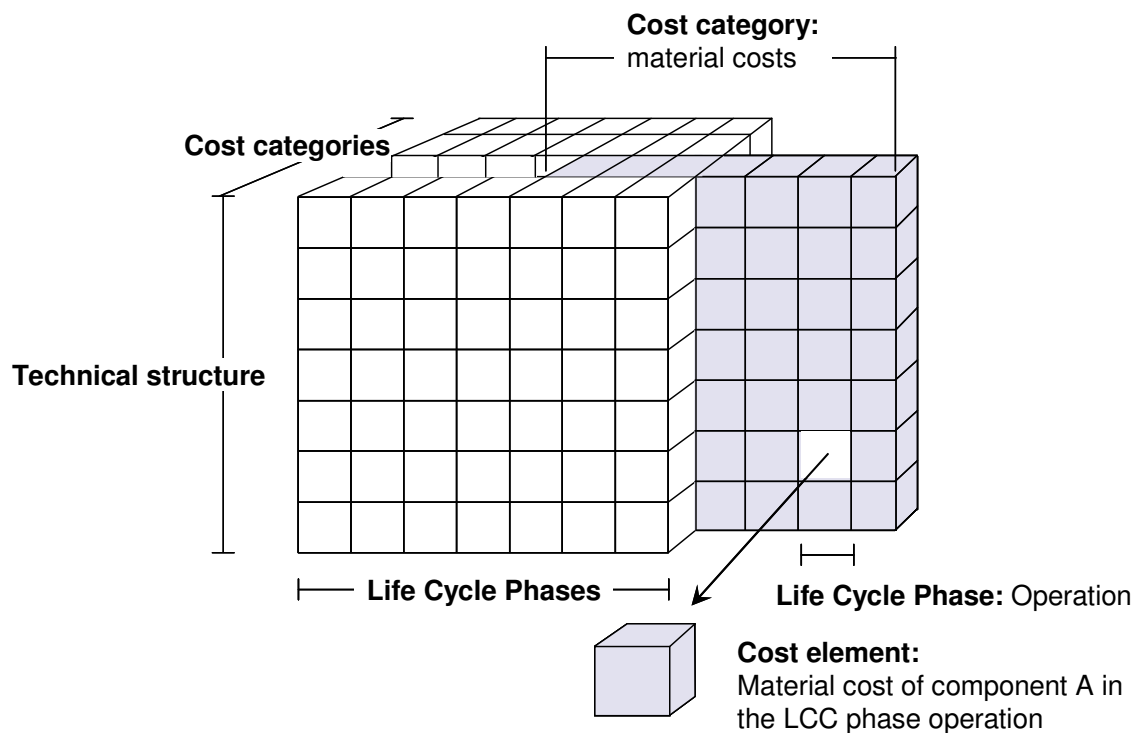


Guideline for LCC and RAMS Analysis



INNOTRACK GUIDELINE

For your notes

Table of Contents

CONTRIBUTIONS	5
GLOSSARY	6
TABLE OF FIGURES	7
1. EXECUTIVE SUMMARY	8
2. INTRODUCTION AND CURRENT STATE-OF-THE-ART	9
2.1. BACKGROUND.....	9
2.2. STRUCTURE OF THE GUIDELINE.....	9
2.3. OBJECTIVES.....	10
2.3.1. <i>Why and when to use RAMS and LCC?</i>	10
2.4. OPTIMISATION STRATEGIES.....	13
3. PRINCIPLES OF RAMS AND LCC ANALYSIS	13
3.1. COMMON DEFINITION OF TERMINOLOGIES	13
3.2. DEFINITION OF LCC-METHODOLOGY AND RAMS-TECHNOLOGY	17
3.2.1. <i>LCC Methodology</i>	19
3.2.2. <i>LCC Cost elements</i>	20
3.2.3. <i>Discounted cash flow or present value method</i>	22
3.2.4. <i>Discount rate and time horizon</i>	24
3.2.5. <i>Documentation of input data and boundary conditions</i>	29
3.2.6. <i>Processing and determination of LCC data</i>	32
3.2.7. <i>Increasing load</i>	34
3.2.8. <i>Uncertainty of parameters – sensitivity analysis</i>	35
3.2.9. <i>Probabilistic approach - Monte-Carlo simulation</i>	36
3.2.10. <i>RAMS Technology</i>	39
3.2.11. <i>V-Model according EN 50126</i>	40
3.3. DESCRIPTION OF THE ECONOMIC BENEFITS FROM RAMS AND LCC ANALYSIS.....	47
3.4. RELATION BETWEEN LCC AND RAMS	51
4. RAMS AND LCC ANALYSIS.....	53
4.1. NECESSITY AND CRITERIA FOR RAMS & LCC ANALYSIS.....	53
4.2. DESCRIPTION OF THE SYSTEM AND BOUNDARY CONDITIONS.....	53
4.3. INVESTIGATION OF DIFFERENT VARIANTS.....	55
4.4. DEFINITION AND APPROVAL OF RAMS PARAMETERS AND SPECIFICATIONS	57
4.5. KEY VALUES FOR ANALYSIS AND MINIMUM QUALITY OF DATA	60
