Railways Asset Management model based on a probabilistic Life Cycle Cost Analysis

Application to the Portuguese Railway Network

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Abstract

The asset management and Life Cycle Costing (LCC) principals perform a vital role in the reduction and optimization of the costs of an infrastructure manager, providing a better decision support technically and financially. It was intended to create an asset management LCC model to rail track superstructure of the Portuguese rail network assembled with the Iberian gauge. This model is able to receive the inputs defined by the user related to the Maintenance and Renewal (M&R) activities and to the characteristics of the track superstructure. As a result, depending on the inputs it performs the scheduling of the individual renewals of the rail, sleepers, ballast and the Switches and Crosses (S&C). When the first three of these renewals accomplish the proximity criteria defined by the user, it is appointed a whole track renewal. Moreover, the model calculates the needs and costs of the M&R operations related with the track superstructure and S&C through the analysis period. Finally, the model combines the deterministic approach with a stochastic approach employing the Monte Carlo simulation in order to handle uncertainty.

Keywords:

Railway, Rail Track Superstructure, Asset Management, Life Cycle Cost, Maintenance and Renewal, Monte Carlo Simulation

1 Introduction

The improvement of efficiency related to costs with M&R activities has always been a major objective by rail administrators. Concerning the annual costing with M&R operations, the largest part is related with the track superstructure, whose assets suffer the most with circulation effects.

The model developed intends to evaluate, from the track characterization and other inputs, when to proceed to a Whole Track Renewal (WTR) or individual renewals of track superstructure main components, the renewals of the S&C and their main elements such as frogs and pointwork sections. Furthermore, the WTR is determined whenever the year prediction of the individual renewals of rail, slippers and ballast is within an interval for anticipation whose boundaries are established by the user. The period of analysis considered was 40 years, the upper limit set by INNOTRACK (2007).

2 Principles of Asset Management and Life Cycle Costing

Asset Management is defined as a group of systematic and wide coordinated activities in an institution which manages optimally their assets as well as their performance, risk and costs during their life cycle according with the strategic plan (Network Rail, 2011). Every asset management programme should be funded on three main aspects: the economic value of assets, costs optimization through their life cycle and the perfect understanding of the organization’s role as manager of the assets (OCDE, 2001). Asset management principals have been used on different infrastructures managers (IM) including highways, water supplying systems or energy sector (OCDE, 2001), whereas on rail sector this approach has been used, despite being used with different levels of sophistication. According to FHWA & AASTHO (2011) asset management is established on six basic elements such as assets' information, IM objectives, performance levels, LCC analyses, risk management and financial planning. Therefore implementing an asset management program is a complex task whose results are not immediate.

The life cycle cost analysis (LCCA) is the economical analyses procedure to gather the total cost of acquisition, maintenance and disposal of a product. It could be applied to the whole life cycle of a product or its elements, considering different parts of phases of its life cycle (IEC, 2005). LCC is assembled on solid economic principals in order to evaluate all the long term efficiencies between two investment alternatives, including the costs optimization, sustainability, and the assets performance, combined with reliability and safety. Its main objective is to quantify the long term consequences on the planning and design phases decisions (FHWA, 1998). The analysis period should be long enough to include at least one large renewal operation (FHWA, 1998). Moreover, it is established for the rail sector that the period analysis on LCC should be between 35 and 40 years (INNOTRACK, 2009). A matter of major concern about LCC is to collect relevant and reliable data. Thus, this is a critical factor which will determine the effectiveness and accurateness of the LCC Analysis (LCCA). The data which is more complicated to predict with a considerable degree of accuracy is the volume of maintenance needs and unavailability parameters through the analyses period. Therefore, the most common technique to predict them is to use the RAMS (Reliability, Availability, Maintainability, and Safety) technology. Furthermore, in a LCCA there are a large number of parameters with a considerable uncertainty. Concerning this point, there are two different approaches to minimize the uncertainty: the deterministic one, which gathers historical values, and the stochastic one, which assigns a given probability to the main values. However, this probability needs to be calculated based on reliable data, generally by applying the simulation of Monte Carlo. Finally, to calculate the results of the analysis at its end, the most suitable method is the Net Present Value (NPV) (FHWA, 1998) (INNOTRACK, 2007), (Zoeteman, 2004). There are several LCC models proposed by different authors with different approaches. As an example, Zhao et al. (2006) presented a LCC model to calculate all the cost related with the rail between two renewals, considering the development of rail defects by a Weibull function. On the other hand, Zoeteman (2004) presented a methodology to build LCC model to railway infrastructure in five steps concerning the loads applied, the maintenance volumes, the cost with M&R activities and unavailability, the infrastructure performance and at last to calculate the LCC based on the previous steps.

