Renewal decisions from a Life-cycle Cost (LCC) perspective: an integrative approach using separate LCC models for rail and ballast components

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Abstract: In this article, an integrative approach to support rail and ballast renewal decisions from a life-cycle cost (LCC) perspective is developed. Rail and ballast LCC models are developed separately. For the rail LCC model, an existing model is used, whereas for the ballast LCC model, a new model is put forward. Ballast LCC model comprehends tamping cost, renewal cost, geometric inspection cost and unavailability cost. Uncertainty related with tamping cost estimations is assessed by Monte Carlo simulation, where a step back is taken to typical approaches, inserting uncertainty earlier in track geometry degradation model parameters, rather than RAM (Reliability, Availability and Maintainability) parameters. The results suggest that potential uncertainty related to unavailability costs are more relevant on renewal decisions, rather than uncertainty associated with tamping costs. Finally, a straight-forward approach to achieve an optimal renewal strategy is developed, integrating both LCC models based on the construction of hypothetical scenarios with distinct renewal tonnages.

Keywords: LCC, Railway infrastructure, maintenance, renewal decisions, uncertainty.

1 Introduction

The ever-increasing demand to obtain value for money in Railway infrastructure investments has contributed towards more conscious and transparent maintenance decision-making processes. In fact, the European Railway sector, a recent vertical separated sector, demand a life-cycle cost perspective in maintenance decisions, namely rail and ballast renewal decisions. Best practices in maintenance strategies have tried to change time-based criteria in track maintenance activities scheduling to condition-based criteria [**1**]. Nevertheless, some activities still are triggered time-based, such as rail grinding, rail lubrication or even track inspection (ultrasonic or geometric inspection). Therefore, rail and ballast renewal decisions still lack a life-cycle cost perspective, and therefore, in this article, a ballast LCC model is put forward and afterwards integrated with an existing rail LCC model. In both models, an example for a 100-km plain track section is assessed, achieving an optimal renewal strategy for both infra components.

2 Ballast LCC model

In this section, an overall analysis of ballast costs throughout its life-cycle is conducted in order to build an LCC model for ballast component.

2.1 Tamping Cost

To assess economic life of ballast, track geometry degradation processes must be understood, as track geometry degradation greatly depends on ballast degradation phenomenon. Many experimental studies have demonstrated that track geometry degradation phenomenon may be distinguished in two phases [**2**]. One is directly after tamping, in which track settlement is relatively fast (till 2 MGT approximately); whereas the other phase is much slower and the relationship between track settlement and time (or load) is approximately linear. In fact, tamping operations are traditionally scheduled based on linear or semi-logarithmic expressions that model the track geometry degradation. For medium- and high-speed tracks, passenger comfort governs these maintenance decisions, using the evolution of the standard deviation of longitudinal defects as the main criteria to schedule tamping operations. Although semi-logarithmic expressions may model the evolution of standard deviation of longitudinal defects in a very reliable way, some simplification is introduced by ignoring the initial phase of large settlements (2 MGT), when estimating regression lines based on the recorded data given by geometric inspection.

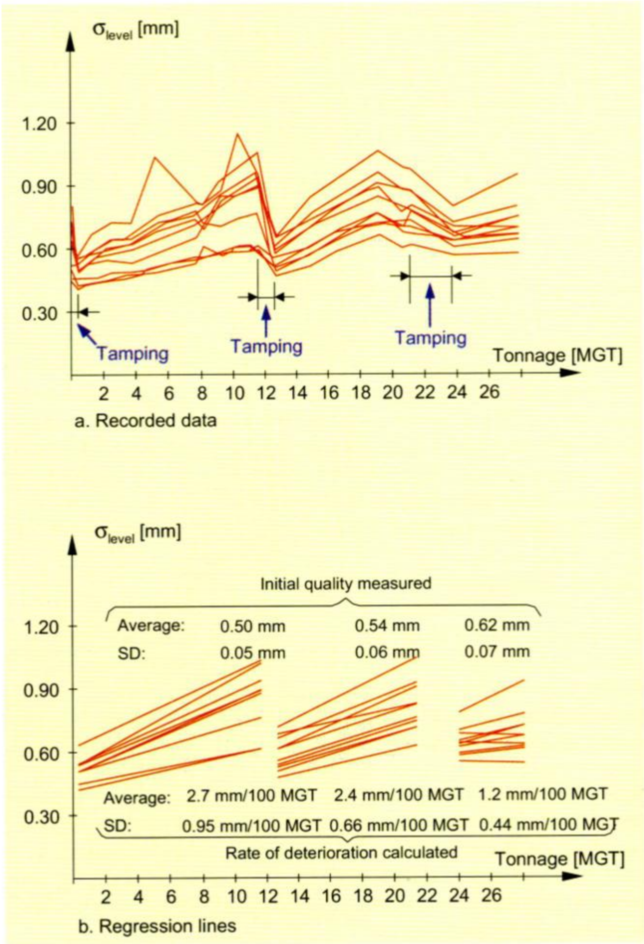

Figure 1 - Example of track level development on 10 successive sections of 200 m on FS, from [3].

The Figure 1 above illustrates recorded data and respective estimated regression lines for 10 successive maintenance sections of 200 meter each. Tamping operations' periods are signalled and statistical measures (average and standard deviation) for the coefficients of regression lines are presented (initial quality measured and calculated rate of deterioration). Therefore, for simplification regression lines are estimated using the following linear relationship:

$$\sigma = c_1 + c_0 T$$

In which: σ is the standard deviation of longitudinal defects; c_1 is the initial quality measured after renewal or tamping operations; c_0 is the rate of deterioration and T is the accumulated tonnage between tamping operations.