4.5.1. <i>Data sources</i>	61
4.6. R, A, M, S ANALYSIS	63
4.6.1. <i>Process description RA, M, S, LCC, SCBA</i>	64
4.6.2. <i>Differentiation of projects</i>	66
4.6.3. <i>Reliability and Availability analysis - operational reliability analysis</i>	67
4.6.4. <i>Maintainability analysis</i>	70
4.6.5. <i>Safety analysis</i>	73
4.7. LCC ANALYSIS	75
4.8. COMBINED RAMS AND LCC ANALYSIS.....	77
4.9. SOCIAL COST BENEFIT ANALYSIS (SCBA)	79
4.10. REFERENCE TO THE FIXED RAMS PARAMETER OR SPECIFICATIONS	82
5. GENERAL ANALYTIC METHODS AND TOOLS.....	85
5.1. ANALYTIC METHODS	85
5.1.1. <i>Root cause analysis</i>	87

5.1.2.	<i>Failure Mode and Effects Analysis (FMEA)</i>	87
5.1.3.	<i>Failure Mode, Effects and Criticality Analysis (FMECA)</i>	87
5.1.4.	<i>Fault Tree Analysis (FTA)</i>	90
5.1.5.	<i>Event Tree Analysis (ETA)</i>	92
5.1.6.	<i>Hazard and Operability Study (HAZOP)</i>	92
5.1.7.	<i>Preliminary Hazard Analysis (PHA)</i>	93
5.1.8.	<i>Delphi Technique</i>	93
5.2.	TOOLS FOR TECHNICAL ASSESSMENT.....	93
5.3.	TOOLS FOR ECONOMICAL ASSESSMENT	94
6.	COMPILATION OF RESULTS	95
7.	OPERATIONAL PHASE AND IMPLEMENTATION	96
7.1.	FEEDBACK FROM OPERATIONAL SITE BACK TO PLANNING/CONSTRUCTION	97
7.2.	VALIDATION OF RAMS AND LCC CALCULATIONS.....	99
7.3.	MONITORING OF THE ANALYSIS.....	100
ANNEX I	EXAMPLES	102
	LEVEL CROSSING OR UNDERPASS?	102
	STANDARD STEEL GRADE VS. HEAT TREATED RAILS?.....	107
ANNEX II	QUESTIONS PER PROJECT PHASE PER RAMS / LCC ANALYSIS	112
ANNEX III	REFERENCES	114
	PUBLICATIONS AND BOOKS	114
	EN STANDARDS.....	114
	PUBLIC DELIVERABLES OF INNOTrack.....	115
	WEBSITES	115

