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Combined RAMS and LCC analysis in railway and road transport infrastructures

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Abstract

Life-cycle cost (LCC) analysis is an assessment technique used to evaluate costs incurred during the life-cycle of a system to help in long term decision making. In railway and road transport infrastructures, costs are subject to numerous uncertainties associated to the operation and maintenance phase. By integrating in the LCC the stochastic nature of failure using Reliability, Maintainability, Availability and Safety (RAMS) analyses, maintenance costs can be more reliably estimated. This paper presents an innovative approach for a combined RAMS&LCC methodology for linear transport infrastructures which has been developed under the H2020 project INFRALERT. Results of the application of such methodology in two real use cases are shown, one for rail and another one for road. The use cases show how the approach is implemented in practice.

Keywords: intelligent maintenance, linear transport infrastructure, RAMS, Life-Cycle Cost, maintenance.

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Nomenclature

RAMS	Reliability, availability, maintainability and safety
LCC	Life-cycle cost
IM	Infrastructure Manager
NPV	Net Present Value
TRV	Trafikverket
IP	Infraestruturas de Portugal
S&C	Switches and crossings
WO	Work Order
CBS	Cost Breakdown Structure
CM	Corrective Maintenance
PM	Preventive Maintenance
TTF	Time-To-Failure
TTR	Time-To-Restoration
MTTF	Mean-Time-To-Failure
MTTR	Mean-Time-To-Repair

1. Introduction

The long technical lifetime of railway and road infrastructure networks (of the order of 40 to 120 years, see e.g. European Committee for Standardization (2002)) and the fact that these complex systems are subject to very different types of failures call for the need of a well define exploitation and maintenance plan in order to control unexpected expenses. Each decision must consider the usage of their assets for at least 40 years into the future even though long term plans, nowadays, are of the order of 10 years. The origin of this complexity lies in the fact that these systems are a mixture of multiple components of different age and status that must work together under a wide range of conditions. On the other hand, replacement and repair of components in these systems is a continuous and on-going process that might generate huge expenses if they are not carefully executed.

The health of transport systems has strong implications in economic growth and social development since they provide mobility and ensure access to markets and resources (see European Environment Agency (2016)). Therefore there is a clear pressure for increasing traffic volumes which in turn leads to a higher utilization of the existing infrastructures and hence to more severe degradation. 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 by 30% and at the same time increasing safety (decreasing fatalities) by a 75% have put strong demands on operational and maintenance optimization (see Shift2Rail (2016) and European Commission (2017)).

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 must keep infrastructure highly available so that the railway undertakings can deliver a highly quality service at affordable price to the end users.

The analysis RAMS (acronym of Reliability, Availability, Maintainability and Safety) is used to evaluate system performance subjected to failure modes, as well as the need of maintenance of the infrastructure by analysing historical corrective and preventive maintenance data. They are a central element in many engineering areas, especially for controlled environments, ranging from manufacturing, automotive, electrical engineering to the nuclear and space industry. Recently, the number of requirements specified for reliability and safety of European rail engineering is rising. Accreditation bodies are increasingly asking for detailed proof of quality in the form of RAMS analyses and these are becoming an essential tool in the railway industry nowadays (see Al-Jibouri et al. (2009) and Kumar et al. (2015)). The inherent problem of transport infrastructures is the difficulty of implementing monitoring technologies, especially in roads, which implies to make use of maintenance work orders.

Life-Cycle Cost (LCC) analysis has been used since the late 60's and it has its roots in the American defence industry Kawauchi et al. (1999). It is an economic technique for decision-making and used to estimate quantitatively the total cost of acquisition, ownership and disposal of a product (see International Electrotechnical Commission (2004), Asiedu et al. (1998)). In Combination with RAMS, these techniques can be used to evaluate the performance of the network in operational and economic terms, and to make economically viable decisions.

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 (Kumar et al. (2015), Zoeteman (2001)). 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 (Smith (2011)) 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.

In this paper we describe a general approach that combines RAMS and LCC applicable to linear infrastructures. The methodology is demonstrated in two use cases, one for rail and another one for road, which are part of the demonstrators in the on-going H2020 project INFRALERT (2016).

