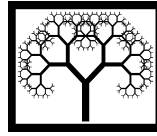


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# **A Decision Support System for Railway Track Maintenance and Renewal Planning**

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## **Abstract**

This paper describes a computerized decision support system that integrates robust track degradation models, calibrated and validated with more than ten years of historical data from inspections in the Portuguese railway network, to support railway track maintenance and renewal decisions. Furthermore the software tool incorporates a data management module that facilitates the assessment of track component conditions. In this paper we present the methodology and the results from the data mining analysis on the track geometry parameters and some important automatic outputs of railway track condition and maintenance, and renewal forecasts that are integrated in this decision support system. The developed software proved to be a useful tool for track managers and engineers to analyze the railway track condition and decide when maintenance is necessary and when is the best time for renewal of railway track components.

**Keywords:** decision support system, railway track, degradation models, maintenance, renewal, scheduling.

## **1 Introduction**

In order to improve railway transport competitiveness, while ensuring quality and safety standards and promoting infrastructure use among operators in a fairly regulated environment, infrastructure managers should contribute to increase efficiency by improving maintenance and renewal (M&R) decision-making processes throughout railway track life-cycle. However, a robust planning of M&R operation requires a large amount detailed data to characterize the condition of the track infrastructure and forecast maintenance and renewal operations.

Despite maintenance management tools are nowadays often used in organizations (where large-scale preventive maintenance schemes are being set up to reduce the probability of failure) since preventive maintenance requires investment, a good balance should be made between its costs and benefits. Therefore, the right time for railway track M&R works must be defined. Railway track M&R operations carried out at the right time are crucial to realizing an efficient and optimized work plans, thus increasing the life of the railway track components, whereas carrying out maintenance and renewal works too late is certainly unsafe and as the railway track gets older, the maintenance and renewal costs increase exponentially.

This study presents the first version of a computerized decision support system (DSS) for scheduling railway track M&R operations. Degradation laws for railway track components were developed based on the statistical assessment of historical data from inspection and integrated as inputs for the model. The paper starts with a brief literature review of the main approaches used in the development of railway track M&R DSS, which is followed by a description of the track degradation models used to forecast M&R operations. Outputs from the DSS are used to demonstrate the applicability and usefulness of the software tool. Finally, the last section contains some concluding observations and future challenges of this study.

## **2 DSS for railway infrastructure M&R planning**

Decision support systems for planning infrastructures M&R operations have been a research subject for long. In railways, the complexity of modeling the infrastructure degradation is particularly high. Therefore, in the last two decades, a high effort was already made to develop rational M&R planning systems (see Table 1). The models described in the following table use as much as possible data from inspections to estimate M&R planning. Besides, in some cases these operations are defined through optimization procedures.

The DSS for rail track M&R operations is an issue with an increasing research interest. Currently, there are three European Projects from the 7<sup>th</sup> Framework Program in which this topic is being studied [4]. ACEM-Rail is one of these and it has as main objective the automation and optimization of railway infrastructure maintenance. The focus of this project is the track components and it aims to reduce costs, time, resources required for maintenance activities and increase the infrastructure availability of conventional and high speed lines. Another project is the AUTOMAIN (Augmented Usage of Track by Optimization of Maintenance, Allocation and Inspection of Railway Networks). The field of this project is also the optimization and automation of rail track maintenance and inspections. Moreover, it will try to introduce new planning and scheduling tools to reduce around 40% the track possession times. Finally, DIAGNO-RAIL is another project in the field of rail track maintenance. However, in this case the goal is to test and implement new methodologies to improve the risk assessment and failure prediction concerning the integrity and functionality of rail systems.

<b>Developer or user</b>	<b>Name of System</b>	<b>Brief Description</b>	<b>Reference</b>
SNCF (French National Railways)	TIMON	Database of track geometric quality for high-speed lines. Estimation of track degradation rate with incorporation of uncertainty (stochastic gamma process). This approach classifies track segments into classes of homogeneous track quality for maintenance scheduling proposes.	[1]
Lulea University of Technology	DECOTRACK - Degradation Cost of Track	Estimation of the influence of changes in traffic on maintenance operations and on track degradation rates.	[2]
Queensland University of Technology	ITDM - Integrated Track Degradation Model	Integration of rail, sleeper, ballast and subgrade degradation models to predict the future behavior of these components.	[2]
Japanese Railway Network	TPM – Transition Process Model	Planning tamping schedule for railway network through an integrated model that considers a degradation model, restoration model and optimal track maintenance scheduling model.	[2]
Association of American Railroads	RTLM – Railway Track Life-Cycle Model	Prediction of rail wear rate, rail defect growth rate, wooden sleeper degradation, turnout degradation, ballast degradation and track roughness growth. Maintenance and renewal costs and policies are estimated through these degradation models.	[2]
British Network Rail	VSTIM – Vehicle Track Interaction Strategic Model	Optimization of maintenance and renewal strategies by considering vehicle and track characteristics. This incorporates a rail and a track degradation model.	[3]
Mermec Group	RAMSYS	DSS for infrastructure maintenance and renewal management (incorporation in GIS, deterioration models, maintenance planning and optimization algorithms).	[4]
Bentley Systems	OPTRAM	This model addresses several maintenance issues. Management of inspection data, asset management, maintenance cost optimization and GIS interface.	[4]
British Rail	MARPAS - Maintenance and Renewal Planning Aid System	Models for wheel, rail, track geometric quality and energy consumption. Uses track roughness to calculate effect of tamping frequency on the overall financial situation to give near optimal result.	[5]
ERRI UIC	ECOTRACK - Economical Track	Rule based expert system for track maintenance (excludes turnouts, crossing). Decision on 3 months to 3 years for maintenance and on 1 to 5 years for track renewal (urgent and spot maintenance are not considered).	[6]
AAR / MIT	TRACS - Total Right-of-way Analysis and Costing System	Engineering-based deterioration models combined with life cycle costing techniques. Applications: technology evaluation, maintenance budgeting, incremental costing.	[6]

Table 1: Summary and description of rail track DSS for M&R planning.