Contributions

Main contributors are

- Chapter1: Burchard Ripke, Deutsche Bahn AG
(burchard.ripke@deutschebahn.com)
- Chapter 2: Burchard Ripke, Deutsche Bahn AG
(burchard.ripke@deutschebahn.com)
- Chapter 3: Wali Nawabi, Deutsche Bahn AG (wali.nawabi@deutschebahn.com)
- Chapter 4: Anton Lamper, ProRail (anton.lamper@prorail.nl)
Ulla Juntti, Banverket (ulla.juntti@banverket.se)
Jonathan Paragreen, Network Rail
(jonathan.paragreen@networkrail.co.uk)
Burchard Ripke, Deutsche Bahn AG
(burchard.ripke@deutschebahn.com)
- Chapter 5: Ulla Juntti, Banverket (ulla.juntti@banverket.se)
Burchard Ripke, Deutsche Bahn AG
(burchard.ripke@deutschebahn.com)
- Chapter 6: Anton Lamper, ProRail (anton.lamper@prorail.nl)
- Chapter:7 Jonathan Paragreen, Network Rail
(jonathan.paragreen@networkrail.co.uk)
Wali Nawabi, Deutsche Bahn AG (wali.nawabi@deutschebahn.com)

Glossary

CBS	Cost Breakdown Structure
EAC	Equivalent Annual Cost
IM	Infrastructure Manager
BV	Banverket
DB	Deutsche Bahn
NR	Network Rail
IRR	Internal Rate of Return
KPI	Key Performance Indicator
LCC	Life Cycle Cost / Life Cycle Costing
LCCA	Life Cycle Cost Analysis
NPV	Net Present Value
PBS	Product Breakdown Structure
PDF	Probability Density Function
PI	Profitability Index
RAMS	Reliability, Availability, Maintainability and Safety
RA	Operation Reliability
ROI	Return on Investment
SCBA	Social Cost and Benefit Analysis
S&C	Switches and Crossings
TPV	Total Present Value
WBS	Work Breakdown Structure
R&D	Research and Development
KPI	Critical performance Indicator
SHE	Safety, Health & Environment
CENELEC	Comite Européen de Normalisation Electrotechnique

G	General information – necessary for all target groups
T	Information for T op management
A	Information for A sset manager
S	Information for S pecialist

Table of Figures

Figure 1: LCC and RAM(S) for assessment of innovations	10
Figure 2: Probability density functions for service life of different track components ...	11
Figure 3: Influence of repair rate on availability	12
Figure 4: Influence of repair rate on life time of component	12
Figure 5: Classification of the maintenance types according to EN 50126	15
Figure 6: Decision tree for LCC	17
Figure 7: Decision tree LCC and RAM	18
Figure 8: Life cycle phases according EN 60300-3-3	20
Figure 9: 3-Dimensional cost matrix of LCC (cost element concept)	21
Figure 10: LCC cost matrix for railway infrastructure analysis	22
Figure 11: Annual costs	23
Figure 12: Effect of discount rate on discounted value	23
Figure 13: Annual costs for two alternatives, discounted with 5.9%	24
Figure 14: Discount rates depending on investors and IM's	25
Figure 15: Proposed discount rate as a function of asset life	26
Figure 16: Influence of discount rate on NPV	27
Figure 17: Residual value – principal approach; alternatives with different life times ..	29
Figure 18: In/Out Frame for documentation of boundary conditions	30
Figure 19: Visualization of used cost elements – top level	30
Figure 20: Documentation of relevant technical parameter	31
Figure 21: Documentation of relevant economical parameter	31
Figure 22: Defined milestones of a LCCA at DB	32
Figure 23: Key phases for reduced LCC	34
Figure 24: Example of sensitivity analysis for a specified maintenance parameter	36
Figure 25: Probability density functions	37
Figure 26: Schematic of Monte-Carlo simulation	38
Figure 27: Schematic - interpretation of results of Monte-Carlo simulation	39
Figure 28: V-Model according EN 50126	41
Figure 29: Schematic representation of the control loop for reliability management ..	48
Figure 30: Conjunction between RAMS and LCC	51
Figure 31: The Railway system	53
Figure 32: Unexpected input/output affecting the reliability and availability	54
Figure 33: The V model according EN 50126	58
Figure 34: Matrix of ProRail	64
Figure 35: Parts of social costs and benefit analysis	79
Figure 36: Risk efficient options [Adopted from Chapman and Ward, 2004]	90
Figure 37: Fault Tree Analysis	91
Figure 38: Event tree for assessing the possible operational consequence scenarios caused by aircraft system failure	92
Figure 39: LCC – Model – the link between technical and economic aspects	94
Figure 40: The optimisation process of assets needs RAMS and LCC relevant data	101
Figure 41: Calculating cost for unavailability	106
Figure 42: Parameters for LCC optimisation	107
Figure 43: LCCA: the LCC model handles technical and economical parameters	108
Figure 44: LCCA: NPV for reference and alternative as function of the load	108
Figure 45: LCCA: NPV as a function of the probability density function	109
Figure 46: LCCA: IN/Out Frame	110
Figure 47: LCCA: used cost blocks	110
Figure 48: LCCA: extract of important technical parameters	111
Figure 49: LCCA: extract of important economical parameter	111