2. RAMS and LCC

2.1. RAMS models

RAMS is a measure of the technical performance of a system. Poor RAMS performance will result into unnecessarily high LCC due to excessive operation and maintenance cost. On the other hand, very high RAMS performance can lead to high design cost if it is not optimally determined. The elements of RAMS include: Reliability, Availability, Maintainability and Safety of the system under study. The data required for RAMS analysis are extracted from operational and maintenance data and the results show how the system performs in terms of failures and maintenance activities. Some relevant RAMS indicators are (European Committee for Electrotechnical Standardization (1999)): reliability/maintainability functions, failure/maintenance rates or the mean times to failure/repair/restoration, etc.

The statistical models and the set of RAMS parameters that can be calculated depend strongly on the level of detail of the available data. The methodology developed here is general and applicable to any type of linear infrastructure system. Commonly used methodologies for RAMS analysis include Failure Modes, Effects and Criticality Analysis (FMECA), Fault Tree Analysis (FTA), Hazard Operability Study (HAZOP) or Preliminary Hazard Analysis (PHA). In this paper we adopt Survival Analysis as the foundations of our models Meeker et al. (1998), Rausand et al. (2004). These RAMS methodologies can be very specialized and sophisticated depending on how many factors one is willing to consider, Garmabaki et al. (2016). Basically reliability and maintainability are modelled and then availability is calculated as the quotient of the mean-up-time (mean time available) to the total operation time.

There are several approaches for single-parameter reliability and maintainability modelling, among them are: Point Processes (Homogenous Poisson Process -constant failure/repair rates and Non Homogenous Poisson Process, -modelling the time dependency of these rates) or using probability distributions to model the reliability or maintainability performances. Here, for the sake of simplicity we will adopt probability distributions.

Our methodology depends on what is known as a failure event. Failure events can be described by an ID for the asset which experiences the event, an associated time of the event, an action associated to the event and a set of additional features incorporating information regarding asset type, asset locations, operational conditions or weather information. These features can eventually define different scenarios and are integrated in the model in the form of covariates through Cox Proportional Hazard models, Meeker et al. (1998), Rausand et al. (2004). Although in this paper we do not study the effect of covariates due to lack of additional explanatory variables, they may provide valuable information in decision making.

The definition of *event* will depend on the RAMS parameter being calculated: for the calculation of reliability or failure rates, an *event* is an action at time *t* that terminates the ability of an asset to carry out specific function; for the calculation of maintainability or repair rate, an *event* is an action at time *t* that puts an asset back in operational state after a failure; finally for the calculation of Safety, an event is an action at time *t* associated with safety issues. For example, in the left panel (a) of Figure 1 each dot represents events related to failure and maintenance intervention on a typical asset. A failure event can be decomposed further in its different maintenance stages as it has been displayed in the right panel (b) of Figure 1.

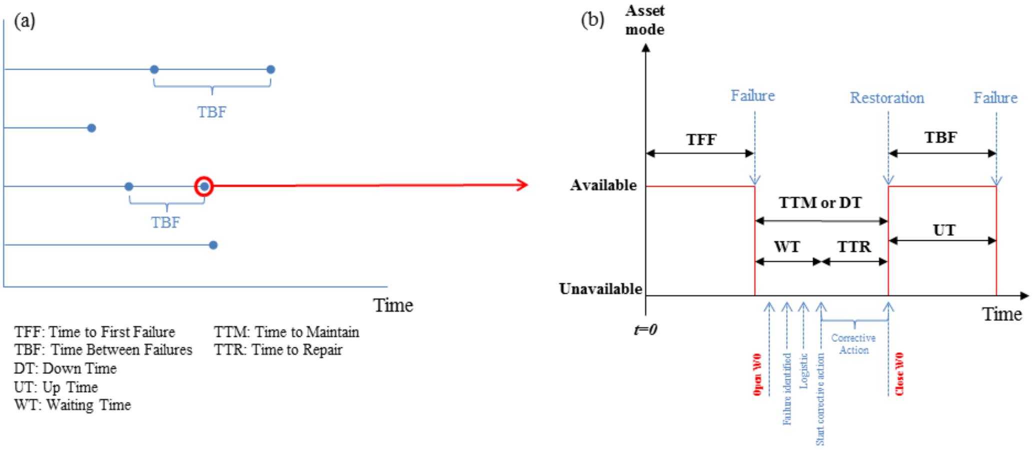

Figure 1: Failure event characterisation. (a) Events plot. (b) Events and maintenance time description.

