

Integration of RAMS in LCC analysis for linear transport infrastructures. A case study for railways.

Álvaro Calle-Cordón¹, Noemi Jiménez-Redondo¹, F J Morales-Gámiz¹,
F A García-Villena¹, Amir H S Garmabaki² and Johan Odelius²

¹CEMOSA, Benaque 9, Málaga 29004, Spain

²Lulea Tekniska Universitet, Universitetsområdet Porson, Lulea 971 87, Sweden

E-mail: alvaro.calle@cemosa.es

Abstract. Life-cycle cost (LCC) analysis is an economic technique used to assess the total costs associated with the lifetime of a system in order to support decision making in long term strategic planning. For complex systems, such as railway and road infrastructures, the cost of maintenance plays an important role in the LCC analysis. Costs associated with maintenance interventions can be more reliably estimated by integrating the probabilistic nature of the failures associated to these interventions in the LCC models. Reliability, Maintainability, Availability and Safety (RAMS) parameters describe the maintenance needs of an asset in a quantitative way by using probabilistic information extracted from registered maintenance activities. Therefore, the integration of RAMS in the LCC analysis allows obtaining reliable predictions of system maintenance costs and the dependencies of these costs with specific cost drivers through sensitivity analyses. This paper presents an innovative approach for a combined RAMS & LCC methodology for railway and road transport infrastructures being developed under the on-going H2020 project INFRAALERT. Such RAMS & LCC analysis provides relevant probabilistic information to be used for condition and risk-based planning of maintenance activities as well as for decision support in long term strategic investment planning.

1. Introduction

Railway and road network infrastructures are quite complex systems which components have a very long technical lifetime (40 to 120 years, see e.g. Ref. [1]) and are subject to different failure. As a consequence each decision must consider the usage of the assets in question for at least 40 years into the future. Long term plans, nowadays, are of the order of 10 years, even with the awareness that the remaining live time can be longer. The complexity of these systems is due to the mixture of components of different age and status that have to work together. Replacement of components is also a continuous and on-going process, and changes must be carefully executed.

On the other hand, the pressure for increases in traffic volume leads to a higher utilization of the existing infrastructure and hence to more severe degradation, which therefore requires more maintenance actions on the network. This fact is recognised in the objectives set by the European Commission for 2020. An expected increase of passenger and freight traffic, the reduction of travel time by 25-50% and life-cycle cost (LCC) by 30% and at the same time increasing safety (decreasing fatalities) by a 75% have put strong demands on operational and maintenance optimization (see Refs. [2] and [3]).



In the case of the railway transport, operational quality can be measured by punctuality. In the road case, this concept could be also applicable by considering the planned speed of corridors. Maintenance activities are programmed or scheduled in time slots in which traffic load is low or inexistent, so the maximum priority is to keep the traffic flow in its highest possible values. Maintenance activities must therefore be performed near capacity limits. Time between asset renewal should be long enough to balance maintenance costs and acquisition costs, and components be replaced by deferred or planned maintenance. On top of that, Infrastructure Managers (IMs) must keep infrastructure highly available so that the railway undertakings can deliver a highly quality service at affordable price to the end users.

In general RAMS (Reliability, Availability, Maintainability and Safety) and LCC (Life-Cycle Cost) analyses are used as tools to optimize the performance of the network and make it economically viable. RAMS analysis is used to establish the need of maintenance of the infrastructure by analysing corrective and preventive maintenance data and a central element in many engineering areas, ranging from manufacturing, electrical engineering to the nuclear and space industry. Although they have a high potential for applications in transport infrastructure management, currently there is a lack of standardisation and stated procedures in its implementation [4]. LCC analysis, on the other hand, is the method used to assess the most cost-effective option among competing alternatives considering investment, operation and maintenance, and unplanned interruptions throughout the assets' life cycle [5].