In Figure 1 it is also demonstrated the average and the standard deviation of coefficients c_1 and c_0 which vary depending on the number of tamping operation. In fact, the average and the standard deviation of c_1 increases through tamping operations, whereas the average and the standard deviation of c_0 decreases. Although the former trend may be quite expectable as successive tamping operations become more inefficient, the latter is quite surprising, as many references point out that the rate of deterioration increases after consecutive tamping operations [**4**]. Therefore, in the example developed later, only values from the first regression line will be used.

In order to assess the uncertainty of tamping costs, the uncertainty of the scheduling of tamping operations should be assessed first, using the Monte Carlo simulation. Therefore, to perform it, coefficients c_1 and c_0 are defined as random variables and a joint probability distribution must be found. Note that if a data set was available, fitting tests and independence tests would be performed in order to find a suitable distribution. Moreover, in order to include the loss of effectiveness of consecutive tamping operations, we will assume that c_1 will increase at a fixed rate r_1; whereas concerning the behaviour of the deterioration rate (c_0) of consecutive tamping operations, we will assume that c_0 will also increase at a fixed rate r_0. In fact, both assumptions contribute to diminish the accumulated tonnage between tamping operations over time. Nevertheless, the evolution over successive tamping operations of the rate of deterioration (c_0) may vary from a maintenance section to another. Therefore, the rate r_0 is also modelled as a random variable, following a normal distribution and independent from c_0 and c_1, representing the fixed rate increase of the rate of deterioration c_0 for a given maintenance section. Note that r_0 is considered a fixed rate because it does not change over time for the same maintenance section, while r_1, as a fixed rate, assumes the same value for all maintenance sections over time. Therefore, the scheduling of tamping operations may be estimated by:

$$T_i = \frac{\sigma_{lim} - c_{1i}}{c_{0i}} + 2MGT; \quad i = 1,2,\ldots$$

$$c_{1i} = c_1.(1+r_1)^{i-1}$$

$$c_{0i} = c_0.(1+r_0)^{i-1}$$

$$\begin{cases} c_1 \sim N(\mu;\ \sigma) \\ c_0 \sim N(\mu; \sigma) \\ r_0 \sim N(\mu;\ \sigma) \\ c_1, c_0, r_0\ \ are\ independent \end{cases}$$

As many factors influence track degradation and assuming that track degradation is a sum of many independent factors (intended as independent random variables), the Central Limit Theorem might be a strong inspiration to assume that track degradation (meaning the standard deviation of longitudinal defects) follows approximately a normal distribution, as stated above. Note that tamping operations are scheduled when the standard deviation of longitudinal defects reach a specified target limit (σ_{lim}), above which passenger comfort becomes compromised.

Note that, as the first expression shows, 2 MGT is summed in each accumulated tonnage because the first phase of large settlements had been ignored, and the estimations of c_0 and c_1 are for the regression lines, also ignoring the first 2 MGT of accumulated tonnage. Having the series $\{T_i; i = 1,2, \ldots\}$ for each maintenance section, we can assess the life-cycle cost for tamping operations for a maintenance section of 200-meter:

$$LCC_{tamping} = \sum_{i=1}^{N} \frac{c_{tamping}}{(1+r)^{\lfloor T_i^{acum} / T_{year} \rfloor}}$$

In which: $LCC_{tamping}$ is the life-cycle cost for tamping operations; $c_{tamping}$ is the cost of tamping for a 200-meter section; r is the discount rate; T_{year} is the annual accumulated tonnage and T_i^{acum} is the accumulated tonnage till the ith tamping operation. In fact, T_i^{acum} may be calculated by $T_i^{acum} = \sum_{j=1}^{i} T_j$. Note that $\lfloor \quad \rfloor$ rounds down the number inside, and therefore, costs are assumed to be discounted at the beginning of each year. N is the last tamping operation before ballast renewal.

Ballast renewal will be necessary when tamping operations become too demanding, meaning that they interfere to a great extent with the availability of the infrastructure, becoming traffic disruptive. N is here determined indirectly, by considering that above a certain percentage (α) of maintenance sections with an interval between tamping operations smaller than a certain amount of accumulated tonnage (β), tamping operations are no longer suitable, and the ballast bed must be renewed. Note that N will vary on each section, representing the number of tamping operations performed, till T_N^{acum} equals $T_{renewal}$ (accumulated tonnage till renewal). Different values for α and β were tried, resulting in different values for $T_{renewal}$ and $LCC_{tamping}$ for each maintenance section. It is important to mention that this technique to gather a collection of values for $T_{renewal}$ and $LCC_{tamping}$ intends to simulate in a realistic way the Infrastructure Manager's (IM) decision-making process of ballast renewal based on parameters like α and β. As IMs benefit from the fact that they own a high number of maintenance sections, as the probability of every maintenance section having a high deterioration rate is very small, the example will present total life-cycle tamping cost per MGT for a 100-km section. Therefore, summing all different $LCC_{tamping}$ for the distinctive 500 maintenance sections, we will reach an estimation of the total tamping cost for the 100 km analyzed. Moreover, by simulating a great number of times, we will reach a collection of values for total tamping cost and respective $T_{renewal}$ and we may quantify the uncertainty associated with this cost. However, a trade-off between life-cycle cost (LCC) and accumulated tonnage must be searched, and therefore we must look to the efficiency of LCC and a new function $TC_{tamping}$ should be defined:

$$TLCC_{tamping} = \frac{\sum_{k=1}^{500} LCC_{tamping,k}}{T_{renewal}}$$

In which: $TLCC_{tamping}$ is the total life-cycle cost of tamping operations for the 100 km of plain track per MGT, $LCC_{tamping,k}$ is the life-cycle cost of tamping operations for the kth maintenance section and $T_{renewal}$ is the respective accumulated tonnage till ballast renewal.