2.2. LCC analysis

The life cycle of an asset can be subdivided into six phases according to the IEC 60300-3-3 standard. 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.

In the above framework, acquisition and termination costs are not subject to ownership time variations, and can be considered as fixed cost parameters. Hence, operation conditions and maintenance policies are the two important variables which mainly have effect on the ownership costs. The combined RAMS & LCC analysis described here focuses exclusively on the ownership LCC because this phase is the most sensitive to variations and therefore needs to be optimised. Cost elements identification that considerably influence the total LCC of the system is the first step in the LCC analysis. According to the standard, 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 structure heavily depends on the system under study and in many cases, it is difficult to define a standard cost structure for LCC breakdown analysis. Therefore, the CBS has to be tailored to the specific system or subsystem under study. Figure 3 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. In this paper only maintenance costs are considered. Maintenance actions can be preventive or corrective. Corrective Maintenance (CM) is assumed to be acute intervention due to unexpected failure 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:

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

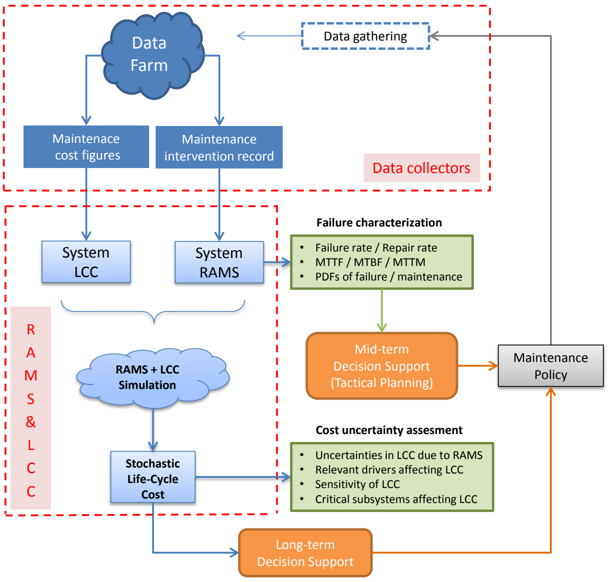

Figure 2: Combined RAMS&LCC workflow

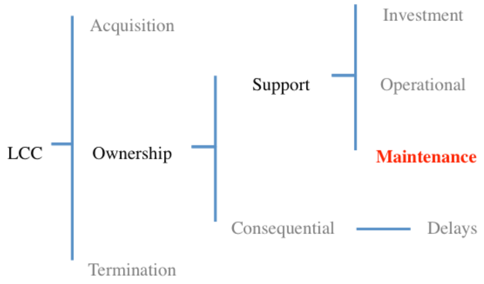

Figure 3: Cost Breakdown Structure

- *Annual Preventive Maintenance Cost:* The cost from PM may include the cost of inspections, condition based and periodical maintenance.

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

In the previous formulas λ_{ij} is the failure frequency for action i and unit j, MRT_{ij} is the Mean Repair Time, and MLT_{CM} is the Mean Logistic Time associated to corrective maintenance, f_{ij} is the maintenance frequency for 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 (in case of replacements), and C_E the cost of the equipment to carry out the intervention.

2.3. Cost uncertainty estimation using stochastic RAMS

The combined RAMS and LCC methodology will allow estimating cost uncertainties due to statistical RAMS. The methodology is outlined in Figure 2 and rests on two basic pillars: *statistical analysis* of maintenance interventions and *accounting information* to estimate costs. Figure 2 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. Moreover, 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 from the system performance is obtained for the LCC.

In the next sections we apply the previously described methodology in two specific use cases, one for rail and one for road.