### 3 Railway track geometry degradation model

Traveling safely and comfortably on railway lines requires the whole railway infrastructure (particularly the railway track infrastructure) to be in excellent condition. A reliable forecast of railway track geometry degradation is essential to estimate and optimize the schedule of M&R operations. The basis of a good decision support system for these works is a robust degradation model.

Railway track geometry is degraded under traffic loads, and must undergo periodic maintenance. Tamping is the operation that restores the track geometry. The requirements for this intervention are usually related to levels of quality that have a direct influence on user comfort and safety. In the most main lines in Europe, the vertical and horizontal track alignments are the main parameters that trigger preventive tamping operations. These are commonly quantified as a standard deviation (SD) for the short wavelength (3m - 25m) of the vertical and horizontal alignment defects in a 200 m track segment. As discussed in Andrade and Teixeira [7] the SD of the vertical and horizontal alignment, when used to trigger preventive maintenance actions are good predictors of corrective maintenance needs regarding all the remaining indicators of track geometry.

The vertical alignment (VA) is commonly quantified as the geometrical error in the vertical plane and measured as the difference (in millimeters) between a point on the top of the rail in the running plane and the ideal mean line of the longitudinal profile. The horizontal alignment (HA) defect is the difference (in millimeters) from the measured mean horizontal position to the reference line of this parameter. The evolution of the standard deviation of these two parameters in each 200 m can be expressed using linear and nonlinear relationships. Even though the nonlinear function obtained in Riessberger [8] provides good approximations to model the degradation of the track geometry parameters described above, the linear function is still widely used and confirmed by several studies [9, 10]. A linear trend of the SD of the vertical and horizontal alignment measure in a 200 m track segment is a widely used approximation [9]. This degradation law is given by the following expression:

$$\begin{aligned}\sigma_{VA}(l) &= c_{0,VA} + c_{1,VA}l \\ \sigma_{HA}(l) &= c_{0,HA} + c_{1,HA}l\end{aligned}\tag{1}$$

where  $l$  = accumulated axle tonnage/loads in million gross tones (MGT) in a 200 m track segment since the last renewal or tamping;  $c_{0,VA}$  = initial value of the SD of the vertical alignment defects;  $c_{0,HA}$  = initial value of the SD of the horizontal alignment defects (in mm) after tamping or renewal;  $c_{1,VA}$  = degradation rate of the

vertical alignment defects; and  $c_{1,HA}$  = degradation rate of the horizontal alignment defects (in mm/MGT).

The effectiveness of ballast tamping operations tends to decrease with the number of tamping cycles. The declining ability of tamping to restore the geometry parameters is explained by the degradation of ballast with traffic loads and successive tamping operations (crushing of the ballast particles). This behavior leads to a track degradation model that exhibits an increasing need for maintenance to preserve riding comfort levels. If we introduce the efficiency parameter related to tamping in Eq. (1), we obtain:

$$\begin{aligned}\sigma_{VA}(g;l) &= c_{0,VA}\beta_{VA}^g + c_{1,VA}l \\ \sigma_{HA}(g;l) &= c_{0,HA}\beta_{HA}^g + c_{1,HA}l\end{aligned}\tag{2}$$

where  $g$  = cumulative number of tamping operations since the last renewal; and  $\beta$  = loss of efficiency of tamping as more of this work is carried out (from the beginning of the ballast life cycle) for the vertical and horizontal alignments.

## 4 Decision support tool

### 4.1. Framework

Extensive use of data, statistical and quantitative analysis, explanatory and predictive models can support almost any decision. In this study, the process of analyzing historical data goes from a descriptive study to a predictive evaluation of the parameters/actions under analysis. Using a predictive model of the infrastructure behavior, the M&R decisions can be planned in an effective way.

In the following figure is presented a general overview of the interactions between the several analysis that create the decision process and also the necessary data that sustain the integrated railway track M&R model described in this study. This figure represents the final framework of the DSS. Currently the investment and cost assessment section are still under development.

In the specific case of railway infrastructure asset management, it is important to introduce a constant update of the inputs of the model during the life cycle of the component to verify the robustness of the solutions of the model. Basically, the validation process occurs iteratively when more data becomes available or when the assumptions considered in the model change.