Recently, combined RAMS and LCC analyses have attracted much attention in the railway sector, with a large number of projects devoted to their development and applications [6, 7]. On the contrary, few experiences of implementing this approach are known in the road sector. Moreover, traditional applications of RAMS and LCC in transport infrastructures have followed a deterministic approach [8] in part due to scarce data availability and computer processing capabilities. The predicting deficiencies inherent of such approaches can be overcome using a probabilistic point of view, where RAMS and LCC figures are described statistically.

This paper describes a general approach that combines RAMS and LCC, applicable to linear infrastructures. The methodology is applied to a specific railway use case that is part of one of the demonstrators in the on-going H2020 project INFRAALERT [9].

2. Combined RAMS and LCC methodology

The combined RAMS and LCC methodology rests on two basic pillars: *statistical analysis of maintenance interventions* and *information from the accounting system to estimate costs*. Figure 1 depicts the general workflow of the RAMS&LCC process. The idea is to create an optimized maintenance policy to be implemented in the real system in accordance with the needs of the system itself. In order to generate such a policy, access to historical maintenance data is needed. From the maintenance (corrective and preventive) intervention record, the RAMS of the system are calculated. The RAMS are a rich set of parameters extracted from the underlying probability distribution functions of the data. Some relevant RAMS indicators are (see also Ref. [10]): the reliability function, failure/maintenance rates, and mean time to failure/maintenance/repair/restoration. Time to restoration is equivalent to down time and it includes repair and logistic times. The models used and the set of RAMS that are calculated will depend strongly on the level of detail of the available data.

The next step in the calculation consists on building an LCC model. The life cycle of an asset can be subdivided into six phases according to the IEC 60300-3-3 standard [11]. From the ownership point of view, regarding costs, these phases are connected with the LCC of the asset as follows: (i) acquisition costs: concept and definition, design and development, manufacturing and installation, (ii) ownership costs: operation and maintenance, and (iii) termination costs: disposal.

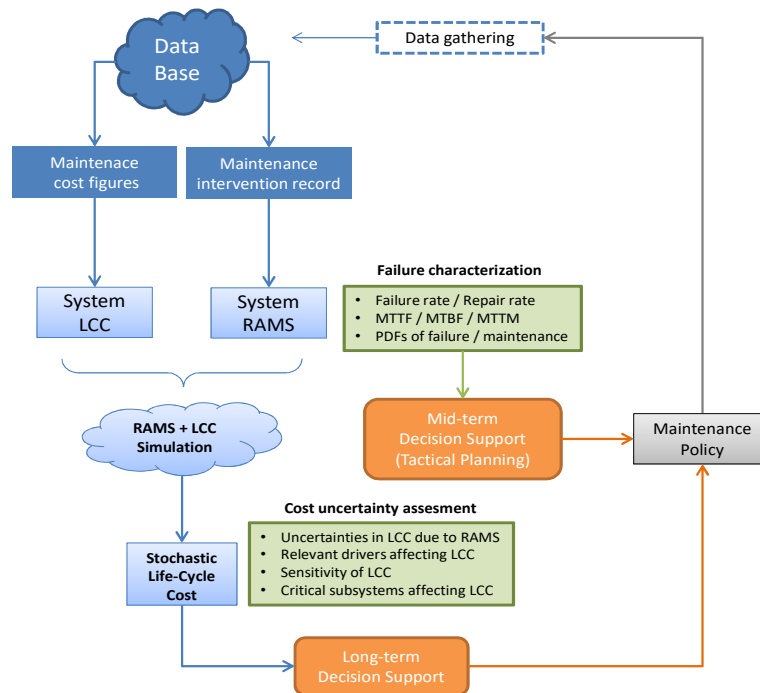


Figure 1. RAMS&LCC workflow.