3. Applications to transport infrastructures

The above proposed LCC have been demonstrated using two real case studies, railway infrastructure from Trafikveket and road infrastructure from Infraestrutura de Portugal (IP). The results of these case studies and analysis have been provided in the subsequent sections.

3.1. Railways

In this use case a reliability analysis of switches and crossings (S&C) is carried out. The data collected for this study has been provided by Trafikverket (TRV) from their failure and maintenance databases and constitutes a part of the INFRALERT railway demonstrator. The data is extracted from Iron Ore Line (Malmbanan), in northern part of Sweden. Some relevant characteristics of the data concerning the case study are: (i) two track sections are considered with a total of 260 km and 61 S&C of different types (ii) data contains relevant information about the track section, position, geometric information, type of asset and year of installation, (iii) a total of 1389 maintenance Work Orders (WO) records from 09/07/2008 to 21/03/2012.

Our interest on S&C here lies in the fact that it is one of the most critical railway subsystems, causing most train delays due to their frequent maintenance, which usually amounts for at least 10% of the total maintenance costs, Trafikverket (2016). The high 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.

The first step in our analysis is the calculation of the RAMS associated to different types of interventions carried out on the switch and recorded in the WOs. The following types are analysed: adjustment (T1), cleaning (T2), clean-up (T3), inspection (T4), lubrication (T5), provisionally repaired (T6), repair (T7), replacement (T8) and restoration (T9). The analysis is carried out at component level with the aim of constructing a *microscopic* cost model later.

From a statistical point of view, the switch is restored to an as-bad-as-old state, i.e. functioning state without substantial improvement after the intervention. Figure 4 shows the event plot for all the S&C analysed. In this plot, each event, represented by a point in time, corresponds to a CM action. The different colours indicate different types of interventions. This may correspond to failures in different components of the given switch. As shown, there are units that suffer a larger number of failures than others. After the failure occurs, the asset is put back to operating state until another failure happens in the same or a different component.

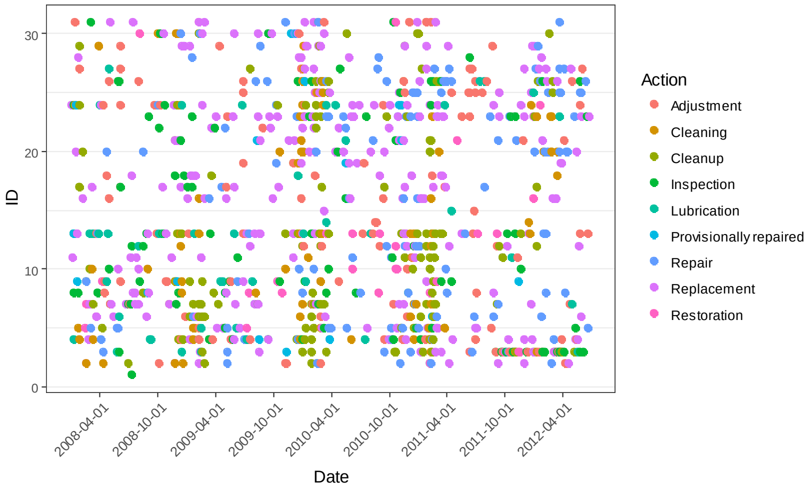

Figure 4: Event plot for S&C interventions

In order to have meaningful results the Time-To-Failure (TTF) and Time-To-Restore (TTR) associated to the different interventions are analysed independently for each component using probabilistic models. In this study, 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. The TTF is determined by transforming the time window between interventions (in days) in Figure 4 to load over the switch in Million Gross Tonnes (MGT) using the reported average gross tonnage per year in each track section. The reliability of the components is modelled using a 2-parameters Weibull distribution and then and the Mean-Time-To-Failure (MTTF) is estimated. The Weibull distribution is selected because it 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 MTTF in MGT per component and intervention is shown in Table

1. It is important to remark that expected useful life for this kind of systems is of the order of 20-40 years, and the time range under analysis is only 4 years. This means that the number of registered failures is low and therefore it is not expected to have a good statistic.