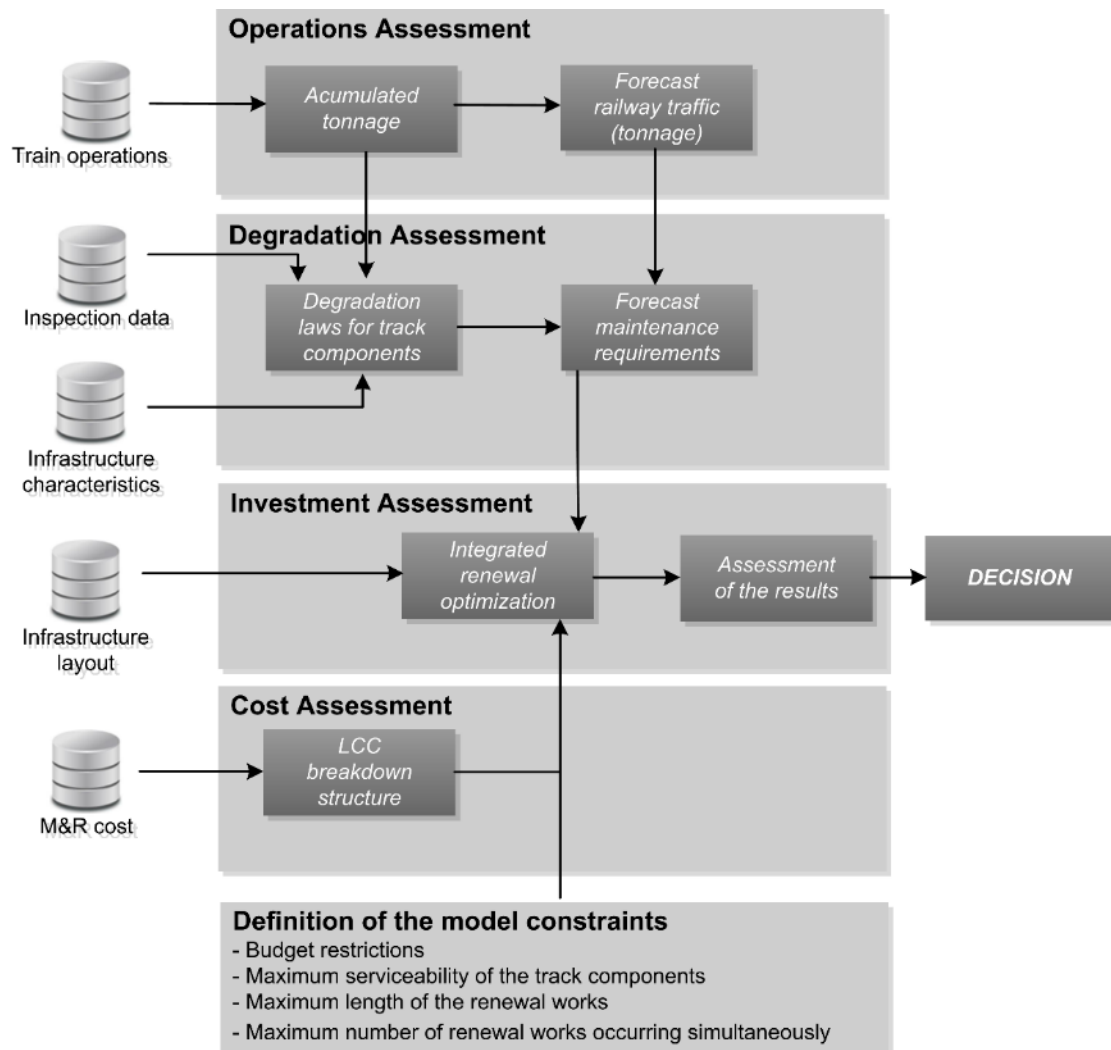


Figure 1: Decision support system framework for railway track renewal.

The DSS for managing railway track M&R operations was developed as a web-based application and is divided in four main modules:

- Import – automatic importation of new data to the databases (e.g. new inspection data, M&R information, etc.);
- Analyze – generate figures to analyze the current or past conditions of railway track components in different segments of the railway network;
- Compute – computes different indicators (e.g. degradation rates, maintenance and renewal forecasts for railway track components, etc.);
- Export – export results from the tool (e.g. pdf reports with conditions indicators and M&R forecast results of railway track components in different sections of the railway network);

## 4.2. Track condition data and analysis

The degradation models integrated in the DSS are supported by an exploratory analysis developed using a cluster analysis to define different groups of track sections with approximately identical infra and operating characteristics. This accomplishes an exhaustive analysis of the following data for the entire railway Portuguese network (data from 2001-2013):

- Inspection data from the EM120 vehicle (track geometry and rail profile);
- Visual inspections;
- Rail ultrasonic inspections;
- Railway track components characteristics (e.g. rail type, sleepers type, age, etc.);
- Spatial and temporal identification of track sections subjected to M&R operations;
- Spatial identification of track singularities (switches, bridges, tunnels, etc.);
- Accumulated traffic tonnage in each segment of the railway network;

Furthermore, with statistical analysis degradation patterns for plain track and for track singularities (switches, bridges, tunnels, etc.) were identified. The following degradation parameters were obtained:

- Degradation rates for the standard deviation of vertical leveling and horizontal alignment defects for all 200m track sections;
- Variation of the efficiency of tamping operations with the life cycle of the ballast;

The results obtained are the base to perform the estimation of the future behavior of all the 200m track sections in the main Portuguese railway network (about 1500 km of railway line). The current estimations of degradation rates for each 200m sections were already used by REFER E.P.E. to establish the 2013 annual tamping plan. Rail wear and fatigue mechanism were studied through the data from an optical measurement system of the rail traversal section installed in the EM-120 inspection vehicle and from rail ultrasonic inspections. However, in order to achieve a more reliable prediction of M&R actions for rail, more effort is still needed in this analysis. To accomplish an integrated degradation model for rail track components, the degradation of sleeper should also be analyzed. At the moment the available data is scarce for this component. We are expecting to get more data that enables the development of a probabilistic model to predict sleepers and rail failures throughout time (function of the accumulated tonnage). Therefore in this paper we focus more on presenting the results and the methodology used to assess track geometry degradation which is mainly related to the ballast behavior.

### 4.3. Railway track condition outputs

As referred, the web-based application incorporates a module that generate figures to analyze the current or past conditions of railway track components in different segments of the railway network. This feature has a major importance since it allows the assessment of the components' condition immediately after having new inspection data. The next figures presents respectively an output example that classifies the rail defects (measured in percentages) in one line of the Portuguese railway network and the number of rail defects per track section. Other rail condition outputs such as number of rail defects per track per rail type, evolution of defects during the different inspection campaigns, etc. are also possible to assess using graphical outputs developed in the tool.

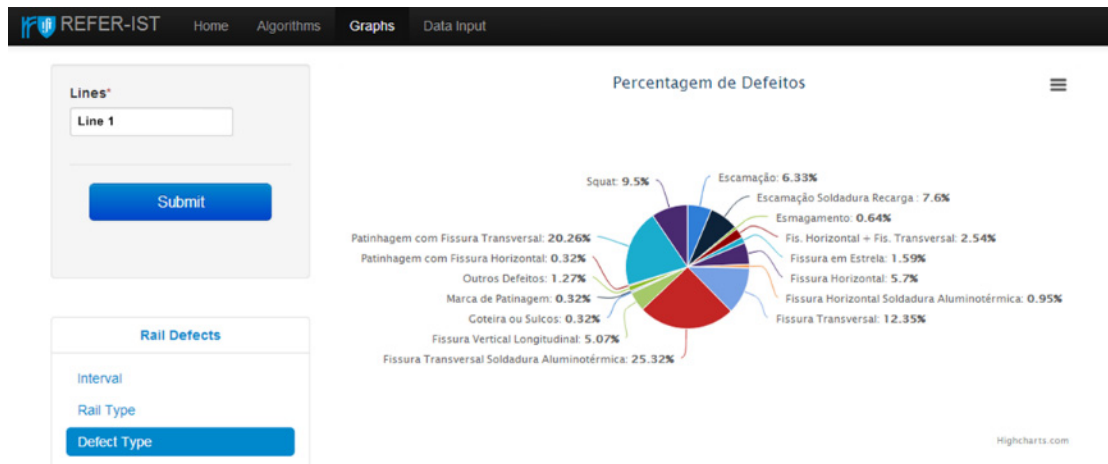


Figure 2: Percentage of Rail defects in one line.