While acquisition and termination costs are usually fixed or not subject to ownership time variations, ownership costs depend on operation conditions and maintenance policies. The combined RAMS & LCC analysis described here focuses exclusively on the ownership LCC because this phase is the most sensitive to variations and therefore able to be optimised. The first step in the LCC analysis consists in identifying the so-called *cost elements* that considerably influence the total LCC of the system. According to the standard [11], it is recommended to develop a Cost Breakdown Structure (CBS) as a basis to the definition of the cost elements in the LCC analysis. The CBS depends on the system under study, being difficult to define a generic structure for the cost elements in the LCC analysis. Therefore, the CBS has to be tailored to the specific system or subsystem under study. Figure 2 shows a simplified CBS that is suitable for road/railway infrastructures. Once the CBS and the cost drivers have been identified, the next step deals with building a model to quantify the cost elements encompassed in a LCC analysis. That means to find appropriate relations among input parameters and the cost elements.

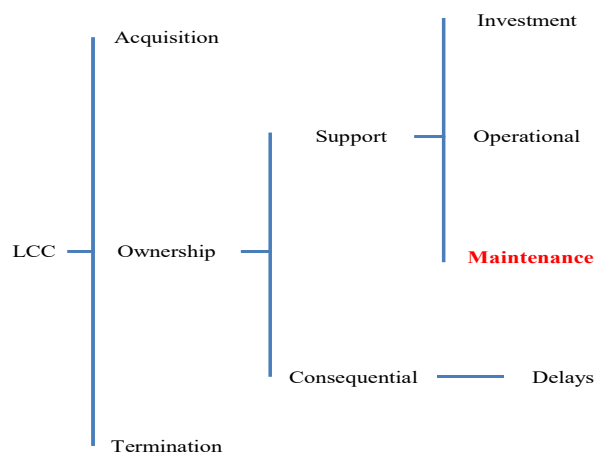


Figure 2. Cost Breakdown Structure.

In this paper only maintenance costs, which depend on the maintenance policy for the different assets and vary among companies, are considered. Maintenance actions can be preventive or corrective. Corrective Maintenance (CM) is assumed to be carried out annually while Preventive Maintenance (PM) can be *annual* and *periodical*. This is so because there may be PM actions carried out off the annual planning with well-defined and fixed costs. The annual costs of maintenance are functions of time while the periodical costs are assumed constant. Moreover, yearly costs are subject to a Net Present Value (NPV) calculation. Annual CM and PM cost can be modelled as follows:

- *Annual Corrective Maintenance Cost*

The costs derived from CM assume failures in the system that lead to replacements or repairs of the components. The replacement/repair cost is therefore of the form:

$$\begin{aligned} CY_{CM} &= \text{Man Hours} + \text{Spare Parts} + \text{Equipment} = \\ &= \sum_{i=1}^m \sum_{j=1}^n \lambda_{ij} \left[C_L n_L (MRT_{ij} + MLT_{CM}) + C_{Pij} + C_{Eij} \right] \end{aligned} \quad (1)$$

where λ_{ij} is the failure frequency of action i and unit j , MRT_{ij} is the Mean Repair Time, and MLT_{CM} is the Mean Logistic Time associated to corrective maintenance.

- *Annual Preventive Maintenance Cost*

The cost from PM may include the cost of inspections, condition based and periodical maintenance.

$$\begin{aligned} CY_{PM} &= \text{Man Hours} + \text{Spare Parts} + \text{Equipment} = \\ &= \sum_{i=1}^m \sum_{j=1}^n f_{ij} \left[C_L n_L (MAT_{ij} + MLT_{PM}) + C_{Pij} + C_{Eij} \right] \end{aligned} \quad (2)$$

where f_{ij} is the maintenance frequency of action i and unit j , MAT_{ij} is the Mean Action Time, and MLT_{PM} is the Mean Logistic Time associated to preventive maintenance. In both Eq. (1) and (2), C_L is the labour cost, n_L the number of workers, C_P the cost of the component, and C_E the cost of the equipment to carry out the maintenance action.

The maintenance cost figures, together with the result of the RAMS are the inputs of the parametric cost models that will implement the LCC calculation. By means of a simulation, where input parameters take a stochastic character, a stochastic prediction taking into account possible uncertainties is obtained for the LCC of the system.