3 Applying an Asset Management by LCC model to the Portuguese rail network

3.1 Data and considerations about the Portuguese rail network

In order to fulfil the requirements for the LCC model, it was necessary to perform a characterization of the track through the whole wide-gauge network of the Portuguese Rail Network (PRN), which did not exist. Regarding this, it was allowed a limited access to the REFER intranet, to some technical reports, some inventories and also a few meetings with REFER experts. During this process it was needed to take some simplifications, such as, in stations only the main tracks were considered, the narrow-gauge network was not considered, discrete section with length were shorter than 300m, whose characteristics (at least one element) were different from the bordering ones, were considered with the same characteristics of the bordering ones. Moreover, to feed to model with information regarding M&R operations costs and needs through the analyses time it was allowed to access the quantity values of the current and recent M&R outsourcing contracts, whose unitary cost values and maintenance needs values were used further in the model.

3.2 Procedures of the determinist model

The LCC model was performed by programming macros at MS Excel on Visual Basic for Applications (VBA). The procedure was divided into three different routines; the first one refers to track renewals, the second to maintenance needs and M&R costs cash-flows by year, and the third regards the S&C renewal and maintenance needs and costs.

Regarding the track renewals it was considered the renewal of all types of rail, sleepers and ballast, and WTR. Concerning the S&C it was considered their renewal as a whole, as well as the scheduling of the frog and the pointwork section substitutions. All the types of S&C were considered except the expansion joints.

Concerning the maintenance operations, the systematic activities which are performed in a time based scheme are grouped as Preventive Systematic Maintenance in one single variable. Otherwise, the condition based ones are represented by themselves in individual variables, presented at table 1.

Table 1 - Considered maintenance operation in the model

Plain track operations		S&C operations
Grinding	Tamping	Check rail replacement
Aluminothermic welds	Repairment of isolated joints	Sleepers replacement
Reloading welds (rail tops and heads)	Local substitution of ballast	Frog reloading welds
Regularization of continuous welded rail	Rail Sliding	Tamping
Rail replacement due defects	Fastenings replacement	Light Tamping
Sleeper replacement due defects	Execution of rail closures	
Changing rail sides and introducing a new bar	Substitution of isolated joints	

In this model a few simplifications were made, such as the S&C and their elements whose opening tangents were 0.09 and 0.1067 that were assumed as 0.11 due to the lack of reliable costs values. In addition, on the non-ballast sections just individual renewals for rails and sleepers (when these ones exist) were considered. Moreover, the effects of circulation speeds, the curves' radii or even the type of rolling stock operating were not considered on the track deterioration. Additionally, disposal costs and profits are not considered in this model. Furthermore, the developed model considers a linear deterioration for track components and S&C in function of time. In order to reflect the traffic and tonnage effects on the assets life cycle, the PRN was divided in three clusters (A to C) through traffic and commercial importance to REFER. As a result, the most important one, A comprehends 1769km, B is about 510.5km and C, the less important one, comprehends 755.2km, the three clusters are represented in Figure 1. Despite of not being assigned on the model execution, it is possible to receive as input different life cycles for different rail profiles (54 E1 or 60 E1), different concrete sleeper type and different S&C (Switchers from expansion devices, and segmentation in the groups of S&C based on the openings). The various life cycles used for the assets on the model are shown at table 2.

The first phase of the model procedure begins with the determination of the first isolated renewal of each track component. This is obtained with equation (1) in which the asset age is added its respective life cycle (by type and cluster). Nevertheless, some assets (rails and concrete sleepers) were relocated from a former location and reapplied in a different line, frequently in a lower importance cluster line. Thus, this situation is also analyzed and reflected on the life cycle of the asset which is used to calculate the years of the first renewal of the asset. Moreover, the further renewals during the analysis are calculated through a cycle routine using equation (1) while the renewal calculated is lower than 2055. An upper limit to number of renewals during the analysed period is established – 3 for rails, 8 for sleepers, 5 for ballast and 3 for WTR.