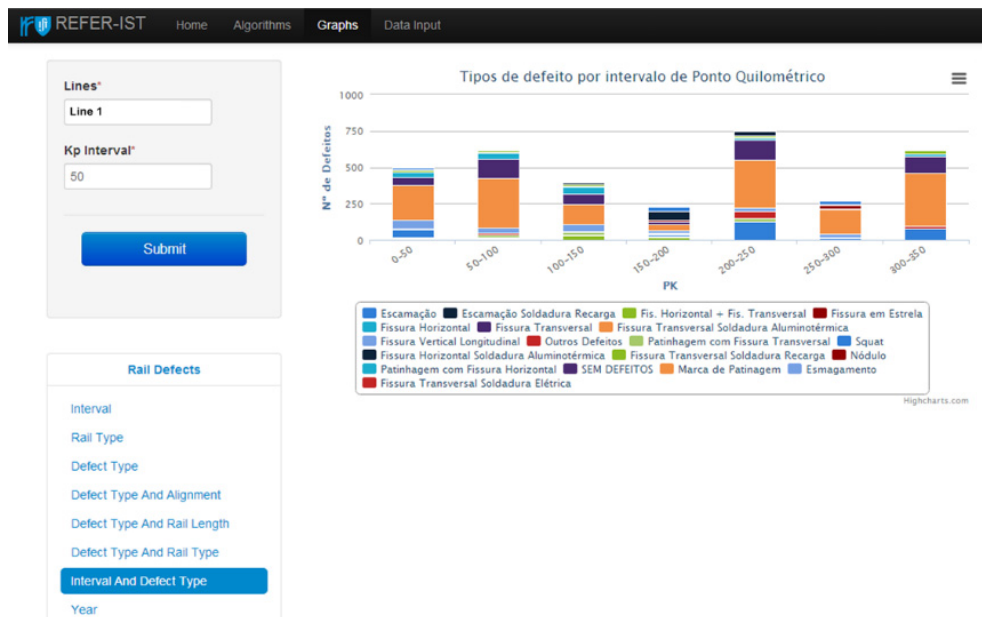


Figure 3: Number of rail defects per track section.



Regarding track geometry condition, it is possible to analyze the percentage of 200m railway track segments that are under the limit established by national standards [11]. This gives an overview of the general condition of track geometry parameters such as the SD of vertical and horizontal alignment. Figure 4 illustrates the percentiles curve for the SD of the vertical alignment defects in one line for an inspection campaign performed in 2013. In this example it is possible to verify that 92% of the 200m track segments at this time were under the limits (represented by the horizontal line) established for these parameters.

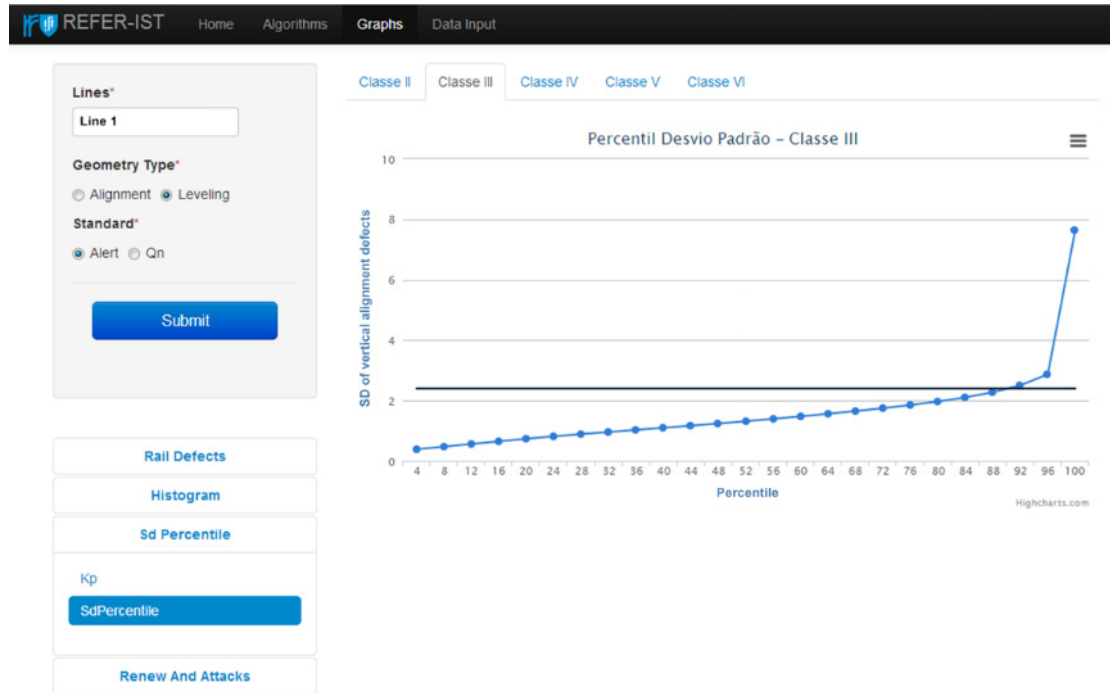


Figure 4: Percentage of segments in one railway line under the limits defined for the SD of the vertical alignment.

