Scheduling tamping through global optimization of maintenance costs

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Abstract

Maintenance is an important and strategic issue for the management of a railway line. In ballasted tracks a suitable planning of tamping actions is necessary to optimize maintenance costs in a defined time horizon.

Optimization problems may be solved by exact algorithms; heuristics and meta-heuristics algorithms (genetic models); hybrid algorithms and multi-objective algorithms. These algorithms have already been applied to optimize railway timetables, assigning locomotive at a minimal operational costs, optimizing networks, assigning extra trains on a railway network, etc (Cacchiani et al., 2010; Guan et al., 2006; Rouillon et al., 2006; Lingaya et al., 2002; Higgins et al., 1996).

The application of global optimization techniques for scheduling preventive maintenance in railways is relatively new and the combination of forecasting models with optimization problems in the management of railway maintenance operations is even more rare. This fact justifies the work developed within this topic and presented here.

In this research a mathematical programming is used to schedule and to predict tamping on ballasted tracks by minimizing maintenance costs. For the model formulation five aspects are taken into account: the inflation rate of maintenance costs over time; the evolution of track geometrical degradation over time; the track layout; the dependency of track quality recovery on the geometrical quality at the moment of maintenance operation; the track quality limits that depend on the train speed. In this model, the geometrical degradation of the track is characterized exclusively by the longitudinal level, however other geometrical parameters could be considered in future with a simple reformulation of the model. The forecasting model for the evolution of the longitudinal level over time is defined by a deterministic approach. The mathematical formulation of the model leads to a mixed 0 − 1 integer nonlinear program. This problem can be reduced into a mixed 0 − 1 integer linear program by exploiting the so-called reformulation–linearization technique (RLT).

An application to a stretch of track on the Portuguese Railway Northern Line is presented in order to validate the developed model. The computational experience highlights the importance of the maintenance model in practice since the results attained show that this model is able to produce useful results in terms of optimal schedules in a reasonable time.

A contribution of the paper is the development of a mathematical model designed to optimize tamping costs with a great potential for National Railway Administrations.

Keywords: Maintenance costs; Global Optimization; Mathematical Programming; Mixed Binary Nonlinear Problem
1. Introduction

Track maintenance covers all the measures for preserving and re-establishing the nominal condition, such as: 1) tamping, to adjust longitudinal profile, cross level and alignment of the track; 2) rail grinding to correct rail corrugations, fatigue and metal flow and to re-profile the rail; 3) rail replacement; 4) track stabilisation to restore the lateral resistance into the original level by track vibration; 5) ballast injection or stoneblowing to correct the track longitudinal profile.

When performing track maintenance, tamping is the measure usually adopted to correct the longitudinal level, which is the geometrical parameter that most influences vehicles and track dynamics in the vertical direction. Therefore several documents, such as EN13848-5 (CEN, 2008) among others, define limits for track quality, considering safety and comfort aspects.

Besides safety and comfort issues, the economic reason is strategic since a great percentage of management costs are due to track maintenance. Thus, minimizing tamping actions, maintenance costs are also minimized (Kong and Frangopol, 2003; Grimes and Barkan, 2006; Macke and Higuchi, 2007).

Mathematical programming is already used for several applications in mechanics, economics and different branches of physics however their application to railway engineering, namely preventive maintenance, has not been applied so far. A review of some works focusing exclusively on optimization models solved by exact algorithms for maintenance scheduling may be seen in Vale et al (2010).