1. Executive Summary

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Life cycle cost analyses (LCCA) at different levels of detail should be the fundamental bases for

- strategic decisions,
- decision between different variants,
- selection of appropriate solutions regarding products and processes or,
- optimizing of existing systems.

The LCCA enables a system approach because it includes besides all costs at all relevant phases also the technical behavior of the product which is described by RAM(S).

Traceable decisions are only possible with coherent rules. This guideline therefore addresses these rules and describes the procedure how to do LCC and RAMS analysis in a practical way. It picks up important questions and gives recommendation for relevant parameters like discount rate or time horizon. Also the documentation of the LCCA, that is important for traceability of results and further actions are addressed in this guideline.

Concerning capital budgeting techniques it was shown that Net Present Value (NPV i.e. Total Present Value in Life Cycle Costing) is the most accurate procedure for decision support. A combination of techniques and indicators can also be advisable as a complement to NPV results: particularly estimation of Annuity factor, break-even or in some cases Internal Rate of Return (IRR) can bring useful indications.

The installation of the methodology in the decision process of companies and the use of LCC and RAMS analyses in projects requires knowledge of the decision-maker about the methodologies. Therefore this guideline addresses different target groups from the top management - responsible for strategic decisions - to the specialists – responsible for technical decisions.

This guideline is a “living document” and now available in the first version. Comments and feedbacks are very welcome to improve the usability of this guideline and to discuss the methodology and necessary implementation strategies. *B.R.*

2. Introduction and current state-of-the-art

2.1. *Background*

Optimization of track constructions or track components regarding technical and economic requirements is essential for railway companies to fit the market and to compete against other means of transport. Due to the long lifetime of the track and track components – ranging between 20 to 60 years – pre installation technical and economic assessments are necessary to optimize the track construction and get the return on investment (ROI) in a manageable timeframe. LCC and RAMS technology are two acknowledged methods for assisting the optimization process.

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LCC is an appropriate method to identify cost drivers and to gather the costs of a system, module or component over its whole lifetime including development, investment maintenance and recycling costs. Different views and evaluations allow the comparison of different systems and deliver necessary information for technical and economic decision.

In the field of railways, LCC methods are starting to be implemented and will provide a definite advantage to the IMs in helping calculate costs for the implementation of innovative technologies.

2.2. *Structure of the Guideline*

As mentioned in previous section this guideline addresses different target groups from the top management - responsible for strategic decisions - to the specialists – responsible for technical decisions. For an easy reading of this guideline, the sections are marked with GTAS for the different target groups or different levels.

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G – General information – necessary for all target groups

T – for Top management,

A– for Asset manager and

S – for Specialist.

RAMS for new and existing systems (modules/components) are marked with **N** or **E**.

The decision tree shown in **Figure 7** summarizes the different steps that are necessary for an RAMS and LCC analysis. The numbers in the boxes refer to the sections that describe the task in more detail. Depending on the superordinated task different subtask are necessary.