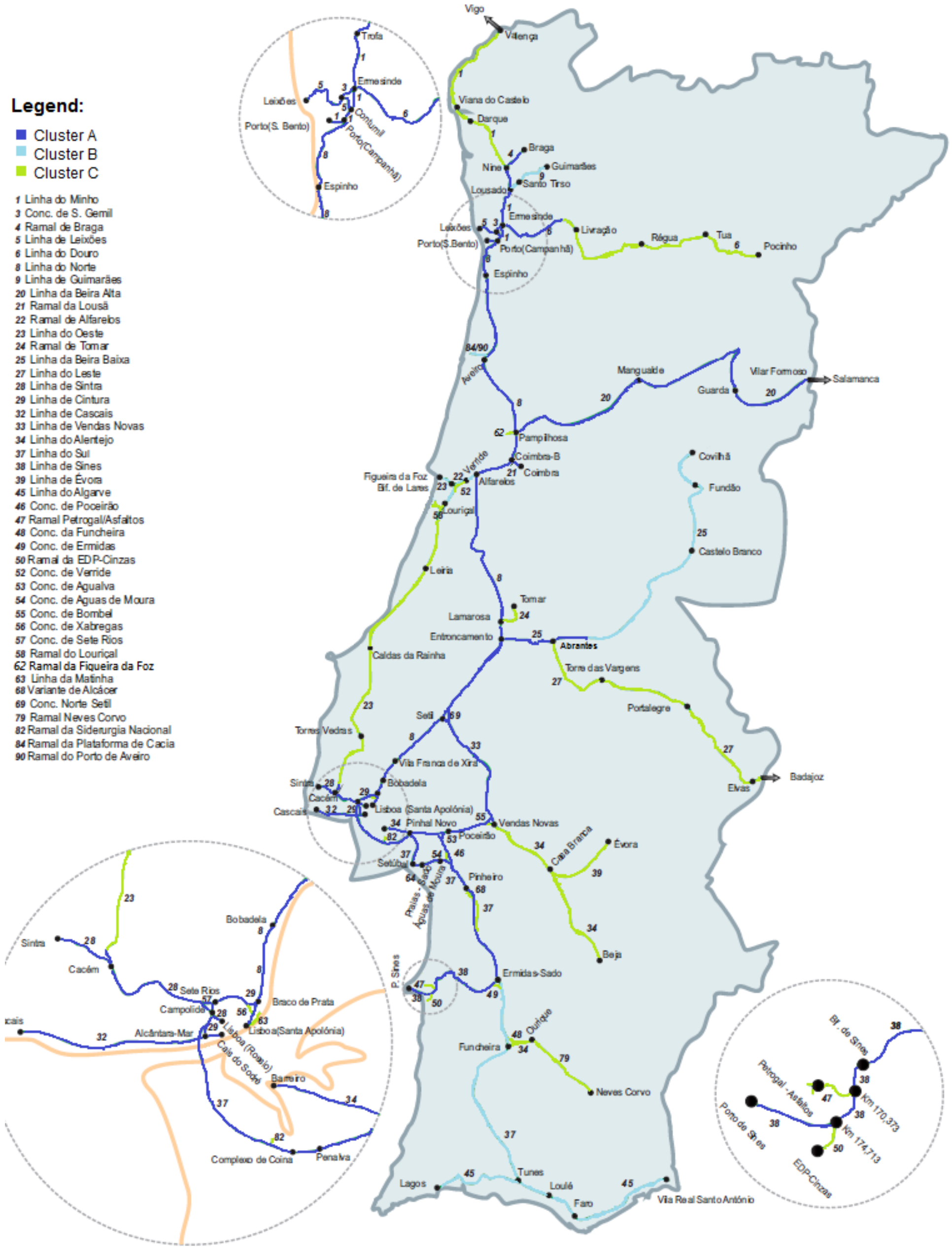

Figure 1 - Map of the analyzed lines and their clusters, adapted (REFER, 2013)

Secondly, on the next step the model analyses which isolated renewals can be joined to the first WTR. Regarding this, a routine in the procedure compares all the individual renewals of rail, sleepers and ballast scheduled for the same year or within an interval established by a defined margin through equation (2), therefore testing all the possible combinations. The margin considered was five years for all the three main assets. This procedure is explained through in figure 2.