Table 1. MTTF and MTTR for switch components with significant number of failures using Weibull and lognormal distributions respectively. Estimated uncertainties are shown in parenthesis and these correspond to 65% CI. MTTF is expressed in MGT and MTTR in hours. Interventions are as follows: Adjustment (T1); Cleaning (T2); Clean-up (T3); Inspection (T4); Lubrication (T5); Provisionally repaired (T6); Repair (T7); Replacement (T8); Restoration (T9). Empty cells mean no data available.

Mean-Time-To-Failure: MTTF (in MGT)

Component	*Parameter*	T1	T2	T3	T4	T5	T6	T7	T8	T9
Conversion Device	Shape	1.03	0.83	1.9	0.68	0.8		3	0.87	
	Scale	30	23	52	29	28		47	29	
	MTTF	**29(5)**	**25(6)**	**46(5)**	**38(8)**	**31(6)**		**42(4)**	**31(6)**	
Control Device	Shape	0.88			2			2.5	0.88	1.9
	Scale	27			19			38	13.8	65
	MTTF	**29(6)**			**17(3)**			**34(4)**	**15(4)**	**57(6)**
Heating	Shape	0.55			11		0.8	1.4	0.71	
	Scale	32			69		42	38	20	
	MTTF	**55(10)**			**66(3)**		**48(8)**	**35(5)**	**25(6)**	
Crossing	Shape				0.5	0.7		0.68	1.2	
	Scale				26	17		22	43	
	MTTF				**51(11)**	**23(6)**		**28 (7)**	**40(6)**	
Blade	Shape			1.6		1.8		2.6		
	Scale			75		25		48		
	MTTF			**67(7)**		**22(4)**		**43(4)**		

Mean-Time-To-Restoration (hours)

Component	*Parameter*	T1	T2	T3	T4	T5	T6	T7	T8	T9
Conversion Device	μ	-0.019	-0.718	-1.50	-0.62	-0.56		0.5	0.393	
	σ	0.740	0.783	0.4	0.98	0.84		1.63	0.65	
	MTTR	**1.3(1.1)**	**0.7(8)**	**0.2(3)**	**0.9(1.1)**	**0.8(9)**		**6(5)**	**1.8(1.2)**	
Control Device	μ	-0.117			-1.11			0.0 1.14	0.291	-0.69
	σ	0.740			0.6			**1.9(1.8)**	0.808	0.61
	MTTR	**1(1)**			**0.4(5)**				**1.9(1.3)**	**0.6(6)**
Heating	μ	-0.6			-0.58		-0.4	0.2	0.28	
	σ	1.21			0.4		1.08	1.20	0.91	
	MTTR	**1.1(1.4)**			**0.6(5)**		**1.2(1.3)**	**3(2)**	**2.0(1.5)**	
Crossing	μ				-0.21	-0.66		1.20	1.42	
	σ				0.4	0.65		0.67	0.99	
	MTTR				**0.9(6)**	**0.6(7)**		**4(2)**	**7(3)**	
Blade	μ			-0.60		-0.95		0.21		
	σ			0.46		0.86		0.75		
	MTTR			**0.6(5)**		**0.6(8)**		**1.6(1.2)**		

The database does not provide information about repair times and therefore maintainability is measured by Mean-Time-To-Restoration (MTTR). This parameter represents the time spent in the different maintenance activities. 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, most of the restoration times are reasonable figures, however, a few of them present unusually large times. This is due to low priority of the intervention and immobilising nature of the failure. 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 calculation of MTTR has been carried out using a log-normal distribution. This assumption is used because it is common in practice that restoration time is consistent except for few occasions where the time is longer than usual. The averaged MTTR in hours per component for the different activities is shown in Table 1 together with the log-normal parameters. As can be seen, all components are restored within 8 calendar-hours.