3. Case study: analysis of railway switches and crossings

In this section we apply the previously described methodology to a use case, specifically to the study of costs associated to failures on switches and crossings (S&C). The data collected for this study has been provided by Trafikverket (TrV) from their failure and maintenance databases and provided for the exclusive use of the INFRAalert consortium for the railway demonstrator. The data belong to a rail corridor in Sweden under the management of TrV, called Iron Ore Line (Malmbanan), in northern Sweden. Some relevant characteristics of the data concerning the case study are: (i) two track sections are considered with a total of 260km and 61 S&C of different types (UIC60 and SJ50), (ii) data contains relevant information about the track section, position, geometric information, type of asset and year of installation, (iii) a total of 6664 records of maintenance Work Orders (WO) from 09/07/2008 to 21/03/2012 (not all of them on S&C).

Switches and crossings (S&C) are one of the most important railway subsystems, causing most train delays due to their frequent maintenance, which usually amounts at least for the 10% of the total maintenance costs [12]. The highly maintenance cost is due to several factors, namely, its complexity and degradation, and the fact that S&C need to be maintained regularly to keep high safety levels. S&C consists of three major parts: switch panel, crossing panel and middle panel (see Figure 3 and Figure 4).

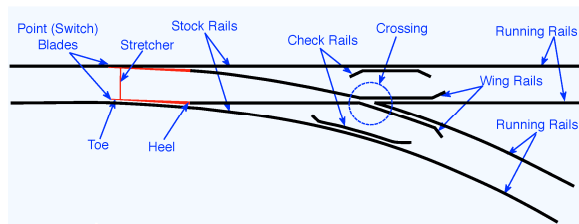


Figure 3: S&C illustration.

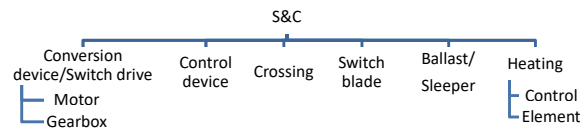


Figure 4. S&C component tree.

The first step in the analysis is the calculation of the RAMS associated to replacement WOs in the switch. It is understood that replacement here means replacement of any of the switch components, i.e. control device, crossing, heating, conversion device, etc. Therefore it is more convenient to say that the switch has been repaired instead of replaced as a whole. The repair brings the system to operation state again, and it is therefore considered that the reliability of the system does not improve substantially after the repair, being the probability of failure the same as before the failure happened. From a statistical point of view the switch is brought to an *as-bad-as-old* state. The event plot shown in Figure 5 provides a clear picture of this repairable characteristic. In this plot, each event, represented by a point in time, corresponds to a CM action associated to a switch restoration. As shown, there are assets (or units) that suffer a larger number of failures than others. This may correspond to failures in different components of the given switch. After the failure occurs, the asset is put back to operating state until another failure happens in the same or a different component.

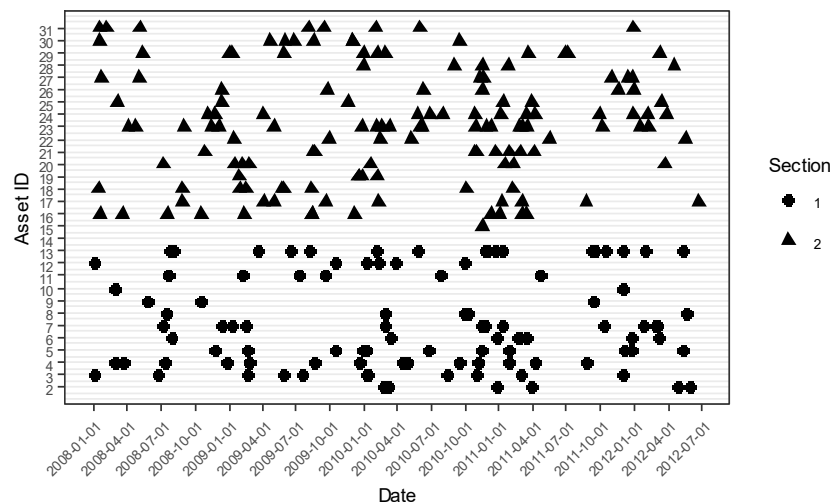


Figure 5. Event plot for replacements in S&Cs components by track section.