2.3. Objectives

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The purpose of this guideline is to support the implementation and use of LCC and RAMS in projects, strategies or daily decision making process.

2.3.1. Why and when to use RAMS and LCC?

In the case you have to optimize an existing system or you have to access an optimization or an innovation you have to do this finally on the basis of costs. But the costs are related to the investment, the cost for operation, maintenance and non-availability. In case of funding by the government you may have to look for social economics. The relation between technical and economical aspects together with future requirements often makes a traceable assessment difficult.

A structured procedure starting from the technical and economical requirements and the analysis of the status quo using RAM(S) and LCC analysis gives goal oriented indicators for the optimization. The assessment of the innovation should also base on the expected RAM(S) performance and the resulting LCC that is the basis for the decision (**Figure 1**)

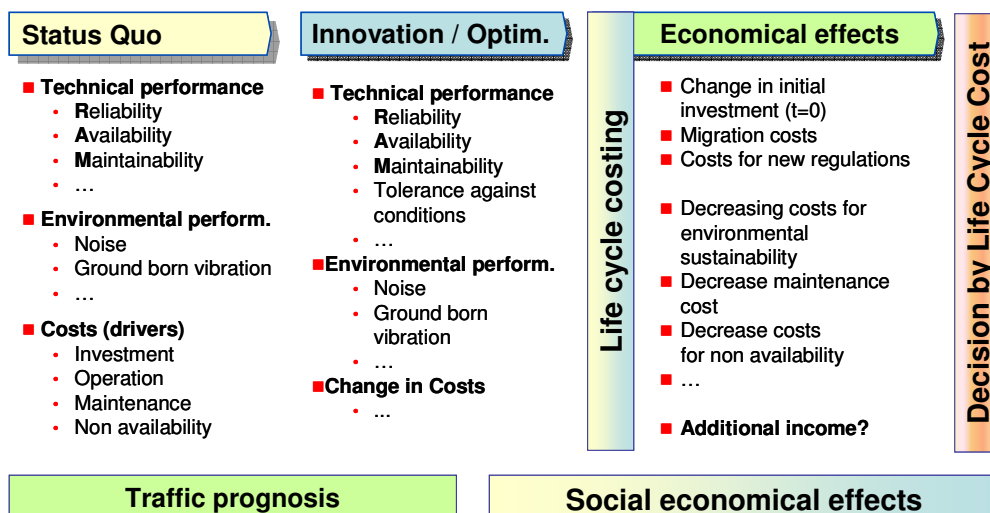


Figure 1: LCC and RAM(S) for assessment of innovations

The straight forward optimization of an existing system requires not only mean values for the life time or failure rates of the different components but the distribution of the long-term behaviour. Often the first appearance of the failure is relevant for non-availability or the maintenance of the system. Mean values leads in these cases to an underestimation of the life cycle costs. Beside the first occurrence of the failure the shape and spread of the probability density function is important for the optimization (see **Figure 2**). In case of a wide spread a technical analysis and improvement is necessary to improve the system behaviour. The collection and analysis of RAM(S) relevant (key) parameters is the basis for the technical optimization because it filters out under or over or bad designed components. Together with an LCC analysis the most important cost drivers and necessary improvements can be identified. This structured process guaranties a fast implementation of the improvements and avoids trial and errors.