To estimate total life-cycle cost presented above, the coefficient values should be set. Next table presents them:

Random variables	μ	σ
c_1 (mm)	0.50	0.05
c_0 (mm/100 MGT)	2.7	0.95
r_0	0.04	0.02

σ_{lim} (mm)	1.0
r_1	0.01
$c_{tamping}$ (€)	600
R	4%
T_{year} (MGT)	12

Table 1 – Coefficients of the model

The Figure 2 below illustrates the life-cycle cost of tamping operations per MGT for different renewal tonnages. In fact, it shows average values and extreme values for the 5th, 10th, 90th and 95th percentiles. Moreover, the respective quadratic trend lines are adjusted to presented values. Note that a collection of more than 100.000 pairs of values for $TC_{tamping}$ and $T_{renewal}$ was gathered as the Monte Carlo simulation requires, in order to quantify the uncertainty related to life-cycle cost of tamping operations per MGT.

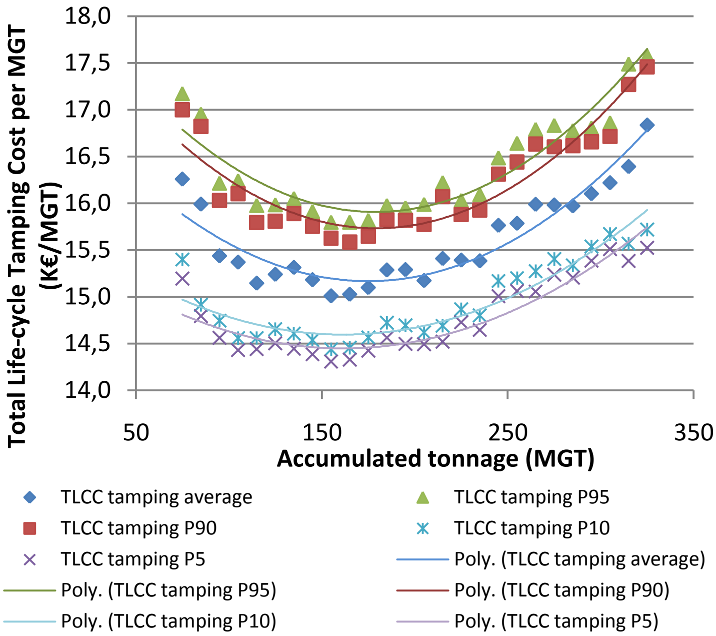

Figure 2 - Total Life-Cycle Cost of Tamping operations per MGT of a 100 km plain track section ($TLCC_{tamping}$).

2.2 Inspection cost

Inspection and renewal costs still need to be included. In fact, inspection mainly consists of geometric inspection and ultrasonic inspection. As ultrasonic inspection will be included later in the rail LCC model, only geometric inspection is here considered. It is assumed that geometric inspection is performed periodically in every trimester. The following expression quantifies the life-cycle cost of geometric inspection per maintenance section ($LCC_{geom.insp}$):

$$LCC_{geom.insp} = \sum_{j=1}^{N} \frac{c_{geom.insp} \cdot n_{insp}}{(1+r)^j}$$

In which: $c_{geom.insp}$ is the cost of geometric inspection per inspection and maintenance section; n_{insp} is the number of geometric inspections per year; r is the discount rate and N is the year when ballast renewal takes place. Note that N may be calculated by $N = \left\lfloor \frac{T_{renewal}}{T_{year}} \right\rfloor$.

An estimation for $c_{geom.insp}$ might be controversial as inspection cost may be difficult to estimate, involving equipment amortizations (if IM uses its own equipment), labor cost associated and therefore, $c_{geom.insp}$ may vary with n_{insp}.

2.3 Renewal cost

Concerning renewal cost, it represents the large expenditure throughout the life-cycle that only takes place at the end of it, and should therefore be discounted based on $T_{renewal}$. The following expression gives the life-cycle cost of renewal per maintenance section ($LCC_{renewal}$):

$$LCC_{renewal} = \frac{c_{renewal}}{(1+r)^{\lfloor T_{renewal}/T_{year} \rfloor}}$$

In which: $c_{renewal}$ is the renewal cost per maintenance section. $T_{renewal}$, T_{year} and r have the same meaning from the equations listed above.

It is important to refer that $c_{renewal}$ should take implicitly into account the traffic interference provoked by ballast renewal operation which, in fact, depends largely on the track layout and its level of redundancy. Moreover, note that to quantify renewal and geometric inspection costs for the analyzed example of 100 kilometers (500 maintenance sections of 200 meters), $LCC_{geom.insp}$ and $LCC_{renewal}$ should be multiplied by 500. Note that it is assumed that geometric inspection is performed at the same time for each maintenance section and that renewal is also performed for all the maintenance sections when the ballast life-cycle ends.