These types of processes are described statistically as point processes [13]. To calculate the Time-To-Failure (TTF) and Time-To-Restore (TTR) after failure, each of the different components needs to be analysed independently using probabilistic models. This separation is needed for consistency as it does not take the same time to replace a heating system than a control device for instance and also because their failure modes are different. Moreover, in our study, in order to have statistically significant results all the switches and components have been assumed to be working under identical environmental conditions. Given the available time window, this assumption allows for a larger number of failure events to be analysed. We have 85 events for control device, 45 for conversion device, 25 for crossings and 67 for heating system.

The TTF is determined by transforming the time window between replacements/failures (in days) in Figure 5 to load over the switch in Million Gross Tonnes (MGT) using the known average gross

tonnage per year in each track section. In Figure 6 the cumulative distribution of failures of units with at least five replacements is shown as a function of the cumulative load (in MGT). Reliability is measure by the Mean-Time-To-Failure (MTTF) and calculated using a 2-parameters Weibull distribution. The Weibull distribution is widely used in reliability and life data analysis thanks to its versatility and ability to model decreasing, increasing or constant failure rates (the so-called bathtub curve). The averaged MTTF in MGT per component is shown in Table 1 together with the Weibull shape and scale parameters. It is important to notice that expected useful life for this kind of systems is of the order of 20-30 years, and the time range under analysis is only 4 years. This means that the number of registered failures is low and therefore the statistics is not very good. In Figure 7 the calculated distributions of TTF, after removing outliers, are shown in form of boxplots for the different switch components.

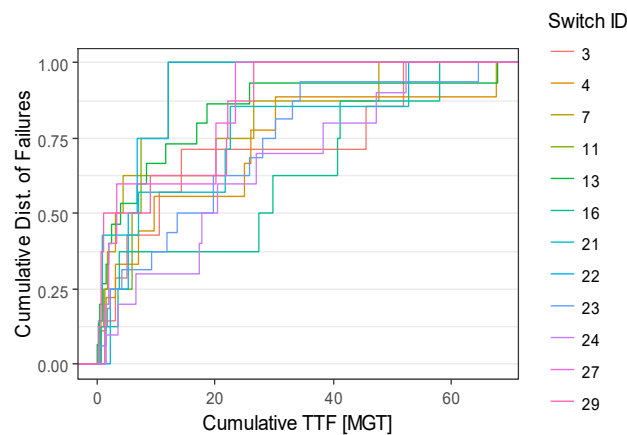


Figure 6. Cumulative distribution of failures for recurrent units.

Table 1. MTTF and MTTR for switch components with significant number of failures. Weibull and lognormal are used as models. Estimated errors are shown in parenthesis and correspond to 65% CI.

Component	Time-To-Failure (MGT)			Time-To-Restore (Hours)		
	<i>Weibull parameters</i>		MTTF	<i>Log-normal parameters</i>		MTTR
	Shape	Scale		μ	σ	
Conversion Device	0.87 (14)	29 (4)	31 (6)	0.393 (15)	0.654 (17)	1.8 (1.2)
Control Device	0.88 (10)	13.8 (1.2)	15 (4)	0.29 (1)	0.81 (1)	1.9 (1.3)
Heating	0.71 (9)	19.5 (2.1)	25 (6)	0.282 (15)	0.91 (1)	2.0 (1.5)
Crossing	1.21 (25)	43 (7)	40 (6)	1.42 (12)	0.99 (6)	7 (3)