The LCC model for the maintenance of S&C is built according to the different activities carries out to correct component failures. Here we are considering only the conversion device (or switch drive), control device, blade, crossing and heating system, because these are the most critical components and therefore the subject of most of the failures. When building the LCC model, one of the most difficult pieces of information to obtain is the cost per action. Depending on the information available, the model will be more precise on the determination of costs. In this study, cost is modelled using the following equation:

$$LCC = n_s \sum_{k=1}^{periods} \sum_{i=1}^{actions} \sum_{j=1}^{components} \frac{1}{(1+r)^k} \frac{M}{MTTF_{ij}} \left\{ C_{P_j} + MTTR_{ij} \left(n_{L_i} C_L + C_{E_i} \right) \right\} \tag{3}$$

Where, n_s is the number of switches; the sums run over type of intervention, type of component and number of periods (in years); M is the Gross Tonnage per year (in MGT); $MTTF_{ij}$ is the Mean-Time-To-Failure of component j (in MGT) and a failure mode associated to intervention i; C_P is the cost of the component (in monetary units) in case of replacements; $MTTR_{ij}$ is the Mean-Time-To-Restore of component j (in hours) and a failure mode associated to intervention i; n_L is the number of workers needed for a given intervention; C_L is labour cost (in monetary units/hour); and C_E is the cost of equipment needed to carried out the intervention.

For illustration purposes Figure 5 shows the evolution of the cost incurred by the different activities in 24-time periods. 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 time-periods*); the discount rate is taken to be 4% ($r=0.04$); average cost per component (C_P) has been set to 10000 monetary units (m.u.); the average labour cost is $C_L = 1$ *m.u./hour*; the number of workers is fixed to $n_L=3$ for all the interventions; and the equipment cost is also fixed to $C_E=5$ *m.u./hour* for all the interventions.

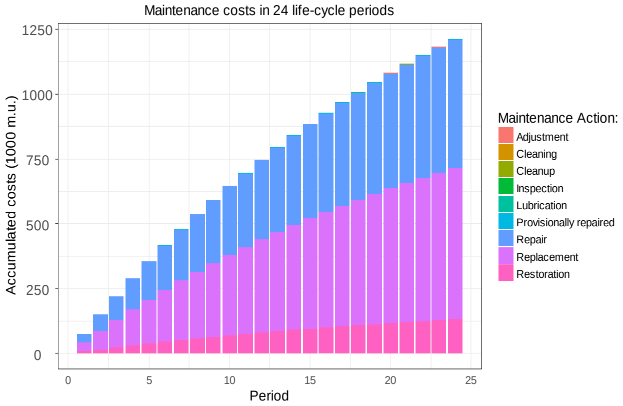

Figure 5: Cost evolution according to NPV calculation in 24 periods

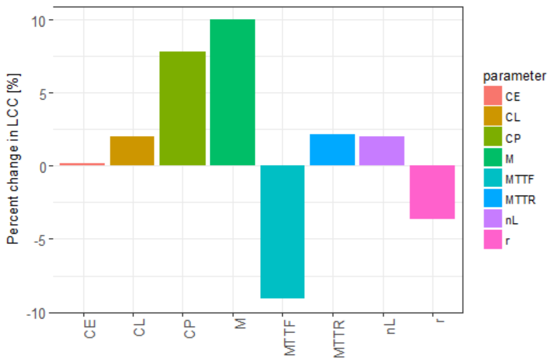

Figure 6. Sensitivity analysis for replacement costs.

Taking into account the above assumptions and the RAMS previously calculated in Table 1 an LCC calculation has been carried out for a switch life-cycle of 24 years. As can be seen in Figure 5 *replacement* and *repair* account for the highest costs in our system. This is so because these actions entail expenses due to new materials. Furthermore, a sensitivity analysis has been carried out in order to study how variations in cost parameters affect the total LCC-value for replacements. Figure 6 shows the percentage change in the total LCC-value for replacement when different parameters in the LCC formula are changed by 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 6, some LCC parameters are more critical than others for maintenance optimization purposes.

3.2. Road

Road has been considered as one of the use cases in INFRALERT. The data belongs to 539 km of roads in the Coimbra region under Infraestruturas de Portugal (IP) jurisdiction. It includes a rich variety of road types (principal, national, regional, etc.). All the available data is based on the IP Pavement Management System (SGPav) which stores information of major or routine maintenance activities. Major maintenance includes relevant works in terms of cost, length and complexity while routine maintenance includes smaller scale and lower complexity works. The network selected for the use case includes sections of an average length of 6.6 km, connecting 87 nodes.