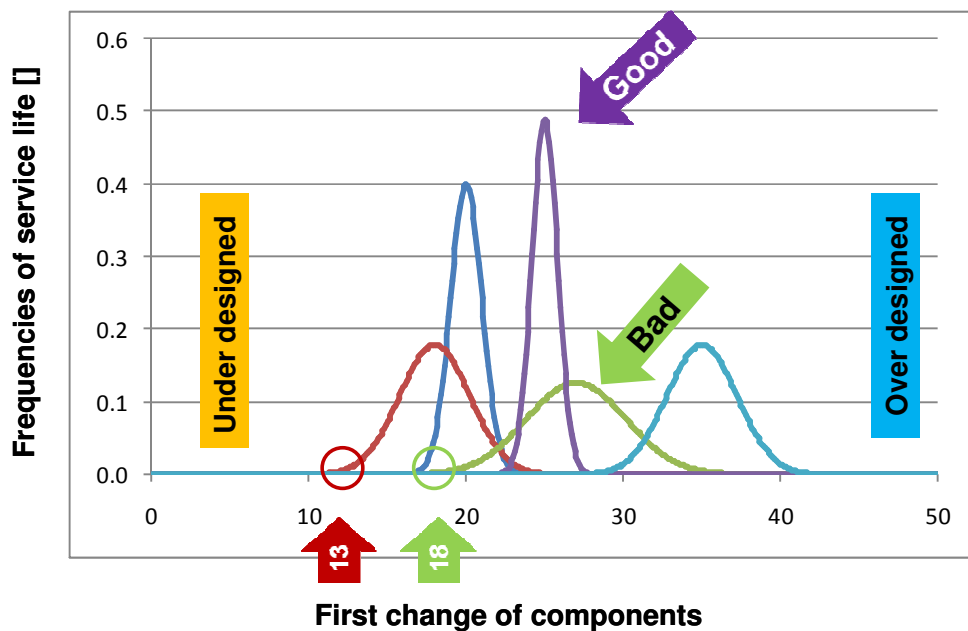


Figure 2: Probability density functions for service life of different track components

Another important question is how to achieve the required availability of the system. The availability depends on the technical performance of the system or component and the repair rate.

Figure 3 shows as an example the influence of the repair rate on the availability of a system.

But both parameters influence also the life cycle costs of the system. Therefore the decision whether to change the technical performance of the component or to adjust the repair rate or to do both should be based on an LCC analysis.

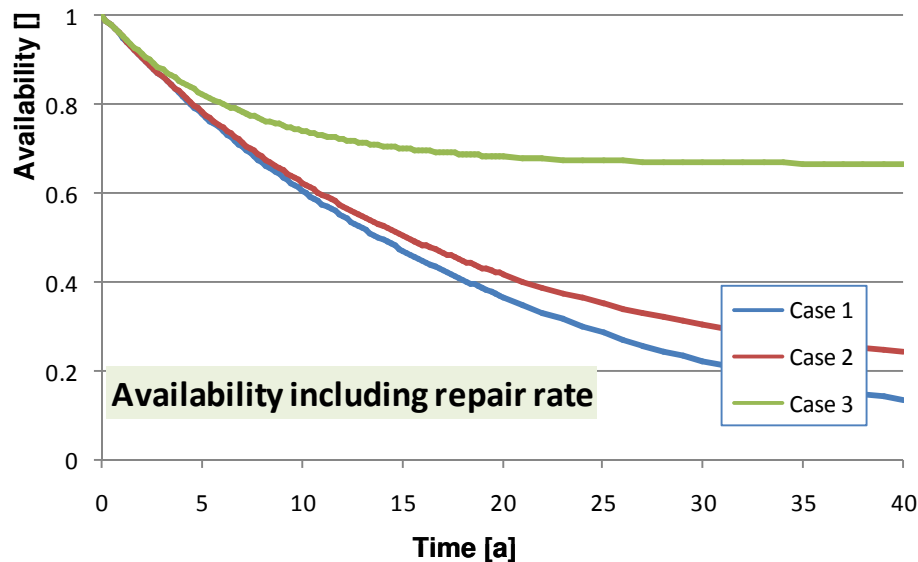


Figure 3: Influence of repair rate on availability

Also the questions regarding the economical relation between maintenance and life time of components are important for economical optimization. In **Figure 4** the influence of the repair rate on the life time is shown. The technical optimum (longest life time will be achieved for a repair rate of 0.007. A higher or lower repair rate leads to a decreased life time.