The database does not provide information about repair times and therefore maintainability is measured by Mean-Time-To-Restore (MTTR). It is possible to present figures for the time spent in the different maintenance activities, as the maintenance crew report on this information. Unfortunately, repair and logistic times cannot be disentangled, and therefore in our model, the MTTR will include the whole restoration time. It is also important to notice that maintenance crew do not report whether the action is partly executed and finished on a later occasion, which may result in non-representative restoration times in some cases. In fact, although most of the restoration times are reasonable figures, a few of them present unusually large times. In order to solve this problem, only maintenance activities with less than 16 man-hours are kept, and unusual long times are considered as outliers and filtered out from the database. The distributions of TTR per switch component are shown in Figure 8 after the outliers have been removed. The calculation of MTTR has been carried out using a log-normal

distribution. This assumption is commonly used for restoration times because of the following reason: it is natural to assume that restoration rate increases at least in a first phase. When the restoration has been going on for a rather long time, this indicates serious problems, for example no spare parts available on the site. Then, it is natural to assume that the restoration rate is decreasing after a certain period of time. This process is well described using a log-normal distribution. The averaged MTTR in hours per component is shown in Table 1 together with the log-normal parameters. As can be seen, all components are restored within 8 man-hours, being crossings the ones taking the longest times.

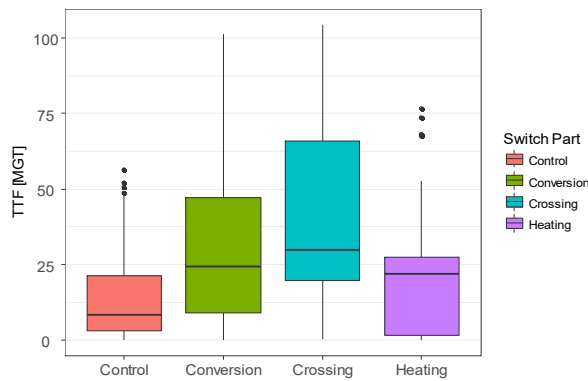


Figure 7. Tukey boxplots for component TTF.

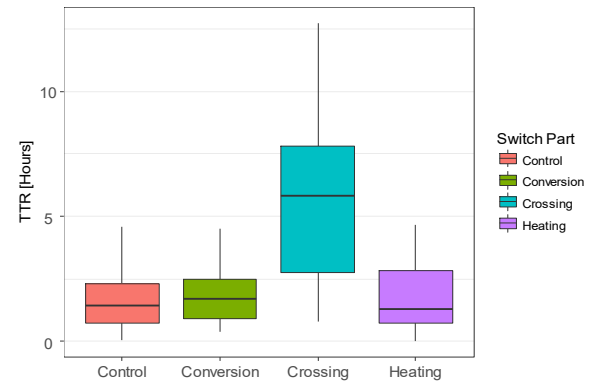


Figure 8. Tukey boxplots for component TTR.

An LCC model for the maintenance of S&C can be built by subdividing the system into a number of subsystems (as shown in the tree of Figure 4). Here we are considering only the *conversion device* (or switch drive), *control device*, *crossing* and *heating system*, because these are the most delicate components and therefore the subject of most of the failures. Within the most frequent maintenance actions for S&C are: (i) corrective or preventive: adjustment, replacement and repair, (ii) preventive: tamping, grinding and inspection.

When building the LCC model, one of the most difficult pieces of information to obtain is the cost per action. As it has been stressed, here we will focus on modelling cost for S&C restoration associated to replacement of components for which RAMS parameters are available. Generally speaking replacement cost is the sum of man-hours plus cost-of-spare-parts plus the cost-of-equipment. Depending on the information available, the model will be more precise on the determination of costs. In our case we will model replacement cost using the following equation:

$$LCC_{replace} = n_s \sum_{i=1}^K \sum_{j=1}^{N-1} \frac{1}{(1+r)^j} \frac{M}{MTTF_i} \{C_{Pi} + MTTR_i (n_{Li} C_L + C_{Ei})\} \quad (3)$$