In this use case the focus will be on *pavement* because an inventory of pavement interventions, maintenance and rehabilitation works has been provided. The road network is divided into sections of different lengths (as short as 100 meters and as long as 25 km). These sections start and end at nodes that usually are at road crossings. For the RAMS analysis these sections have been divided into homogeneous sub-sections according to interventions that were done over the years. A total of 8986 interventions have been registered covering a long time period from 1933 to 2016. Of all these events the most interesting ones are those from 1980, a time in which the Portuguese administration adopted newer techniques and materials with the subsequent evolvement of the whole road network.

The most relevant road maintenance activities as registered in the database for pavement interventions are shown in Table 2 together with the nomenclature used in this paper. Interventions have been gathered in types T2 to T5 according to their magnitude. With this grouping no distinction among activities performed with different materials (bitumen, grade of aggregates, etc.) is made. In fact, this grouping makes sense because the selection of a given material depends on factors such as weather, availability, budget, design decisions, etc. The proportion of activities for our use case is as follows: T2 (13.6 %): surface treatment; T3 (13.2 %): thin asphalt surfacing; T3.1 (41 %): surface layer milling and fill; T4 (20 %): structural overlay; T5 (10 %): pavement (re)construction.

Table 2. Maintenance activities on pavement

Intervention	*Type*	*Description*
RSdTS	T2	Surface treatment (double surface dressing)
MBFdTS	T2	Surface treatment (double micro-surfacing)
MBABBAREFPAV	T4	Pavement strengthening (open-graded rubberized asphalt concrete)
AC10surfPAV	T3	Thin asphalt surfacing with AC10
AC14surfPAV	T3	Thin asphalt surfacing with AC14
AC10surfREFPAV	T4	Pavement strengthening with AC10
AC14surfREFPAV	T4	Pavement strengthening with AC14
AC14surfFRESAG	T3.1	Profile milling and fill with AC14
AC14surfPAVNOVO	T5	Pavement (re) construction with AC14

The failure event plot corresponding to the interventions carried out in pavement from 1980 to 2016 is show in Figure 7. By visual analysis it is clear that most of the interventions during the last ten years correspond to T2 and T3.1 while a great road re-construction program (T5) started in the 80's in Portugal.

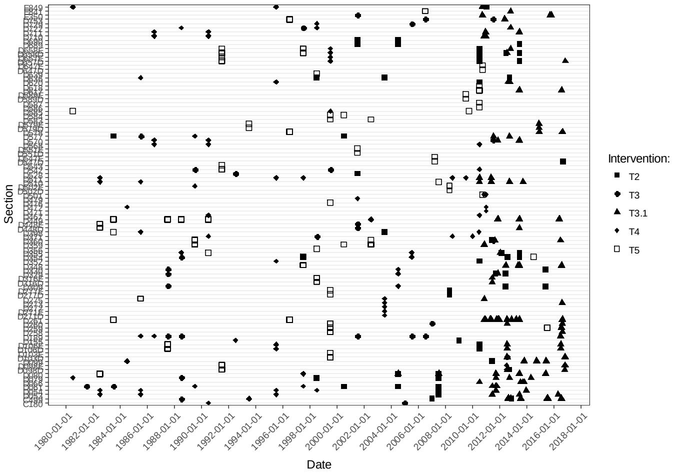

Figure 7: Pavement intervention events

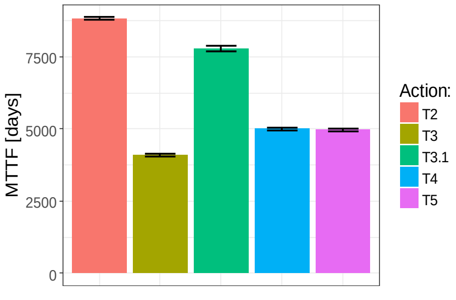

Figure 8: Pavement MTTF by failure mode

It is important to remark that each one of these event points in Figure 7 do not correspond to isolated interventions in a given section but to a grouping of interventions carried out in different sub-sections of the section. This is exemplified in Figure 9 for the case of section D570 which was intervened on 2013/06/15. This day several T3.1 works were carried out in different parts of the road. For such purpose, the sections have been divided into homogeneous subsections so that RAMS parameters can be more reliably calculated.

