$$\rho_{\mathrm{C/B}} = \frac{\Delta\mathrm{LCC}_S + \Delta\mathrm{LCC}_P + \Delta\mathrm{LCC}_{\mathrm{M\&O}} + \Delta\mathrm{LCC}_{\mathrm{RLT}}}{\mathrm{LCC}_I} \tag{21.11}$$

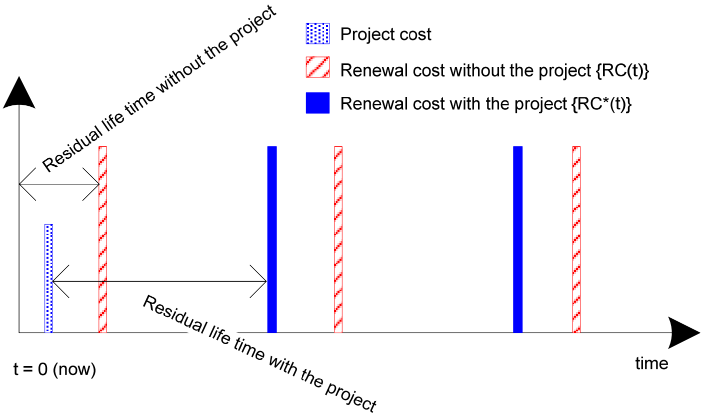

Fig. 21.3 Renewals if and if not the project is executed

21.4.4 Illustraitive example

As a calculation example we consider a rail-grinding project. Grooves and wave formations imply strong impact on the track and rolling stock due to increased dynamic loads and vibrations. This again gives shorter life length of the rails, the sleepers, fastenings and ballast. Increased noise, energy consumption, and lower comfort can also be expected.

A 160-km section on the Rauma line in Norway has rails of age 40 to 50 years and rail grinding is recommended primarily to extend the life length of the rails.

Safety costs

The derailment frequency due to rail breakages is estimated to 0.01 per year. For the most severe consequences we have the following distribution $P(C_4) = 13.5\%$, $P(C_5)= 11\%$ and $P(C_6) = 5\%$ where the consequence classes are explained in Table 21.5.

The material damage costs given a derailment is estimated to 1 300 000 €. Thus the yearly “safety costs” is found to be $0.01 \cdot (0.135 \cdot 1.7 + 0.11 \cdot 11 + 0.05 \cdot 175 + 1.3)$ million €, which equals 110 000 €. It is further expected that the rate of rail breakages leading to derailments will increase by a factor $d = 7\%$ if no grinding is performed. If the grinding project is executed the derailment probability the first year is assumed to be reduced by a factor of 50%, and the deterioration factor is also assumed to be reduced to $d = 3\%$ each year, and by utilizing equation (21.8) we have the following contribution to the safety part of the LCC (the calculation period is set to $N = 5$ years, which is the expected residual life of the rails if no grinding is performed):

$$\Delta \mathrm{LCC_S} = 110\ 000 \left[\frac{1 - \left(\frac{1+0.07}{1+0.04} \right)^5}{0.04-0.07} \right] - 55\ 000 \left[\frac{1 - \left(\frac{1+0.03}{1+0.04} \right)^5}{0.04-0.03} \right] \approx 300\ 000\ €$$

Punctuality costs
Due to a high number of cracks it is recommended to reduce the speed from 80 to 70 km/h for a section of 20 km. The speed reduction corresponds to 2 minutes increase in travelling time. Slightly more than thousand passengers travels this line per week, thus the yearly delay time costs is in the order of 50 000 €. In addition, there is also freight delay time costs in the order of 60 000 € the first year. An increase in the speed restriction of d = 10% is expected if the grinding project is not executed. If the grinding project is executed, we may relax on speed restriction yielding a punctuality loss the first year of 40 000 €, and then a yearly increase of d = 3%. Again, utilizing equation (21.8) we have:

$$\Delta \mathrm{LCC_P} = 110\ 000 \left[\frac{1 - \left(\frac{1+0.10}{1+0.04} \right)^5}{0.04-0.10} \right] - 40\ 000 \left[\frac{1 - \left(\frac{1+0.03}{1+0.04} \right)^5}{0.04-0.03} \right] \approx 400\ 000\ €$$