Where, n_s is the number of switches; K the number of switch components under analysis; N the life period of the switch in years; M is the Gross Tonnage per year (in MGT); $MTTF_i$ is the Mean-Time-To-Failure for component i (in MGT); C_{Pi} is the cost of component i (in Euro); $MTTR_i$ is the Mean-Time-To-Restore of component i (in hours); n_{Li} is the number of workers needed for replacement of component i ; C_L is labour cost (in Euro/hour); and C_{Ei} is the cost of equipment for replacement of component i . For illustration purposes, the following assumptions will be made:

- The average gross tonnage per year is assumed to be $M = 20$ MGT.
- The life of the switch will be estimated to be 600 MGT ($N=24$ years).
- The discount rate is taken to be 4% ($r=0.04$).
- Average cost per component (C_P): crossing (500 €/unit), heating device (200 €/unit), control device (1000 €/unit), and conversion device / switch drive (1000 €/unit).
- The average labour cost is $C_L = 25$ €/hour.

- The number of workers will be fixed to be $n_L=3$ for the different replacements.
- The equipment cost for replacement will be fixed to $C_E=5$ €/hour for the different replacements.

Taking into account the above fixed values and the RAMS previously calculated in Table 1 we obtain the following costs per component for a switch life-cycle of 24 years: conversion device (11.605 €), control device (24.680 €), heating device (8.550 €) and crossing (5.842 €). Using the above set of parameters, the total cost per switch associated to failures that lead to replacements in these components would be around 50.700 €. The differences in cost per component can be easily visualised in the bar-plot of Figure 9.

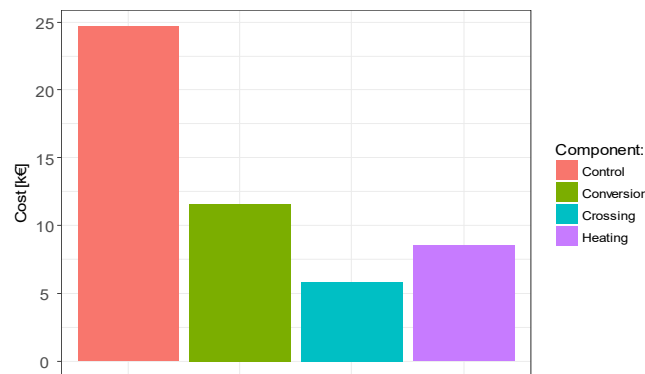


Figure 9. Replacement cost per switch component during 25 years.

Furthermore, a sensitivity analysis has been carried out in order to study how variations in cost parameters affect the total LCC-value. Figure 10 shows the percentage change in the total LCC-value for replacement when different parameters entering the LCC formula are changed a 10%. It can be seen that four parameters (C_P , M , $MTTF$ and r) affect the LCC-value significantly. Moreover, replacement equipment cost (C_E), labour cost (either number of workers, n_L , or wage, C_L), switch component costs (C_P), averaged yearly gross tonnes (the load, M), and the time to restore failures (MTTR) contribute positively to the LCC-value. On the other hand, the time between failures (MTTF) and the discount rate (r) contribute negatively to the total LCC-value. As shown in Figure 10, some values can be considered more critical concerning the preventive maintenance rate and for maintenance optimization purposes.

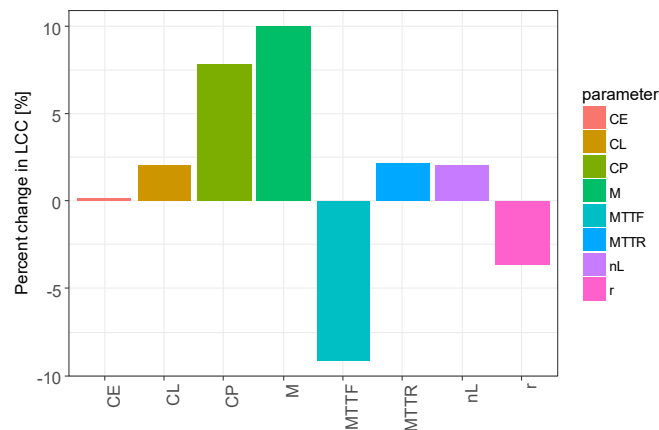


Figure 10. Sensitivity analysis of selected LCC parameters. Parameter changed a 10%.