Other assessments of the railway track geometry condition can be obtained. Next figure presents an example of the results for the degradation rates of the SD of the vertical alignment defects in one selected line. It gives the information about the dispersion of this values in the line represented by a frequency diagram. In practical terms, it allows to have an overview of the degradation speed of track geometry parameters in the different segments of the selected railway line. Recent research results on analysing the dispersion that characterizes railway track geometry degradation can be found in other studies from the co-author [12].

In order to verify the condition of specific track sections of a railway line, it is possible to analyze the track geometry condition in sections selected by the user. The next figure presents the percentage of 200 m segments under and above the limits of the SD of the vertical alignment within the railway track sections of a line defined by the user.

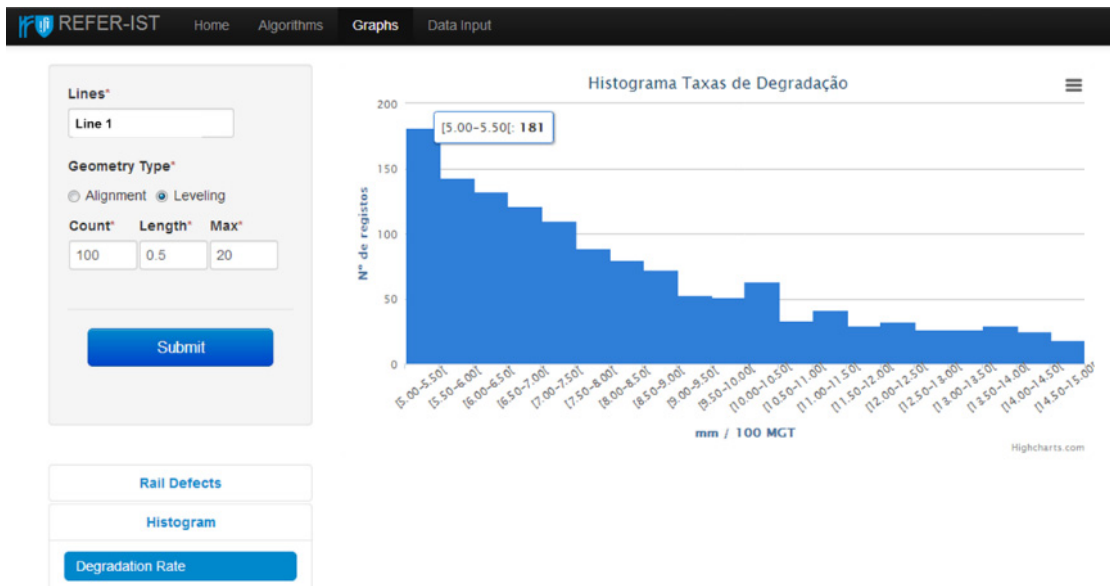


Figure 5: Histogram with the distribution of degradation rates in one railway line.

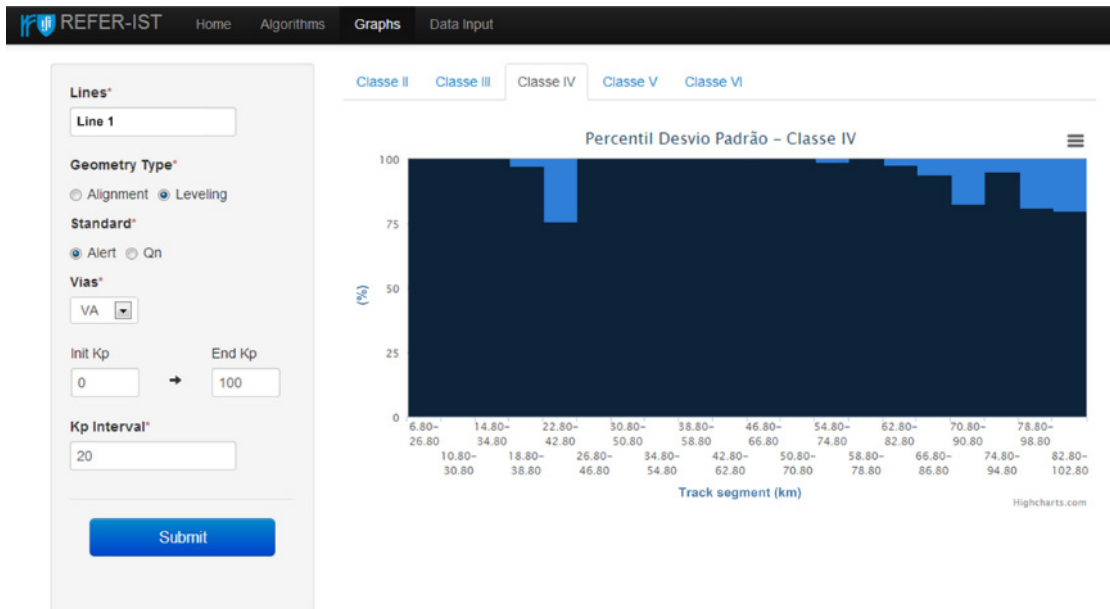


Figure 6: Characterization of the track geometry condition in different segments of a railway line.

#### 4.4. Forecast ballast tamping and renewal operations

Since track geometry quality is measured at fixed inspection intervals, when tamping is performed within an inspection period the immediate gain after a tamping operation is not precisely considered. Therefore, as explained in Figure 7, the values of degradation rates before and after tamping were used to estimate a more exact gain in the SD of the vertical alignment defects and of SD of horizontal defects. With this assessment we ensure greater accuracy in measurement of the restoration of track geometry quality through tamping operations.