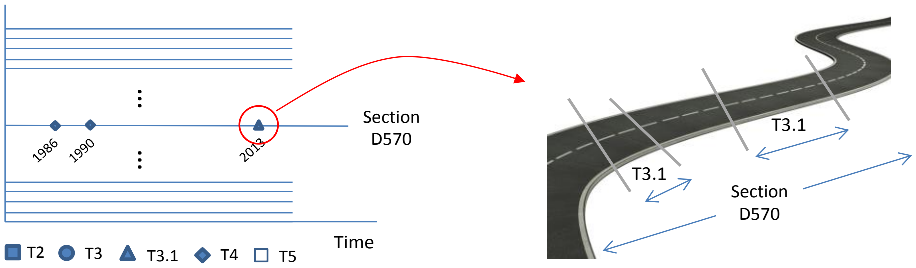

Figure 9: Detail on intervention of sections

Figure 8 shows a box plot with the results of the calculation of the MTTF for the road system using the aforementioned procedure, i.e., subdividing road sections into homogeneous subsections. A 2-parameters Weibull distribution has been used to fit the data. Error bars in the plot indicate statistical variations around mean values. As we can see our calculation is quite accurate in determining this parameter.

4. Conclusions

This paper has presented a methodology that combines RAMS and LCC analyses in linear transport infrastructures. The methodology has been demonstrated in two real use cases, in railway and road, focusing on the analysis of maintenance costs associated to interventions on switches and crossings and pavement. These use cases are part of the INFRALERT project demonstrators. It has been shown that RAMS can be used together with individual cost figures, in LCC formulas to obtain stochastic cost estimates and cost driver's dependencies. This knowledge can be used in cost effective long-term decisions. Adequate data, collected in the right way, and quality of reporting is crucial to obtain reliable results, which can set the bases for maintenance data collection in these types of infrastructures.

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References

European Committee for Standardization (CEN) 2002 Basis of structural design Eurocode 0 (EN-1990).
European Environment Agency. Freight transport demand, EEA, Copenhagen, 2016.
Shift2Rail Joint Undertaking (S2R JU) 2016 Annual work plan (Brussels).
European Commission (EC) 2017 Research & Innovation URL [accessed 30/01/2017] http://ec.europa.eu/research/transport/index.cfm?pg=transport&lib=rail.
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.
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).
Kawauchi, Y; Rausand, M. Life-Cycle Cost (LCC) Analysis in Oil and Chemical Process Industries, 1999, Chiba.
International Electrotechnical Commission. Dependability Management - Part 3-3: Application Guide - Life Cicle Costing. 2004, Geneva. IEC 60300-3-3.
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.
Zoeteman A 2001 Life cycle cost analysis for managing rail infrastructure European Journal of Transport and Infrastructure Research 1 pp 391-413.
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).
INFRALERT, 2016. INFRALERT: Linear Infrastructure Efficiency Improvement by Automated Learning and Optimised Predictive Maintenance Techniques. H2020 Programme. European Commission. Research Directorate (Grant agreement No 636496). http:infralert.eu.
European Committee for Electrotechnical Standardization (CENELEC) 1999 Railway applications - The specification and demonstration of Reliability, Availability, Maintainability and Safety (RAMS) Part 1: Basic requirements and generic process (EN 50126-1).
Meeker W. Q. and Escobar L. A., Statistical Methods for Reliability Data, New York: John Wiley & Sons, 1998.
Rausand M. and Hoyland A., System reliability theory: models, statistical methods, and applications, John Wiley & Sons, 2004.
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
Trafikverket 2016 The Swedish Transport Administration Annual Report (Borlänge: Swedish Transport Administration) URL [accessed 20/09/2016] http://online4.ineko.se/trafikverket/Product/Detail/44395