2.4 Unavailability cost

Another life-cycle cost that must be included in the model is the cost of unavailability of the infrastructure. Most temporary maintenance operations (e.g. tamping operations) are performed during non-operative time (maintenance night shifts), and therefore considered non-disruptive. However, as tamping operations become more demanding they will interfere with the normal operation of infrastructure, causing delays and even train cancellations. In fact, performance payment regimes contracted between the regulator entity and the IM determine the penalties for bad performance on availability. These regimes have an exponential behaviour [**5**], meaning that as unavailability increases, penalties become more severe. Therefore, quantifying unavailability costs may be quite complex and demand more information on the robustness of the operation schedule. However, in order to quantify total life-cycle cost we will assume a function of unavailability costs with exponential behaviour depending on $T_{renewal}$. Note that this assumption might be quite controversial, but no reference has been found to quantify these costs directly. Moreover, it is important to mention that more studying is needed on these aspects and therefore, they represent a challenging point for further research. Having said that, life-cycle unavailability cost of infrastructure per MGT for the example of 100-km plain track may be estimated by the following expression:

$$TLCC_{unavailability} = \begin{cases} 0 \quad , & T_{renewal} < T_{disruptive} \\ 300.\, e^{0.02 T_{renewal}} \quad , & T_{renewal} \geq T_{disruptive} \end{cases}$$

In which: $TLCC_{unavailability}$ is the total life-cycle unavailability cost per MGT for 100-km of plain track (€); $T_{renewal}$ is the accumulated tonnage till renewal (MGT) and $T_{disruptive}$ is the accumulated tonnage limit above which tamping operations become traffic disruptive. Note that this limit depends on multiple factors, such as: maintenance equipment, human resources teams, IM internal organization, the number of maintenance bases, the extent of track analyzed and of course capacity (number of slots).

The expression above does not take into account the discount rate. Therefore, we will assume that this expression only remains valid for this example for a constant discount rate $r = 4\,\%$. Note that this discount rate takes the same value used to discount the different types of costs presented.

2.5 Evaluation of ballast economic life

Having presented the costs associated with economic life of the ballast bed, we may systematize the total life-cycle cost per MGT of the ballast bed for the example of 100-km plain track by the following expression:

$$TLCC_{ballast} = TLCC_{tamping} + TLCC_{renewal} + TLCC_{geom\ .insp} + TLCC_{unavailability} =$$

$$= TLCC_{tamping} + 500 \times \frac{LCC_{renewal}}{T_{renewal}} + 500 \times \frac{LCC_{geom\ .insp}}{T_{renewal}} + TLCC_{unavailability}$$

Next table gives estimation of the coefficients needed to calculate remaining costs presented above:

$c_{geom.insp}$ (€)	20
n_{insp}	4
$c_{renewal}$ (€)	40 000
$T_{disruptive}$ (MGT)	135

Table 2 – Remaining coefficients of the model

As the aim of this model is to optimize the efficiency of total life-cycle cost, minimizing total life-cycle cost per MGT, total life-cycle costs presented are referred to costs per MGT. Moreover, it is important to refer that each component of presented cost is calculated by the expressions shown above, for a constant discount rate $r = 4\,\%$. Therefore, the Figure below shows the total life-cycle cost per MGT for ballast of the analyzed example:

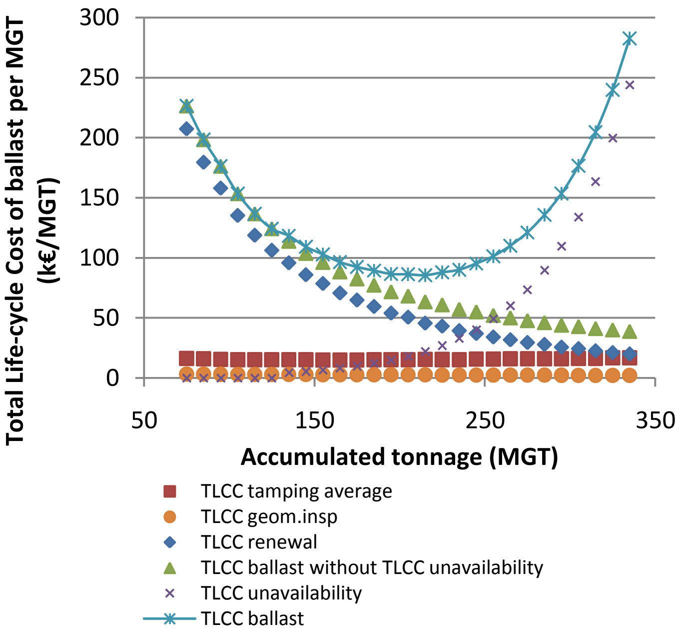

Figure 3 - Total Life-cycle Cost of ballast per MGT of a 100-km plain track section ($TLCC_{ballast}$).

As Figure 3 above illustrates the major components that contribute to total life-cycle cost of the ballast bed per MGT are the renewal cost and the unavailability cost. This may compromise the present research as unavailability costs need further investigation, though total life-cycle cost of ballast per MGT shows a minimum between 150 to 250 MGT, which is the usual interval referred to ballast renewal. In fact, the minimum value for total life-cycle cost of ballast per MGT is 85 573 € for an accumulated tonnage of 215 MGT. Note that total life-cycle cost of ballast per MGT without unavailability cost is also presented.

Moreover, it is important to refer that the cost of tamping operations and geometric inspection do not have a major impact on total life-cycle cost. That is mainly the reason why Monte Carlo simulation results to quantify the uncertainty associated with the tamping cost are not presented in Figure 3, as it does not have any major impact on total life-cycle cost, and therefore, not affecting the maintenance strategy of ballast renewal. Nevertheless, it should be highlighted that Monte Carlo simulation performed to calculate tamping operations costs would give relevant data to estimate unavailability costs, but again this is left out of analysis for further research. Note that the scheduling of tamping activities, given by $\{T_i; i = 1,2, \dots\}$ for each maintenance section would provide data to investigate on how demanding infra availability tamping operations become as the ballast renewal is postponed. Therefore, the argument above gives evidence that uncertainty in ballast LCC estimations may be due to unavailability costs, rather than tamping costs, and therefore further analysis should focus on the variability of RAM parameters rather than on the variability of degradation model parameters. Nevertheless, they are related and further research is needed to link them.