2. Model formulation

2.1 General description

The main objective of the proposed model is to provide a methodology for an optimized schedule of preventive maintenance activities in a finite time horizon based on track quality, technical aspects related to tamping operations and inflation rate. The model seeks an optimal solution corresponding to the minimum of the total number of tamping actions \( M \) on a track for a predefined time horizon, considering the increase of the maintenance costs through the inflation rate \( t \). If \( m_{ij} \) is the binary variable associated to a preventive maintenance action on track segment \( i \) and time period \( j \), then the objective function takes the form:

\[
\min C_{\text{tamping}} \sum_{j=1}^{n_p} (1 + t)^{\lambda} \sum_{i=1}^{n_t} m_{ij}
\]  

where \( C_{\text{tamping}} \) is the cost of tamping in the present time, \( \lambda \) is a parameter that represents years, \( n_t \) is the total number of track segments and \( n_p \), the total number of time periods.

For the mathematical model formulation, some assumptions are taken into account:

a) the degradation of track geometry is characterized by the increase of the standard deviation of the longitudinal level, which means that irregularities of alignment, cross level, gauge and twist are disregarded for now;

\[
\sigma_g = \sigma_{g_{i-1}} + d_i - m_{ij} r_{ij}
\]  

b) maintenance actions \( m_{ij} \) correspond to tamping operations;

c) the inflation rate \( t \) is constant over time;
d) the recovery of track quality is linearly dependent on the value of the standard deviation of the longitudinal level of the track segment at the time of maintenance as shown in expression (3)

\[ r_{ij} = a (\sigma_{ij-1} + d_i) + b \]  

(3)

where:
- \( a \) and \( b \) are real parameters evaluated by linear regression of the data;
- \( d_i \) is a real parameter which represents the degradation rate of the standard deviation of the longitudinal level on segment \( i \);
- \( r_{ij} \) is the recovery after maintenance of the standard deviation of the track longitudinal level on segment \( i \) and time period \( j \);
- \( \sigma_{ij-1} \) is the standard deviation of longitudinal level on track segment \( i \), and at the period of time immediately previous to the maintenance operation;
- \( \sigma_{ij-1} + d_i \) is the standard deviation of longitudinal level at the time of maintenance.

This assumption is considered, because it has been concluded that the recovery effectiveness of the longitudinal level depends on the quality of the track at the time of maintenance operations (ORE, 1988).

e) tamping operations begin and end on a straight alignment, according to UIC (2008) recommendations

\[ \sum_{j \in l(k)} m_{ij} \geq \left| I(k) \right| m_{kj} \]  

(4)

with \( k \in \{1, \ldots, n_j\} \), \( j \in \{1, \ldots, n_p\} \) and \( I(k) \subseteq \{1, \ldots, n_t\} \) is the set of consecutive indexes of track segments that includes segment \( k \) in curve and an initial and final segments in straight alignments.

Thus, if a tamping operation is predicted for a segment in curve, then the set of track segments that includes the segment (C) in curve and is bounded by straight segments (R) is also subjected to maintenance. Figure 1 shows this aspect.

![Figure 1 – Track layout influence on maintenance scheduling](image)

The mathematical formulation leads to a mixed integer binary nonlinear program. By exploiting the so-called reformulation–linearization technique, proposed by Sherali and Adams (1999), it is possible to reduce this program into a mixed integer binary linear programming problem.

There are two novel aspects in the present research work. The first one is the development of a predictive maintenance model that considers both technical and financial aspects for optimizing maintenance actions. Finally, the second novelty of the research is the application of global optimization techniques combined with forecasting models for scheduling tamping operations in railways tracks. In short, the proposed approach for optimizing and scheduling tamping may be a very useful tool for National Railway Administrations for maintenance operations management.

3. Computational experiments

The proposed model is applied to a 33.4 km stretch of railway track and the commercial program Cplex of the GAMS collection (Brooke et al., 1998) has been used to process the mixed-integer linear programs.
3.1 Data

In the proposed model, the following data are considered:

- the standard deviation of the longitudinal level of each track segment at an initial time instant (Figure 2); in this figure, the limit indicated in red corresponds to the alert limit indicated in EN 13848-5 (CEN, 2008);

![Figure 2](image)

**Figure 2** – Standard deviation of the longitudinal level of each track segment at an initial time instant

- the degradation rate of the standard deviation of the longitudinal level at each track segment which is considered to be constant over time (Figure 3);

![Figure 3](image)

**Figure 3** – Degradation rate of the standard deviation of the longitudinal level at each track segment

- the track layout (Figure 4);

![Figure 4](image)

**Figure 4** – Track layout (C – curve; R – straight alignment)
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- the quality recovery attained after tamping:
  \[ r_{ij} = 0.4257 \sigma_{ij-1} - 0.153 \]
- the inflation rate: 0 and 2 %.