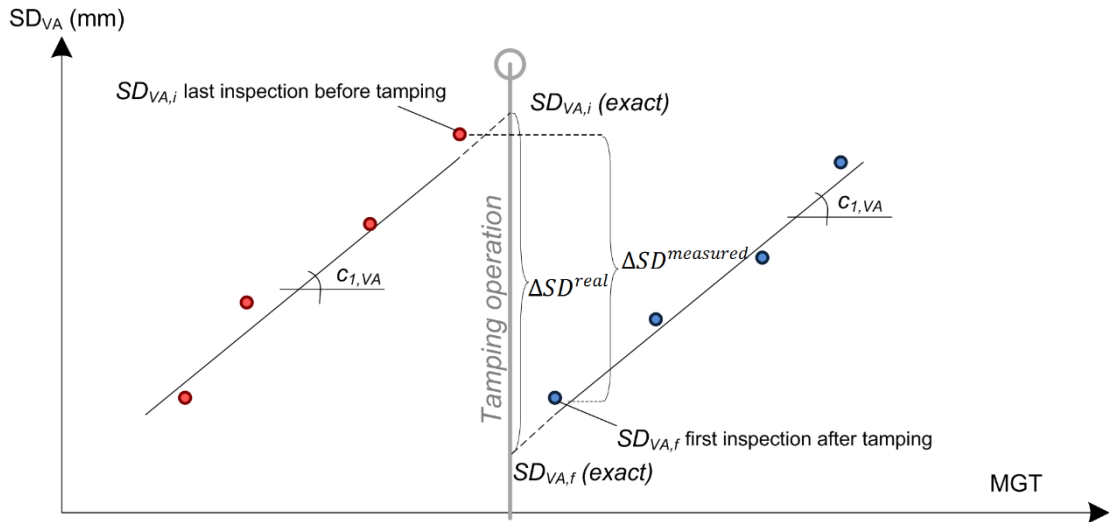


Figure 7: Railway track geometry recovery through tamping.

The percentage of error obtained in the estimated effect of a tamping operations and the real effect ( $\Delta SD_{VA}^{real} - \Delta SD_{VA}^{measured}$  and  $\Delta SD_{HA}^{real} - \Delta SD_{HA}^{measured}$  presented in Figure 7) can have a significant error in the estimation of tamping recovery values for these two track geometry parameters. In extreme situations, for an inspection period of 6 months, it can be obtained estimations with  $\approx 40\%$  error.

As referred previously, the effectiveness of ballast tamping tends to decrease the more advanced the railway track life cycle stage, which leads to a track degradation model that exhibits an increasing need for maintenance to preserve ride comfort levels. In order to represent this behavior, the writers calibrated the parameters that represent the declining efficiency in recovering the track geometry quality parameters ( $\beta_{VA}^g$  and  $\beta_{HA}^g$  defined in eq. (2)) with an increasing number of tamping operations. These were obtained using the adjusted results explained before  $\Delta SD_{VA,HA}^{real}$  (see Figure 7). Using this results and the degradation rates computed for each segment, we developed a simulation procedure to forecast the required tamping operations in the next years of operation in the Portuguese railway network. The different steps of the simulations process are described in Figure 8.

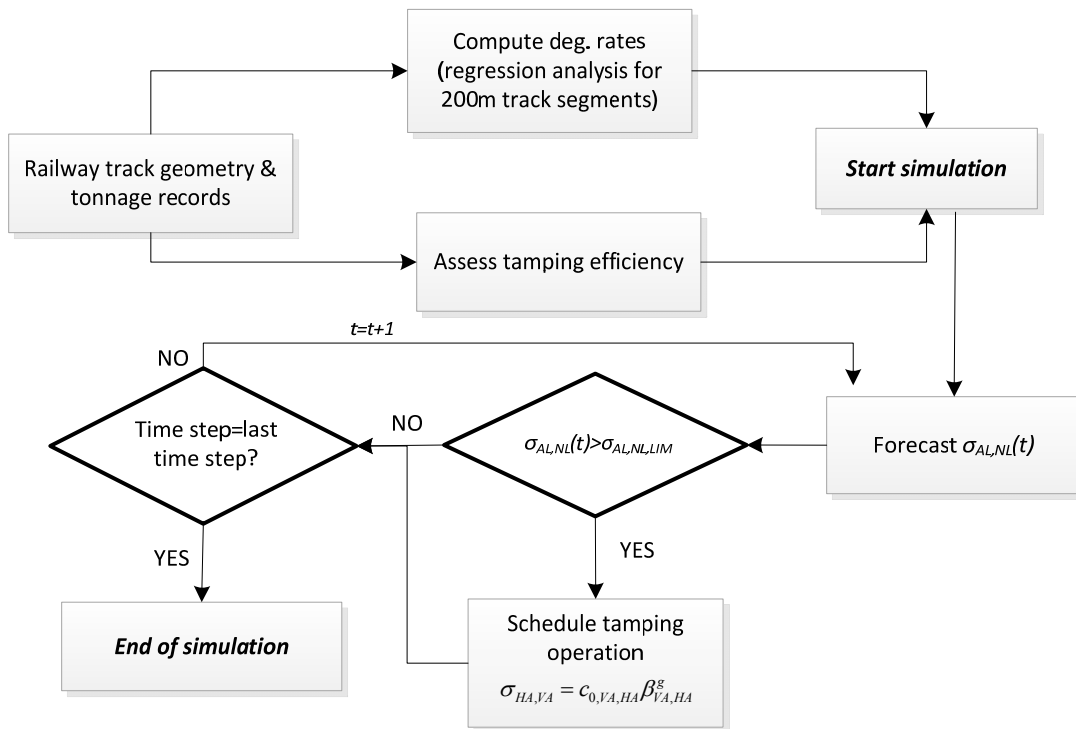
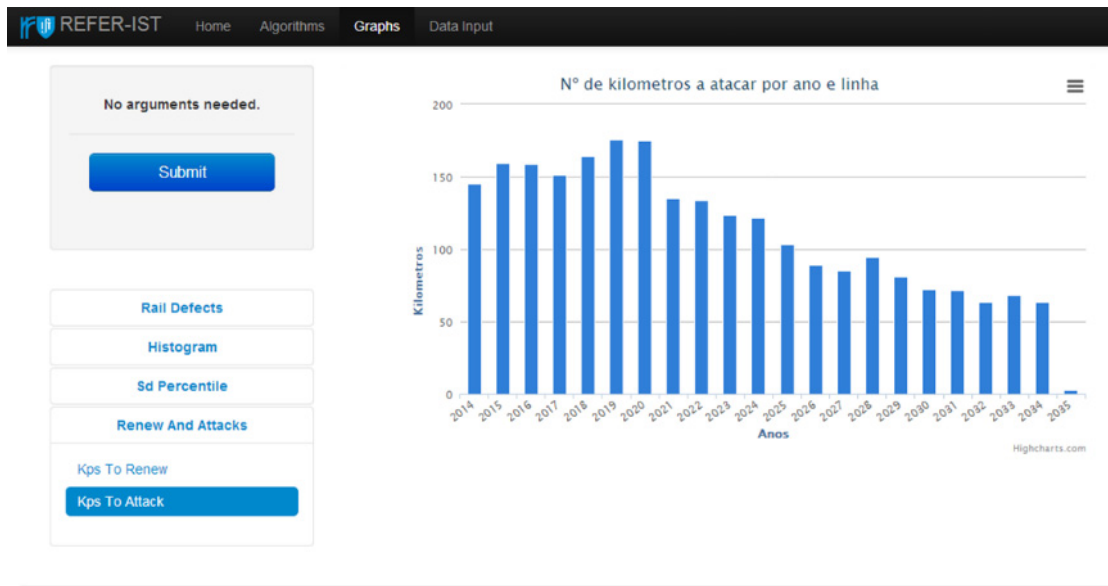