In addition, other functionality of the model regards the possibility to substitute timber sleepers by concrete ones when a WTR is performed. Another resource of the model consists in forcing the anticipation of the WTR to the time of the first renewal of any component to renewal, whatever the remaining life cycle of the other two assets is, ignoring the intervals previously defined. In order to achieve this, it is necessary to mark the line track sections where this operation is pretended

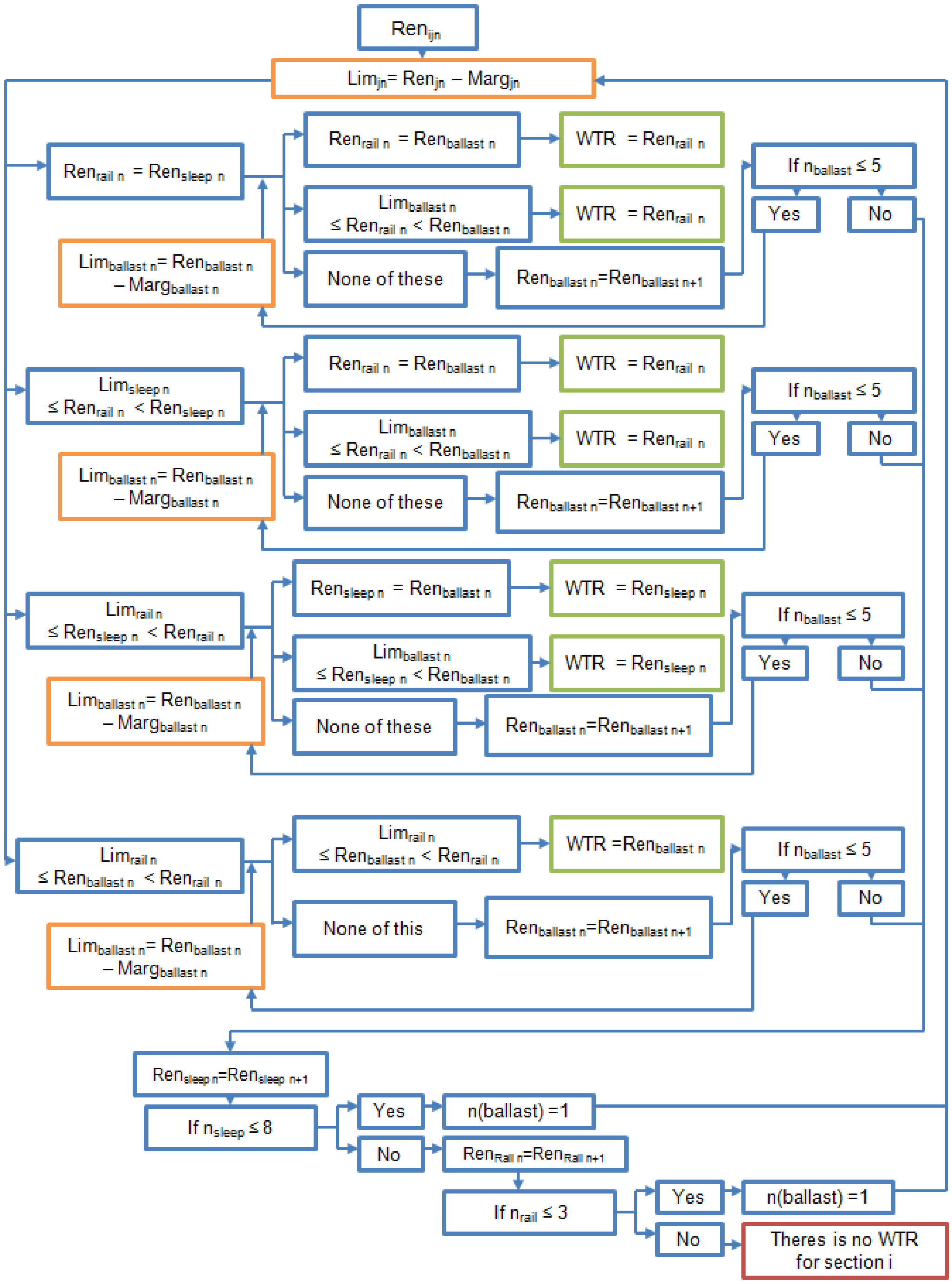

Figure 2 - Flowchart for the scheduling routine of the WTR

Table 2 – Life cycles for the superstructure and S&C assets (values in years)

Cluster	Rail	Concrete Sleepers	Timber Sleepers	Ballast	S&C	Frogs and Pointworks
A	40	40	10	20	40	20
B	45	45	12	22	45	22
C	50	50	15	25	50	25