All the data introduced in the model are obtained with the application of the tool proposed by Vale and Calçada (2011).

In the computational experience a five year time horizon, defined by time intervals of 90 days, is considered and two different inflation rates are analysed: 0 and 2%. Also the influence of track layout on the results is analysed.

### 3.2 Results and discussion

Table 1 indicates, for each scenario, the total number of maintenance actions associated with the optimal solution attained by the Cplex code. The results show that the total number of actions is independent of the inflation rate, but dependent on the track layout.

<table>
<thead>
<tr>
<th>Inflation rate</th>
<th>Model without the constraints related to track layout: track with no curves</th>
<th>Complete model: track with curves and straight alignments</th>
</tr>
</thead>
<tbody>
<tr>
<td>t= 0 %</td>
<td>302</td>
<td>474</td>
</tr>
<tr>
<td>t= 2 %</td>
<td>302</td>
<td>474</td>
</tr>
</tbody>
</table>

The distribution over time of tamping actions is presented in Figures 6 and 7 for the four simulations, considered in order to analyse the influence of the track layout and the inflation rate on the distribution over time of tamping actions.

Figure 6 – Influence of inflation rate on the distribution over time of tamping actions
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The numerical results clearly indicate that maintenance actions are performed in a concentrated way when track layout is considered in the model and that tamping is scheduled sooner for higher inflation rates.

Table 2 includes the percentage of maintenance actions over the years. For an inflation rate of 2%, the annual percentage of actions decreases over time. The results also show that almost 50% of all maintenance operations are predicted in the first year of the time horizon for case $t=2\%$.

Table 2 – Percentage of maintenance actions over the years

<table>
<thead>
<tr>
<th>Inflation rate</th>
<th>Year 1</th>
<th>Year 2</th>
<th>Year 3</th>
<th>Year 4</th>
<th>Year 5</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t=0%$</td>
<td>33.3%</td>
<td>19.8%</td>
<td>24.9%</td>
<td>15.6%</td>
<td>6.3%</td>
</tr>
<tr>
<td>$t=2%$</td>
<td>49.6%</td>
<td>19.0%</td>
<td>16.5%</td>
<td>14.6%</td>
<td>0.4%</td>
</tr>
</tbody>
</table>

In Figure 8, the evolution of the standard deviation of the longitudinal level over time is represented for two track segments in order to assess in detail the influence of inflation rate on the forecast evolution of the track longitudinal level.
In segment 5 the track quality is similar in both cases at the end of each time horizon while in segment 39, the track quality is higher when $t=0\%$. This is because the maintenance action is performed at a time horizon which will allow a higher quality recovery.

4. Conclusions

A mathematical programming approach for optimizing and scheduling maintenance may be a very useful tool for National Railway Administrations for the maintenance operations management. This paper presents a preventive maintenance model for scheduling tamping in ballasted tracks. As far as the model is concerned, it is able to produce useful results in terms of optimal schedules. One of the features of the model is that it allows analysis of the distribution of maintenance actions over time which is an advantage for evaluating the maintenance costs over time. This model is still in development and improvements are being considered in order to take into account other geometrical track parameters, to consider logistic aspects and also to take account of more accurate degradation rates.

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References:


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ORE. 1988. Dynamic vehicle/track interaction phenomena, from the point of view of track maintenance (Question D161, RP3). ORE.