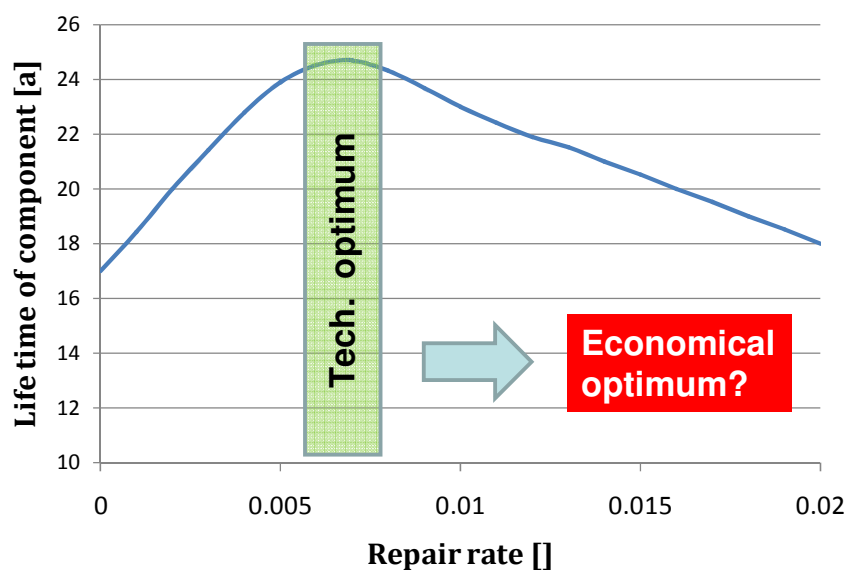


Figure 4: Influence of repair rate on life time of component

The economical optimum is not necessarily related to the technical optimum. Only a RAM(S) analysis in conjunction with life cycle costing predicts the optimum repair rate taking into account the system requirements and costs.

2.4. *Optimisation strategies*

The optimization of existing track designs either for standards, new installations or for upgrades of existing lines could be achieved on a component or system or line level. Targets for the optimizations are

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- Technical and operational performance of components,
- Maintenance procedures,
- Maintenance strategies or
- Social economics.

Optimization strategies could start from the perspective of costs or technical performance. Independent of the approach the optimal solution has to fulfil the requirements at lowest costs. But this means, that each optimization needs at least technical requirements which takes into account future demands. To define technical requirements of existing systems in a good way a technical and economical analysis is necessary to point out the weak points of the system.

3. Principles of RAMS and LCC Analysis

3.1. *Common definition of terminologies*

To begin with, there should be an agreement on the same and consistent definitions to have a common understanding of the terminologies regarding LCC and RAMS. For example there is different interpretation of maintenance. What is the meaning of NPV (Net Present Value) or Annuity within a LCC calculation? These terms and definitions will be explained in the following sections.

TGS

LCC analysis is a method for calculating the total cost of a system or a product over its total lifespan. A very central target is the systematic process for evaluating and quantifying cost impacts. LCC analysis is primary a method for decision making through economic assessment,

comparison of alternative strategies and design. Within a LCC analysis all payments – also future payments – will be referred to a reference date using the discount rate.

Cash value or Capital value

Value of all discounted payments at the time of the reference date (in general: 31th of December of the current year)

Net present value (NPV)

The net present value means the value of all payments referred to the reference date e.g. beginning of uptime (time 0). The NPV is the discounted cash inflow and outflow.

Annuity

The annuity means in the investment appraisal a regular constant payment per year.

Imputed interest rate

Imputed interest rate means the Interest rate, which is applied for the entire required capital, thus for the own capital.

The Net present value and annuity as outputs of a LCC analysis are the primary criteria for decision making. The Break-Even-Point or ROI (return of investment) is the second important key value to show the benefit of a system or product by a LCCA.

Discount rate

An important question for the LCC analysis is - *Which discount rate has to be taken into account?* This important question will be discussed in detail in section 3.2.

The discount rate is roughly the opportunity cost of capital: it is the cost of using the capital in one project renouncing to earn a return in another project. Its value is defined mostly empirically for a given project, in a given country or region, for a given firm and at a given time. The value of the discount rate can have a very serious impact on the decision making process of a cost benefit or life cycle cost analysis.