After the scheduling of the first WTR, the process is repeated to verify whether or not, the appointment of a second or third WTR in that track section during the analysis period. Considering the year of the first WTR, the following individual renewals are predicted and, based on theses ones, the routine which determines a WTR, presented in figure 2, is reused to schedule the second one, and at last these two steps are repeated one last time to verify the hypothesis of a third WTR. Finally, the individual assets renewals which are not substituted by a WTR are verified and scheduled definitively, regarding their usability period.

$$Ren_{ij,n+1} = Ren_{ij,n} + Vida_{ijk} \tag{1}$$

$$Lim_{ijn} = \ Ren_{ijn} - \ Marg_j \tag{2}$$

The second phase of the model is related with the amounts of the annual cash-flows of the M&R operations and the M&R annual volumes through the 40 years of the analysis. The volumes of each renewal by category are calculated through MS Excel filters applied to each of the 40 years. Once volumes are known the costs are calculated by equation (3) for rail and individual sleepers renewal, ballast renewal for equation (4), and WTR by equation (6). Regarding the track maintenance activities, the annual needs had to be calculated as fix values for all analysis, in spite of the limited information gathered from the maintenance outsourcing contracts. The annual volumes of conditioned maintenance were obtained by an annual percentage of the eligible network based on MTBM (Mean Time Between Maintenance) of each operation, or failure rate - λ, depending on each operation, based on the best practices and the quantities registered on the contracts. The costs of maintenance activities are calculated with equations (7) and (8), depending on whether the used parameter is MTBM or λ, respectively.

The third and final phase of the model concerns S&C renewals and maintenance. The S&C renewal is determined by a similar routine to the track assets renewals. Furthermore the model analyses the anticipation of S&C renewals in order for this to be held at the same time of a WTR on the track section where the analysed S&C is assembled, whether or not the S&C renewal is predicted to the same year or within the interval defined through a margin, similarly to what was performed on WTR. The anticipation margin was set on five years. Moreover, further S&C renewals are scheduled again after the latter, the process is repeated until the renewal year reaches 2055 or the maximum of three renewals established is achieved.

$$CustoRen_{jma} = DistRen_{jma} \times (Mat_{jm} + Sub_{jm}) \tag{3}$$

$$CustoB_a = DistRen_a \times (B_{kmlv} + Desg + ADefinitivo + EstDin\ ) \tag{4}$$

$$CustoRenGV_{ma} = DistRen_{ma} \times (Mat_m + LevGV + AssGV) \tag{5}$$

$$CustoRIV_a = CustoRenGV_a + CustoBRIV_a \tag{6}$$

$$CustoAM_b = \sum_{s}^{3} (\ DistRede_{bs} \times \frac{Per_{bs}}{100} \times \sum CustoParcelasAM_b) \tag{7}$$

$$CustoAM_b = \sum_{s}^{3} (\ DistRede_{bs} \times Fact_{bs} \times \sum CustoParcelasAM_b) \tag{8}$$

Concerning the S&C maintenance activities, the substitution of frogs and pointwork sections have to be scheduled, as a result of their life cycle. However, there were not available historical data regarding previous substations of these main elements of S&C, it was assumed that their substitution was held on right time, depending upon their life cycle. Therefore, the year of substitution of frogs and pointwork sections was obtained by the equation (1), as wells as the other renewals considering the year of manufacture of the S&C, whereas for further substitutions, they are calculated by the same equation adding to the year of the following S&C renewal (after the previous frog or pointwork substitution), the life cycle of these main elements. Otherwise, the needs of the remaining S&C maintenance activities are calculated as a fixed valued through the time, similarly to the track maintenance activities. Finally, the costs related with S&C operations of M&R are obtained in the same way to what was perform for track, except that the annual volumes of M&R are gathered by a routine with a group of counters which determine the number of S&C by type and specifications for each year of the analysis concerning if it is taken for isolated renewals, during a WTR, or for frogs or pointwork sections substitutions. On the other hand, for the remaining maintenance operations the S&C are counted, without considering the years of the operations.

Finally, the model calculates the total annual costs of all M&R operations considered on the model and afterwards it obtains the NPV, which is the most used method to analyse LCC (Zoeteman, 2004) (FHWA, 1998), using a 4% discount rate (INNOTRACK, 2007), (FHWA, 1998).

3.2 Stochastic approach

Since the deterministic models is assembled, it is performed a sensibility analysis to handle uncertainty adopting the Monte Carlo simulation. The Monte Carlo simulation consists in simulate the model a certain number of times, using values for the desired parameters (the most uncertain ones) generated from an associated probability density function to every iteration, reflecting their uncertainty to the results analysed. Thus, the Monte Carlo simulation was performed for 2000 iterations, using the software @Risk, one of the two suggested (FHWA, 1998).