4. Conclusions

This paper has presented a methodology for the combination of RAMS in the LCC analysis of linear transport infrastructures. The methodology has been demonstrated in a railway use case but it is also suitable for roads and, in fact, it will be applied to a road network within the H2020 INFRAALERT project [9]. The paper has focused on the analysis of repair costs of switches and crossings in a railway line that is part of one of the demonstrators of INFRAALERT. It has been shown how to use historical maintenance records to statistically characterize system failures in terms of RAMS, and how to use this information, together with individual cost figures, in LCC formulas to obtain cost estimates and cost driver's dependencies. The parameters that influence the LCC results have been identified using sensitivity analysis. This knowledge can be used to apply cost effective long-term maintenance decisions. From the results obtained in this paper it can be concluded that adequate data is crucial to obtain reliable results and that the data must be collected the right way by maintenance operators, since the quality of the reporting and registering is crucial for a good statistical analysis. Nevertheless, this methodology can set the bases for maintenance data collection standards in the railway or road sectors.

Acknowledgements

This research was carried out within the INFRAALERT project. This project has received funding from the EU Horizon 2020 research and innovation programme under grant agreement No 636496. The authors also thank Trafikverket for providing the data in the case study analysis.

References

- [1] European Committee for Standardization (CEN) 2002 Basis of structural design - Eurocode 0 (*EN-1990*)
- [2] Shift2Rail Joint Undertaking (S2R JU) 2016 *Annual work plan*
- [3] <http://ec.europa.eu/research/transport/index.cfm?pg=transport&lib=rail>.
- [4] Al-Jibouri S and Ogink G 2009 Proposed model for integrating RAMS method in the design process in construction *Architectural Engineering and Design Management* **5** pp 179–92
- [5] Asiedu Y and Gu P 1998 Product life cycle cost analysis: state of the art review *International journal of production research* **36** pp 883-908
- [6] Kumar U, Ahmadi A, Verma A K and Varde P 2015 *Current Trends in Reliability, Availability, Maintainability and Safety: An Industry Perspective* (Switzerland: Springer International Publishing)
- [7] Zoeteman A 2001 Life cycle cost analysis for managing rail infrastructure *European Journal of Transport and Infrastructure Research* **1** pp 391-413
- [8] Smith D J 2011 *Reliability, Maintainability and Risk 8th Edition: Practical Methods for Engineers including Reliability Centred Maintenance and Safety-Related Systems* (Oxford: Butterworth-Heinemann)
- [9] Infralert 2016 *INFRAALERT: Linear Infrastructure Efficiency Improvement by Automated Learning and Optimised Predictive Maintenance Techniques* (EC H2020 Programme Grant agreement No 636496)
- [10] European Committee for Electrotechnical Standardization - CENELEC 1999 Railway applications - The specification and demonstration of Reliability, Availability, Maintainability and Safety Part 1: Basic requirements and generic process (*EN 50126-1*)
- [11] International Electrotechnical Commission - IEC 2004 Dependability Management - Part 3-3: Application Guide - Life Cycle Costing (*IEC 60300-3-3*)
- [12] Trafikverket 2016 *The Swedish Transport Administration Annual Report* (Borlänge: Swedish Transport Administration) URL <http://online4.ineko.se/trafikverket/Product/Detail/44395>
- [13] Garmabaki A H S, Ahmadi A, Block J, Pham H and Kumar U 2016 A reliability decision framework for multiple repairable units *Reliability Engineering & System Safety* **150** pp78-88