3 Rail LCC model

To assess the economic life of rail component, an existing model from Railway Research Centre at the University of Birmingham using a stochastic analysis of rail failures is used [**5**]. This present article will not comprehend the intricacies of the rail LCC model, remitting the reader to that reference. However, some aspects should be highlighted. Concerning inspections costs, geometric inspection is assumed to be conducted periodically and that the related cost has no influence on the determination of rail economic life, and thus it is not included. In fact, as geometric inspection cost is considered in the ballast LCC model, the future integrative approach presented later remains valid. The rail life-cycle cost (LCC) per unit traffic (MGT) is given by the following expression:

$$C(T) = \left\{ c_R + \frac{c_I T}{s_I} + \frac{c_g T}{s_g} + \left[(1+\varepsilon)c_f + \varepsilon c_x\right] N_f(T) + c_d N_d(T) \right\} \frac{1}{T}$$

Note that economic life is also assessed based on efficiency criteria, as the equation above balances inputs (LCC) and outputs (rail life-cycle - T). In fact, optimizing LCC should be understood as optimizing LCC per unit of traffic, and thus searching for a minimum of the function $C(T)$.

Nevertheless, as the model does not take into account the depreciation of the value of money through time, meaning that no discount rate is considered in the evaluation of costs, the costs considered above are discounted to the base year, representing the present value of LCC per unit traffic (MGT) according to a constant discount rate (r) as the following expression shows:

$$C_o(T) = \frac{1}{T}\left[\frac{c_R}{(1+r)^{T/T_{year}}} + \sum_{n=0}^{N} \frac{T_n . C(T_n) - T_{n-1} . C(T_{n-1})}{(1+r)^{T_n/T_{year}}}\right]$$

In which: $C_o(T)$ is the present value of $C(T)$; T_{year} is the annual accumulated tonnage; T_n is the cumulative tonnage at year n, thus $T_{-1} = 0$ and $T_N = 0$, and it may be calculated $T_n = n . T_{year}$. In fact, N should be given by $N = \left\lfloor \frac{T}{T_{year}} \right\rfloor$.

For the studied example of 100-km plain track section, the model was implemented using macros programmed with Visual Basic in Excel. Note that some residual error of numerical integration may arise from the model implementation, and therefore a reasonable trade-off between computational time and error significance must be pursued. Having said that, we will assume the same values for the parameter values for rail defects as in the example of the article, presented in Table 2 below:

Defects	α	η (MGT)	P-F interval (MGT)	β_j
ATW defects	1.01	315.8	10	0.7
Flash butt weld defects	2.00	286.6	10	0.7
Squats defects	2.50	191.8	5	0.6
Tache ovale defects	2.17	182.3	7	0.7

Table 2 - Parameter values for rail defects used in the example analyzed, from [5].

The coefficients of the model are also based on the values used in the example referred, but the costs presented are in Euros (€), instead of British pounds (£). Table 3 presents the values used for the example of a 100-km plain track section:

c_R (€/km)	c_f (€/failure)	c_d (€/defect)	c_I (€/km)	c_x (€/accident)
160000	7000	1000	145	3944000

c_g (€/km)	n_0	ε	$\gamma(q)$	S_g (MGT)	S_I (MGT)
2700	22	0.000556	0.6	10	2.5

Table 3 - Coefficients of the model used in the example analyzed, adapted from [6].

Running the model, assuming the values presented above for parameter values for rail defects and coefficients, the life-cycle cost of rail for a 1-km section per MGT for different renewal tonnages is assessed as the Figure 4 below shows:

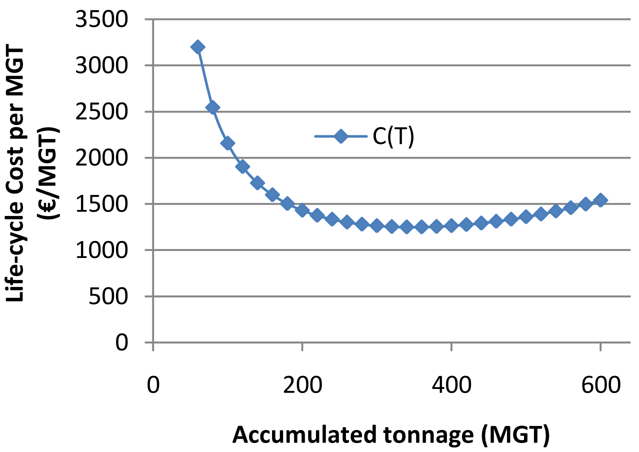

Figure 4 – Life-cycle Cost of rail per MGT for a 1-km section.

Figure 4 exhibits a minimum for life-cycle cost per MGT for $T = 340\,MGT$, with $C(340) = 1249$ € and $C(300) = C(400) = 1263$ €, which only deviates around 1% from the minimal value, which shows that the cost curve is steady at its minima. However, these costs should be discounted depending on the discount rate used and on the annual accumulated tonnage. The next two Figures (5 and 6) intend to give a perception of the sensibility of life-cycle costs respectively discounted to discount rate and annual accumulated tonnage. As illustrated, life-cycle cost of rail per MGT $(C(T))$ is influenced by the discount rate and the annual accumulated tonnage. In fact, the present value of $C(T)$, defined earlier as $C_0(T)$, decreases as discount rate increases for the same values of accumulated tonnage (Figure 5); whereas $C_0(T)$ increases as annual accumulated tonnage increases for the same values of accumulated tonnage. Note that $C_0(T)$ is identical to $C(T)$ if we assume a value for discount rate equals to zero, though this is not realistic since it implies that money has the same value through time.