Furthermore, it was necessary to define the model inputs and their own probability distribution function. Concerning the high volatility on M&R unitary cost values, it was decided to analyse all the unitary costs, applying the triangular distribution to all of them (FHWA, 1998). Moreover, regarding the life cycles of assets considered, it was decided to insert all these values as inputs on the model with a triangular function associated to them (FHWA, 1998). Therefore, the failure rate and MTBM were associated to triangular (FHWA, 1998) or normal distributions (Andrade, 2008) depending on which case. The discount rate was set with a normal distribution. (Boussabaine & Kirkham, 2004), and the total number of inputs introduced in the model was 249. Otherwise the outputs considered were, besides the NPV, the value for each year of the analyzed period of: the total distance of renewals (all of them), total number of S&C renewed, the total costs with these renewals, the total costs with maintenance (track and S&C) and the total global costs, making the total amount of 401 outputs. The adjustment parameters of the distribution functions for the inputs were defined relying on the deterministic values, for the most probable ones, and on values of the maintenance contracts. For a few exceptions, on these ones, the values of the parameters were determined from values presented by other authors and on the REFER expertise.

4 Results

4.1 Deterministic results

The deterministic results regarding the distances of the individual asset renewals and WTR are shown on figure 3. These results reveal the existence of a comprehensive peak in 2015 due the assets that are ending their lifespan or whose lifespan has already been exceeded, including a considerable extension of reused asset on the secondary lines in this situation. Additionally, for 2035 it is verified a significant volume of ballast renewals, which reflects the peak of 2015 for the line cluster

A. Furthermore, the results project an import cycle of renewals from 2039 until 2050, which reflects the substantial investments made during the final of 1990s and the beginning of the 2000s. The total costs of all M&R operations considered are presented on figure 4, except 2015 which is much higher than other due the significant amount of renewals. The analysis results allow realizing the impact of the renewal operations, especially the WTR, over the total cost through the time. Finally, the deterministic NPV is about 2,013,841,643.80 EUR for the 40 years of the analyzed period.

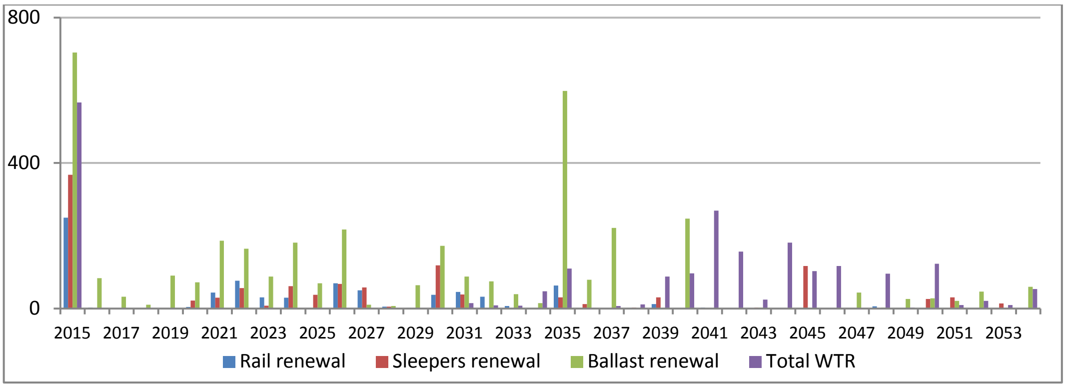

Figure 3 – Total annual renewals distances (km)

4.2 Stochastic results

Regarding the stochastic results of the model performed through Monte Carlo simulation, referring the renewal distance, it is only presented the ballast renewal annual distances, on figure 5, as a representative indicator of all the different track renewal results. Furthermore, the mean of the ballast renewal distance shows higher and stable values through the analysis, as signal of the less WTR established and, as expected, the 2015 peak is maintained. In addition, it is also verified the considerable increase of renewal volumes in the period from 2030 to 2040, related with the three deterministic peaks of 2035, 2037 and 2040, which are now more distributed through time. Regarding the global annual costs, exhibited on figure 6, it is verified the resilience of the 2015 peak, as well as the reduction of the volatility of the values through the analyzed period, obtaining more stable results, validated for all the statistic parameters performed. Finally the histogram of the probabilistic NPV is presented on figure 7, and its main statistics are shown on table 3. Moreover, the most probable value is 2,209,575,705 EUR, and from the figure is also possible to retain the convergence of results is an indicator that there is no need to perform more iterations on simulation of the model.