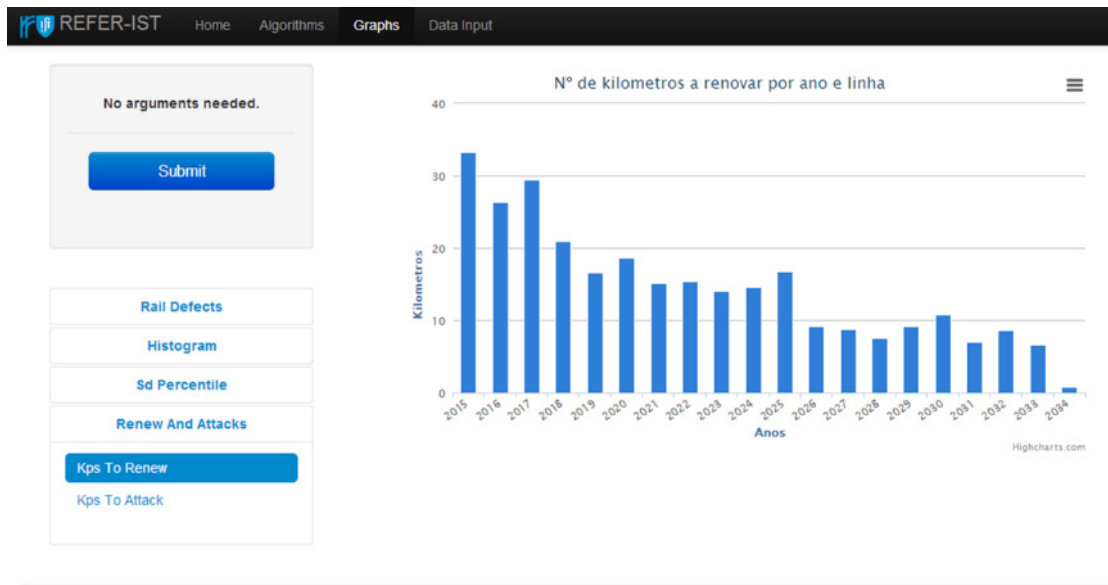
Figure 8: Simulation procedure to estimate the tamping requirements in each track segment.

An example of the simulation outputs for this analysis is presented in Figure 9. This figure illustrates the forecasted extension of tamping operation scheduled in each year of operation of one railway line. Since the DSS was designed to be flexible, the software tool allows the adjustment of the track geometry limits and perform sensitivity analysis to analyze what are the implications in terms of investment in tamping operations, of imposing for instance speed restrictions in track segments to postpone tamping operations. It is also possible to define different renewal criteria for the railway track components and forecast the number of renewal operations required in a pre-defined time span. Figure 10 presents the outputs for a renewal criteria in which is required a ballast renewal operation when in a 200m track segment the tamping cycle reaches a values of 6 months. Note that the forecast of tamping operations is influenced by the ballast renewal criteria defined in this example.



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Figure 9: Tamping forecasts.



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Figure 10: Renewal forecasts.

The outputs presented in the previous figures will give the infrastructure manager the possibility of scheduling M&R operations according to pre-defined criteria and to estimate the respective investment. This tool is still under development and cost function are not yet considered. The next steps of the development of the tool includes the integration of an optimization algorithms that allow to perform an

informed decision making that considers the railway track life cycle costs. This model was formulated considering the possibility of performing different combinations of renewal operations of the railway track components. More specifically, the ballast, rail and sleepers renewal operations can be combined between them to achieve a better solution for the optimization problem. Previous research performed by the authors shows the interest of grouping renewal operations [13].

In short, the objective function (see eq. (3)) that we are implementing aims to minimize the life cycle costs during the life span of the analysis. The first part of the objective function gives cost of renewal operations; the second part defines the track maintenance costs; the third part gives the economy of scale savings when track segments are renewed together; the fourth part defines the residual value of the track components in the end of the planning time span  $T$  (this value depends on the remaining serviceability of the different components).

$$\begin{aligned} \min LCC = & \sum_{w \in W} \sum_{t \in T} \sum_{n \in N} C_{wtn}^r + \sum_{k \in K} \sum_{t \in T} \sum_{n \in N} C_k^m X_{ktn} - \sum_{w \in W} \sum_{t \in T} \sum_{n \in N} C_{wtn}^r P_{wt} \\ & - \sum_{k \in K} \sum_{n \in N} R_{kn} \end{aligned} \quad (3)$$