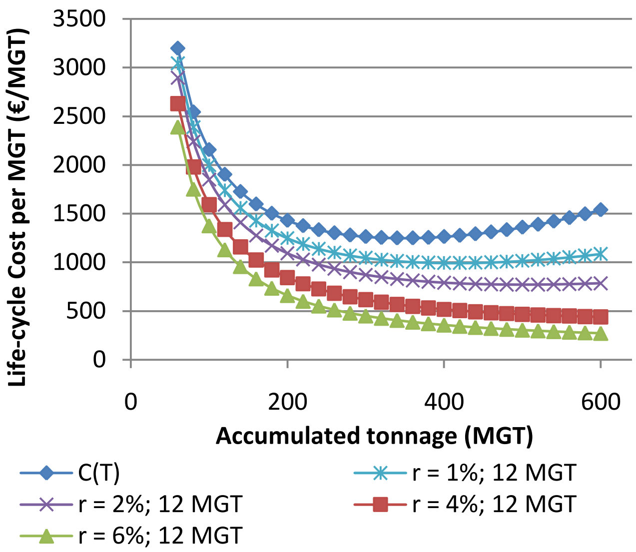

Figure 5 - Sensibility of the present value of Life-cycle Cost of rail per MGT for a 1-km section to different discount rates (1%, 2%, 4% and 6%), for an annual accumulated tonnage of 12 MGT.

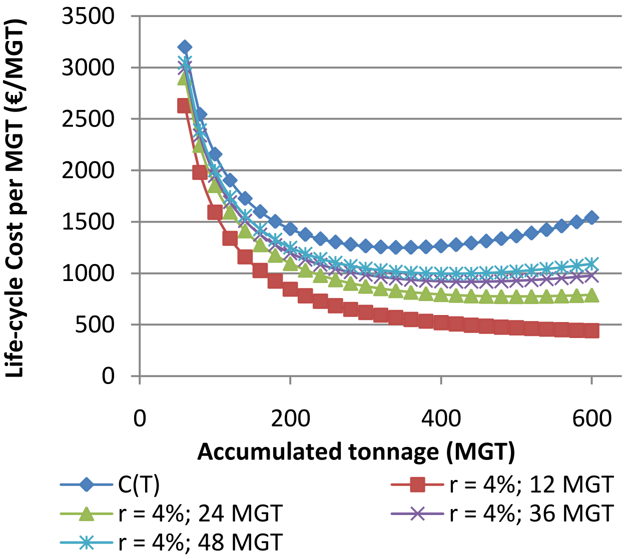

Figure 6 - Sensibility of the present value of Life-cycle Cost of rail per MGT for a 1-km section to different annual accumulated tonnages (12 MGT, 24 MGT, 36 MGT and 48 MGT), for a discount rate of 4%.

Note that some functions presented above do not exhibit a minimum value in the interval 0-600 MGT analyzed. In fact, for the example it was assumed an annual accumulated tonnage of 12 MGT and a discount rate of 4%, and as seen in it does not exhibit a minimum value in the interval 0-600 MGT (Figures 5 and 6 in red). Therefore, when both rail and ballast cost models are integrated, we will face the problem of choosing when to renew rails. At that time, new assumptions will be drawn in order to overcome this situation.

4 Integrating ballast and rail LCC models

Although both LCC models of rail and ballast are discussed separately, an integrative strategy approach should be developed, comprehending the outputs of both models and determine best renewal times (quantified by accumulated tonnage) for each component or both components in case of simultaneous renewal. No LCC model was developed to assess economic life of fastenings and sleepers, and thus only the life-cycle costs of rail and ballast components are integrated. A straight-forward approach to integrate both cost models is based on the construction of hypothetical scenarios with distinct renewal times for each component, while quantifying total life-cycle costs per MGT for each scenario. Therefore, the best scenario is that which presents the minimum total life-cycle cost per MGT, calculated by the following expression:

$$TLCC_{ballast+rail} = \frac{1}{T_{rail}} \Bigg\{ T_{ballast\ 1} \times TLCC_{ballast}(T_{ballast\ 1}) + T_{ballast\ 2} \times \frac{TLCC_{ballast}(T_{ballast\ 2})}{(1+r)^{T_{ballast\ 1}/T_{year}}} + T_{rail} \times TLCC_{rail}(T_{rail}) \Bigg\}$$

In which: $TLCC_{ballast+rail}$ is the total life-cycle cost per MGT of ballast and rail; $T_{ballast\ 1}$ and $T_{ballast\ 2}$ are respectively the accumulated tonnages at first and second ballast renewals[1]; T_{rail} is the accumulated tonnage at rail renewal; r is the discount rate and T_{year} is the annual accumulated tonnage. For further calculations they will assume the values: $r = 4\%$ and $T_{year} = 12\ MGT$. $TLCC_{ballast}$ and $TLCC_{rail}$ are given by the functions in Figure 7.

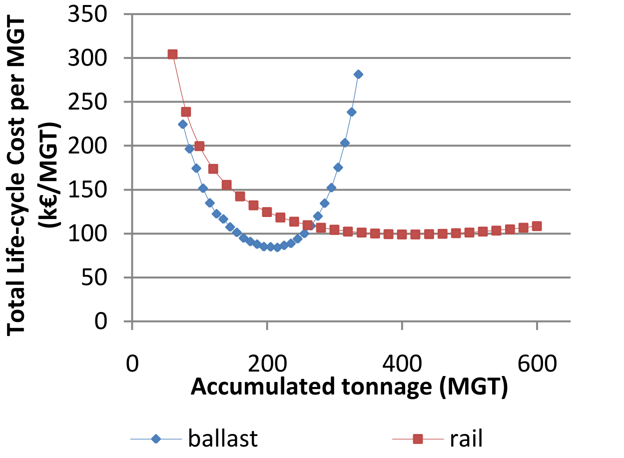

Figure 7 - Total Life-cycle Cost per MGT of rail and ballast components for a 100-km plain track section.