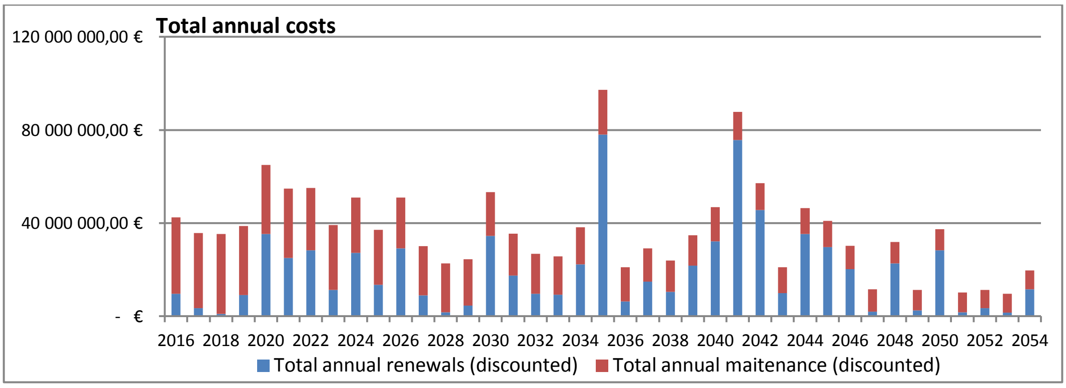

Figure 4 – Total annual costs (EUR)

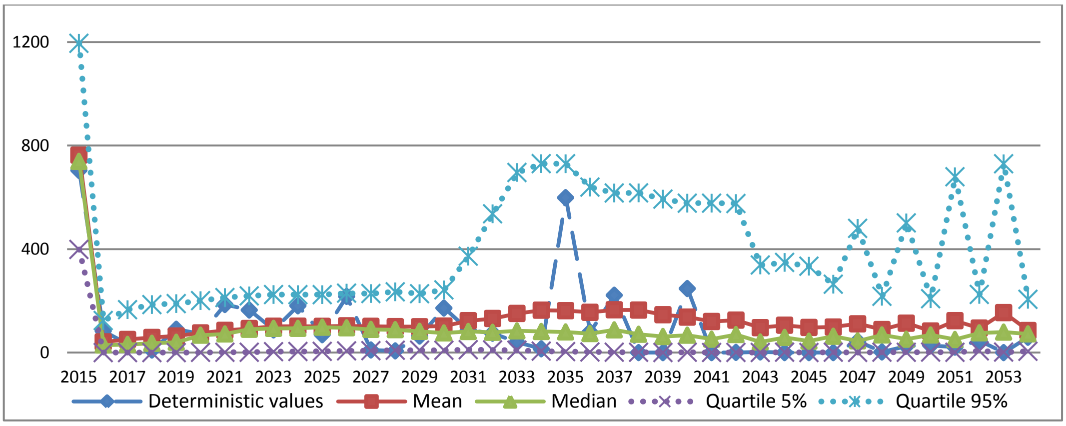

Figure 5 – Total distance of ballast renewals after simulation (EUR)

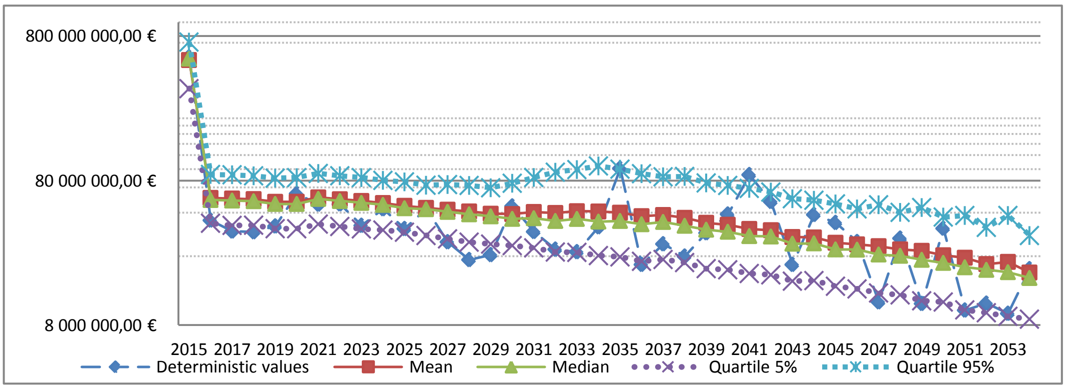

Figure 6 – Total annual costs after simulation, (logarithmic scale - EUR)