Maintenance and operation costs
From different studies it is found that rail grinding every 40 megaton reduce the wear of other components (sleepers, ballast and fastenings) corresponding to 3 € per metre per year. This corresponds to a yearly (fixed) cost of 400 000 € for the actual 160 km section. Using equation (21.7) with N = 5 this corresponds to an NPV value of 2.1 million €. Reduction of critical cracks that have to be fixed is estimated to 10 per year, and with a cost of 2 500 € per crack to be fixed this gives an NPV value of 110 000 €. Finally, extra yearly ultrasonic inspection accounts for 12 000 € per year corresponding to an NPV value of 50 000 €. The total extra maintenance and operation costs are therefore found to be almost 2.3 million €.

Extended lifelength
By the rail grinding project it is assumed that the rails may be kept going for another 15 years, whereas a rail renewal is expected after 5 years if the project is not run. The lifelength of new rails is approximately 40 years. The costs of new rails is in the order 250 € per meter. The LCC contribution is thus the difference in changing the rails in 5 years, 45 years, 85 years etc, versus changing the rails in 15 years, 55 years, 95 years etc. A discount rate r = 4% calls for only counting the two first renewals, hence:

$$\mathrm{LCC_{RLT}} = 250 \times 160\ 000\ [1.04^{-5}+1.04^{-45}-1.04^{-15}-1.04^{-55}] \approx 12.9 \text{ mil. €.}$$

Project costs

The costs of rail grinding is in the order of 8 € per meter, giving a total cost of 1.3 million €. In addition we have to expect a second grinding within 5 to 10 year, giving an additional contribution. The net present value of the grinding activity is then 2.2 million €.

Cost benefit ratio

Summing up we find the following contribution to the change in LCC (million €):

$\Delta \text{LCC}_S = 0.3$
$\Delta \text{LCC}_P = 0.4$
$\Delta \text{LCC}_{\text{M\&O}} = 2.3$
$\Delta \text{LCC}_{\text{RLT}} = 12.9$
$\text{LCC}_I = 2.2$

This yields a cost benefit ratio of $\rho_{\text{C/B}} = 7.2$, meaning that for each Euro put into rail grinding, the payback is 7 Euros.

By calculating the cost benefit ratio for the various maintenance and renewal projects, we get a sorted list of the most promising projects. In principle, we should execute those projects having a cost benefit ratio, $\rho_{\text{C/B},}$ higher than one. If the budget constraints imply that we can not execute all projects with $\rho_{\text{C/B}}$ higher than one, it would be necessary to have a thorough discussion related to the budget for maintenance and renewal. Since most organizations suffer from the short term costs cutting syndrome, it is a hard struggle to argue for spending more money now in order to save money in a five to ten years perspective.

Even if we can not do much about the budget situation, we may use the results from the cost-benefit analysis to prioritize between the various projects.

21.5 Conclusions

The two case studies presented elaborate on some of the challenges in Norwegian rail maintenance. Both the railway undertaking (NSB) and the infrastructure manager (JBV) aim at implementing more proactive strategies for maintenance and renewal based on more formal methods such as RCM and NPV/CBA. These methods require reliability parameters of a much higher level of detail than the current experience databases can offer today. Therefore both NSB and JBV have started the process of restructuring databases, and emphasize the importance of proper failure reporting. Due to the lack of experience data it has up to now been necessary to utilize expert judgment to a great extent. It is further important to emphasize that optimization models like the ones presented here should be considered as decision support, rather than decision rules. In order to improve on these areas we believe that more systematic collection and analysis of reliability data is an important factor, and here the rail industry may learn from the offshore industry where joint data collection exercises have been run for 25 years (OREDA 2002).

Another challenge of such modelling is the lack of consistent degradation models. For example, for the track there is a good qualitative understanding of factors affecting degradation such as water in the track, contamination, geometry failures, heavy axels, etc. However, the quantitative models for degradation taking these factors into account are not very well developed. Research has paid much attention to design problems to ensure long service life but it is difficult to use the research results for maintenance and renewal considerations. More empirical research on degradation mechanisms will also be important in the future.

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