Note that in the equation above, the total life-cycle cost per MGT of the second ballast should be discounted to the base year (beginning of operation) at a constant discount rate (r), given an annual accumulated tonnage (T_{year}). Once again, optimal life-cycle is obtained by the efficiency of total life-cycle cost, and therefore, total life-cycle costs per MGT for the 100-km plain track section example are calculated.

As seen in the ballast model, the 100-km plain track section has an optimal life-cycle of 215 MGT with a corresponding total life-cycle cost per MGT of 85 573 €, whereas in the rail model no optimal life-cycle was identified for the present value of life-cycle cost with an discount rate set at 4% and an annual accumulated tonnage set at 12 MGT. Note that in the ballast cost model, the same values for discount rate and annual accumulated tonnage were assumed, as the integrative cost model should sum values discounted at the same discount rate. Nevertheless, in order to search for scenarios to exemplify the integrative cost model, we will have to make some assumptions in order to use a value for the optimal rail life-cycle. Therefore, we will assume that the discount rate is lower for the rail model. Obviously, this is wrong as both separate models should contemplate costs discounted at the same discount rate, though for practical reasons, to exemplify how to do this integrative approach, we will assume that the discount rate is equal to 1 % and the annual accumulated tonnage is equal to 12 MGT. Note that total life-cycle cost function of rail per MGT is for a 1-km plain track, and therefore it should be

[1] Note that accumulated tonnages are counted since the start of infrastructure operation or the last time the component was renewed. Therefore, the accumulated tonnage at second ballast renewal corresponds to the accumulated tonnage since first ballast renewal.

multiplied by 100 for the analyzed example of a 100-km plain track. This function has a minimum of 420 MGT with a corresponding total life-cycle cost per MGT of 992.1 €. As this value is per km, for the 100-km plain track section, minimum total life-cycle cost of rail per MGT is 99 210 €. Figure 7 shows total life-cycle costs per MGT functions for rail and ballast components for the 100-km plain track section example.

As the minimal values for total life-cycle cost per MGT of rail and ballast are very similar, it is not obvious which renewal strategy optimizes life-cycle of components, while minimizing total life-cycle cost per MGT of infrastructure. Therefore, twenty-five distinct scenarios were built with different renewal times for ballast and rail. As the rail optimal life-cycle fits with approximately two optimal ballast life-cycles, only scenarios with simultaneous rail renewal and ballast second renewal are investigated $(T_{ballast\ 1} + T_{ballast\ 2} = Trail$.

In the next page, Table 4 illustrates the twenty-five scenarios that were analyzed with the respective total life-cycle costs per MGT. The best scenario is marked in bold, scenario 9, corresponding to a total life-cycle cost per MGT (ballast + rail) of 160 466 €, which consists of a first ballast renewal at an accumulated tonnage of 195 MGT, and a simultaneous rail renewal and second ballast renewal at a rail accumulated tonnage of 430 MGT[2]. Therefore, note that though ballast optimal life-cycle was set at 215 MGT in the separate model analysis, none of ballast renewals is set at optimal life-cycle (195 and 235 MGT). This happens because of the additional discount that total life-cycle cost per MGT function of ballast (for the second ballast renewal) suffers, related to the given shape of that function, presenting a steeper slope on the right of the minimum value.

Nevertheless, note that this simplistic approach to integrate rail and ballast LCC models, through the construction of hypothetical scenarios, may be improved by considering gains of efficiency for simultaneous renewal, obtained as renewal activities are clustered. In fact, future research should contemplate these efficiency gains by including them as negative costs in an integrative LCC model.

[2] Note that a rail accumulated tonnage of 430 MGT corresponds in this case to a second ballast accumulated tonnage of 235 MGT (= 430-195).

5 Conclusions

LCC plays a primordial role towards a more conscious and transparent management of Railway infrastructure. In fact, this article puts forward an innovative approach to assess LCC uncertainty through assessing the uncertainty of degradation model parameters. Nevertheless, Monte Carlo simulation was only performed to assess life-cycle tamping cost uncertainty in the ballast LCC model. It showed that compared to other costs, tamping uncertainty does not contribute decisively to ballast LCC uncertainty, and renewal decisions are mainly conducted by unavailability costs. Therefore, more emphasis on RAM (Reliability, Availability and Maintainability) parameters and assessment of unavailability costs is needed.

Concerning ballast renewal, the ballast LCC model assessed only the uncertainty related to tamping costs, which proved to be negligible compared to the potential uncertainty related to unavailability costs. The ballast LCC model developed includes four component costs: tamping cost, renewal cost, geometric inspection cost and unavailability cost. Tamping and geometric inspection costs had lesser impact on the optimal life-cycle of ballast than renewal and unavailability costs. Concerning rail renewal, the rail LCC model showed that there is a wider flexibility on rail renewal than on ballast renewal, as the rail cost curve is steadier at its minima. Moreover, no uncertainty considerations were made in rail LCC ballast, as in order to perform the Monte Carlo simulation, the existing rail model needs some adaptations.

Integrating rail and ballast LCC models was conducted through a simplistic approach based on the construction of hypothetical scenarios. It showed that the optimal renewal strategy, for the analyzed example for a 100-km plain track, had a first ballast renewal at 195 MGT and a second ballast renewal at 235 MGT, occurring simultaneously with a rail renewal at 430 MGT.