5 Conclusions

To conclude, The Asset Management and LCC principles reveal to be two important methodologies to produce a wide analysis of the railways M&R operations costs, in order to optimize costs and perform long term previsions. The Monte Carlo Simulation plays a fundamental role to understand and handle uncertainty. Furthermore, the reliability and amplitude of the data determine how far can the analysis and its detail go, thus a wide effective performance and data monitoring system is a key factor on a asset management by LCC model. In addition, the developed model is able to be applied to other cases with a reduced level of adjustments.

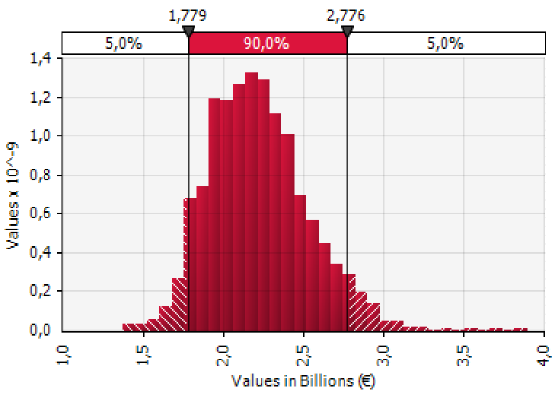

Figure 7 – NPV histogram of the simulation results

Table 3- NPV results after simulation

Deterministic value	2 013 841 644€
Mean	2 221 429 628€
Median	2 198 534 513€
Standard Deviation	306 665 799€
Miniminum	1 375 191 3278€
Maximum	3 895 456 460€
Quartile 5%	1 779 234 967€
Quartile 95%	2 776 441 734€

Abbreviations:

LCC – Life Cycle Cost/Costing;
LCCA -– Life Cycle Cost Analysis;
M&R – Maintenance and Renewal;
MTBM – Mean Time Between Failure;
NPV – Net Present Value;
PRN - Portuguese Rail Network;
RAMS - Reliability, Availability, Maintainability, and Safety;
S&C - Switches and Crosses;
VBA - Visual Basic for Applications;
WTR - Whole Track Renewal;

Symbols

ADefinitivo – Definitive tamping (EUR/km);
AssGV – Assembling of new rails and sleepers (EUR/km)
B_{kmlv} – Unitary costs f ballast supplying (EUR/km);
$CustoAM_b$ – Annual cost with maintenance operation *b* (EUR)
$CustoB_a$ - Ballast renewal costs for year *a* (EUR);
$CustoBRIV_a$ – Ballast renewal costs during a WTR for year *a* (EUR);
$CustoParcelasAM_b$ - Remaining unitary costs of maintenance operation *b* (EUR/km, EUR/m or EUR)
$CustoRen_{jma}$ – Renewal cost for component *j,* of type *m,* in year *a* (EUR);
$CustoRenGV_{ma}$ – Renewal cost of rails and sleepers in a WTR with type *m* of rail and sleeper for year *a* (EUR);
Desg – Ballast removal with ballast cleaning (EUR/km);
$DistRede_{bs}$ – Distance, where maintenance operation *b* is performed (km);
$DistRen_{jma}$ - Renewal distance of component *j,* of type *m,* in year *a* (km);
EstDin – Dynamic stabilization (EUR/kmlv);
$Fact_{bs}$- Annual rate of execution of maintenance operation *b* of the network of cluster *s* (km^{-1})
LevGV – Rails and sleepers dismantling (EUR/km)
Lim_{ijn} – Limit for the renewal *n* of the component *j* on section *i* (years);
Mat_{jm} – Acquisition cost of materials for component *j* of type *m* (EUR);
$Marg_j$ – Margin for anticipation of renewal for a WTR of component *j.*
Per_{bs}- Annual percentage of cluster *s* network, where is performed (%)
Ren_{ijn} – Renewal *n* of the component *j* on section *i*, (years);
Sub_{jm} – Remaining unitary costs of the renewal for component *j* of type *m* (EUR);
$Vida_{ijk}$ – Lifespan of component *j*, for the cluster *k*, on section *i* (years);

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