In the objective function  $K = \{1, \dots, k \dots K\}$  represents the set of railway track components (ballast, rail and sleepers),  $N = \{1, \dots, n \dots N\}$  the set of track segments in the railway line under assessment,  $T = \{1, \dots, t \dots T\}$  are the set of time steps in the planning time span (e.g. in years) and  $W = \{1, \dots, w \dots W\}$  the set of renewal works that can be executed (e.g. ballast, sleepers and rail renewal or combination of works). The variables presented in the expression are:  $X_{ktn}$  = number of maintenance operations for each track component  $k \in K$  performed at time step  $t \in T$  in each track segment  $n \in N$  and it is computed based on the degradation model of each track component;  $R_{kn}$  = residual value of track component  $k \in K$  in track section  $n \in N$  obtained at the end of the planning time horizon  $T$  (ensure that the renewal scheduling does not depend on the value of the planning time horizon);  $P_{wt}$  = percentage saved in the unit renewal cost  $w \in W$  initiated in time period  $t \in T$  (scale economy factor) by performing clusters of segments  $n \in N$ . Finally the parameters are as follows:  $C_{wtn}^r$  = cost of the renewal work  $w \in W$  performed in the time step  $t \in T$  in the track segment  $n \in N$  and  $C_k^m$  = maintenance cost for track component  $k \in K$ .

Eq. (4) defines the track residual at the end of the planning time span.

$$R_{kn} = \left( \frac{X_k^{max} - \frac{X_{ktn}}{L_n}}{X_k^{max}} \right) RC_k L_n \quad \forall t = T, k \in K, n \in N \quad (4)$$

Where  $X_k^{max}$  = threshold that identifies the maximum yearly number of cumulative maintenance operations (maximum serviceability) of the track component  $k \in K$ ;  $RC_k$  = renewal cost of component  $k \in K$  for large scale major renewal operations (minimum renewal cost for each track component) and  $L_n$  length of the segment  $n \in N$ .

Model constraints will be imposed indirectly by penalizing the objective functions with a quantity proportional to the degree of violation (i.e. distance to feasibility). In eq. (5) is presented the yearly budget restriction to be applied in the model.

$$\sum_{w \in W} \sum_{n \in N} C_{wtn}^r + \sum_{k \in K} \sum_{n \in N} C_k^m X_{ktn} - \sum_{w \in W} C_w^r P_{wt} \leq B_t \quad \forall t \in T \quad (5)$$

Where  $B_t$  = maximum budget in the time step  $t \in T$ .

The problem formulation will also include constraints such as maximum yearly length of renewal operations in one line.

## 5 Conclusions

This paper presents a computerized decision support tool for M&R planning of the railway track components. In the role of the Infrastructure Manager, this DSS model allow the implementation of an informed maintenance policy to keep the track performance level in the desired conditions.

The developed decision support methodologies are supported by condition-based M&R management system that uses data mining techniques to forecast railway track M&R operations. The basis of these forecasts relies on databases that contains track inspection results, detailed track characterization (e.g. age of components, type of track components, etc.) and information about accumulated tonnages. The web-based application also uses this data to generate outputs that facilitates the assessment of the track component condition after performing inspection and verify failure progressions by comparing with historical data from previous inspections. Furthermore, this flexible tool allows the definition of decision rules to forecast M&R operations and perform sensitivity analysis that fits the outputs into more realistic scenarios.

In order to achieve a more robust degradation model, some other developments such as testing additional variables that can have an important influence on the railway track geometry degradation rates should also be considered. For instance, train speeds is a variable that influence the degradation evolution and should be measured in the degradation function. Future steps to further improve the model, will also include the incorporation of other degradation factors (rail wear and rail corrugation, for example) and the consideration of more maintenance operations related to railway track components (e.g. grinding operations and manual tamping).

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## References

- [1] C. Meier-Hirmer, et al., "Comparison of Different Types of Modelling for Track Maintenance Optimisation", in 15ème Congrès de Maîtrise des Risques et de Sûreté de Fonctionnement: Lille. 2006.
- [2] INNOTRACK, "D1.3.2 - The State of the Art of the Simulation of Vehicle Track Interaction as a Method for Determining Track Degradation Rates". 2008.
- [3] RSSB, "Development of the Vehicle Track Interaction Strategic Model". 2012.
- [4] ACEM-Rail, "D.1.1 Report on the State of the Practice of Railway Infrastructure Maintenance", S.F. Programme, Editor. 2011.
- [5] M. Shenton, and J. Tunna. "Planning Track Maintenance and Renewal for the Business Manager and Civil Engineer". in 1991 Heavy Haul Workshop. 1991. Vancouver.
- [6] A. Zoeteman, and C. Esveld, "State of the Art in Railway Maintenance Management: Planning Systems and their Application in Europe", in IEEE International Conference on Systems: Netherlands p. 4165-4170. 2004.
- [7] A. Andrade, and P. Teixeira, "Unplanned maintenance needs related to rail track geometry". ICE Transport 166 (Proceedings Of The Institution Of Civil Engineers -Transport), 2013: p. 1-11 (accepted for publication in 14.02.2013).
- [8] K. Riessberger, "Extending Maintenance Cycles and Ballast Life". in 7th International Heavy Haul Conference. 2001. Brisbane, Australia.
- [9] C. Esveld, "Modern railway track". 2nd ed. ed. 2001, Zaltbommel: MRT Productions. xxvi, 653 p.
- [10] S. Jovanovic, H. Guler, and G. Evren, "Modelling railway track geometry deterioration". Proceedings of the ICE - Transport, 2011. 164(2): p. 65-75.
- [11] REFER, "IT.VIA.018 - Tolerâncias dos parâmetros geométricos da via". 2009.
- [12] A. Andrade, and P. Teixeira, "Uncertainty in Rail-Track Geometry Degradation: Lisbon-Oporto Line Case Study". Journal of Transportation Engineering, 2011. 137(3): p. 193-200.
- [13] L. Caetano, and P. Teixeira, "An availability approach to optimizing railway track renewal operations". Journal of Transportation Engineering, 2013. 139(9): p. 941-948.