Note that separate LCC models for fastenings and sleepers still need to be developed. Another important limitation is the lack of integrated data analysis, and the use of different sources of data for rail and ballast LCC models. Note that Infrastructure Managers still lack comprehensive databases on track quality and infra data relating infra component degradation through time, so that degradation model parameters uncertainty may be estimated by assuming that they are random variables that follow proper probability distributions given by the historic data. Apart from that, another limitation is the fact that unavailability costs are not properly justified using a performance payment regime, and in fact an expression for unavailability costs is assumed so that total life-cycle costs of ballast per MGT has a minimum value in the interval 150-250 MGT. Moreover, it is important to remind the reader that different discount rates were also used for ballast and rail LCC models so that the integrating approach of separate LCC models could be exemplified. Nevertheless, proper integration should be done by using the same discount rate in both separate models in future research. Moreover, when integrating rail and ballast separate LCC models, no considerations on any efficiency gain to cluster renewal activities has been made, and in fact, clustering of maintenance and renewal activities may bring some reduction of life-cycle costs, and in the future research they may be included as negative costs in an integrative LCC model. In conclusion, more work on how fruitful the idea of inserting uncertainty considerations in degradation model parameters, linking uncertainty generated from it to maintenance operations scheduling uncertainty and RAM parameters uncertainty, and availability costs uncertainty based on a performance payment regime is needed.

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Notation

c_0 - Rate of deterioration of standard deviation of longitudinal defects in mm/MGT
c_1 - Initial quality measured after renewal or tamping operations in mm
$c_{geom.insp}$ - Cost of geometric inspection per inspection and maintenance section
$c_{renewal}$ - Cost of ballast renewal per maintenance section
$c_{tamping}$ - Cost of tamping for a 200-meter section
$C(T)$ - Rail Life-Cycle Cost per MGT for a rail life-cycle T
$C_0(T)$ - Present Value of $C(T)$
$LCC_{geom.insp}$ - Life-Cycle Cost of geometric inspection per maintenance section
$LCC_{renewal}$ - Life-Cycle Cost of ballast renewal per maintenance section
$LCC_{tamping}$ - Life-Cycle Cost for tamping operations
$LCC_{tamping,k}$ - Life-Cycle Cost for tamping operations for the kth maintenance section
n_{insp} - Number of inspections per year
r - Discount Rate
r_0 - Increase Rate of c_0
r_1 - Increase Rate of c_1
σ - Standard Deviation of longitudinal defects
σ_{lim} - Limit Standard Deviation of longitudinal defects
$T_{ballast\ 1}$ - Accumulated tonnage at first ballast renewal
$T_{ballast\ 2}$ - Accumulated tonnage at second ballast renewal
$T_{disruptive}$ - Disruptive tonnage (accumulated tonnage limit above which tamping operations become disruptive.
T_i - Accumulated Tonnage for a maintenance section when the ith tamping operation is performed
T_i^{acum} - Accumulated tonnage till the ith tamping operation
T_{lim} - Tonnage Interval between two successive maintenance sessions (tamping operations)
T_{rail} - Accumulated tonnage at rail renewal
$T_{renewal}$ - Accumulated tonnage at ballast renewal
T_{year} - Annual Accumulated Tonnage in MGT
$TLCC_{ballast}$ - Total Life-Cycle Cost of ballast component per MGT for the 100-km plain track
$TLCC_{ballast+rail}$ - Total Life-Cycle Cost of ballast and rail components per MGT for the 100-km plain track
$TLCC_{geom.insp}$ - Total Life-Cycle Cost of geometric inspection per MGT for the 100-km plain track
$TLCC_{rail}$ - Total Life-Cycle Cost of rail component per MGT for the 100-km plain track
$TLCC_{renewal}$ - Total Life-Cycle Cost of ballast renewal per MGT for the 100-km plain track
$TLCC_{tamping}$ - Total Life-Cycle Cost of tamping operations per MGT for the 100-km plain track
$TLCC_{unavailability}$ - Total Life-Cycle Cost of unavailability per MGT for the 100-km plain track

Scenarios	Renewal accumulated tonnages (MGT)			TLCC per MGT (€/MGT)			
	$T_{ballast\ 1}$	$T_{ballast\ 2}$	T_{rail}	$TLCC_{ballast}$ ($T_{ballast\ 1}$)	$TLCC_{ballast}$ ($T_{ballast\ 2}$)	$TLCC_{rail}$ (T_{rail})	$TLCC_{ballast+rail}$
1	215	205	420	84199	84920	99210	163521
2	205	215		84920	84199		162005
3	195	225		85181	86581		160991
4	185	235		87974	88846		161022
5	175	245		90941	94082		161744
6	225	205	430	86581	84920	99312	165332
7	215	215		84199	84199		162261
8	205	225		84920	86581		161512
9	195	235		85181	88846		**160466**
10	185	245		87974	94082		161229
11	225	215	440	86581	84199	99414	164064
12	215	225		84199	86581		161778
13	205	235		84920	88846		160992
14	195	245		85181	94082		160686
15	185	255		87974	100154		161626
16	225	225	450	86581	86581	99635	163675
17	215	235		84199	88846		161387
18	205	245		84920	94082		161319
19	195	255		85181	100154		161209
20	185	265		87974	108939		162783
21	235	225	460	88846	86581	99855	165543
22	225	235		86581	88846		163260
23	215	245		84199	94082		161707
24	205	255		84920	100154		161826
25	195	265		85181	108939		162359

Table 4 – Renewal scenarios for ballast and rail with respective total life-cycle cost per MGT (ballast + rail).