Maintenance

In terms of maintenance issue the decision within the InnoTrack project was that the definitions in EN 50126 should build the base for a common terminology.

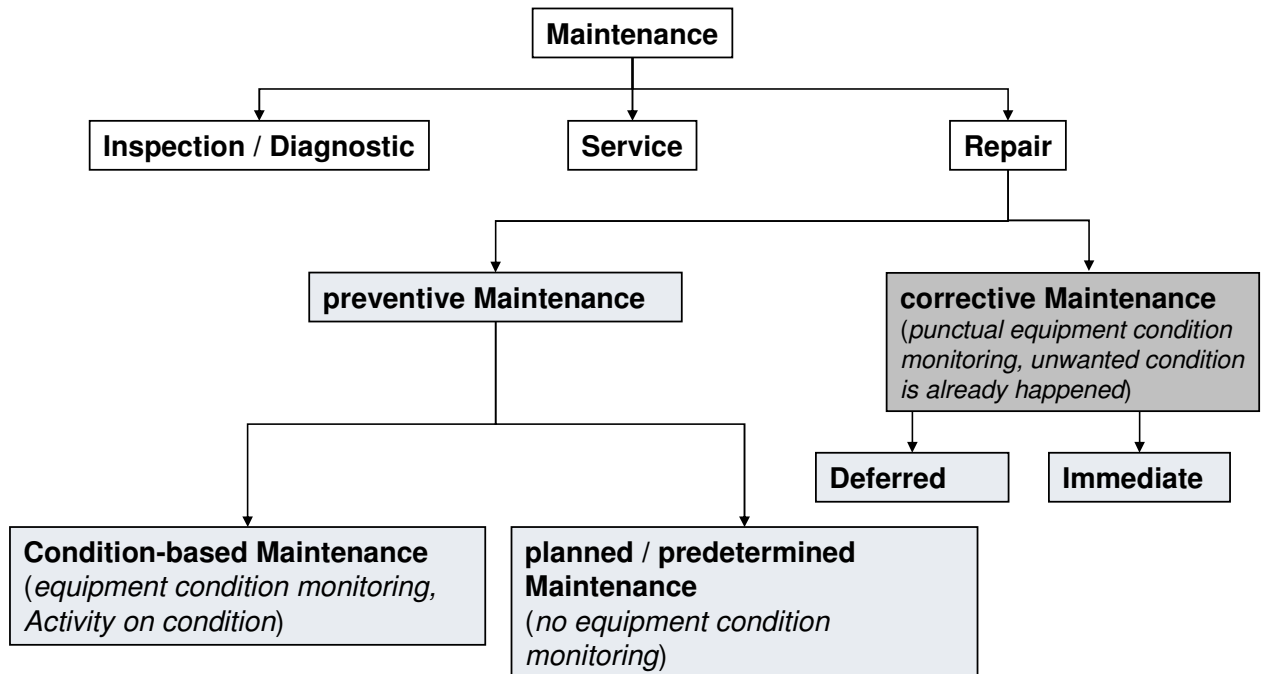


Figure 5: Classification of the maintenance types according to EN 50126

In it the maintenance is the generic term and consists of inspection/diagnosis, service and repair. During the repair is differed between preventive as well as corrective repair, which are in each case two further distinctions. This organization with the definitions is also conformal to cost block structure of the DB AG, which was specified in the project INNOTRACK as basis for the illustration of the cost structure of the LCC model.

The model of DB is created according to EN 50126 and DIN EN 13306 (2001). Its worth to point out that there are different description possibilities for the definition of maintenance and/or maintenance strategies (e.g. see Banverket): Banverket defines the inspection as a preventive maintenance measure under condition based maintenance, service/maintenance under predetermined maintenance for the evaluation of the condition of facilities.

As shown in the above figure “Inspection” is seen as a separate activity not included in the “condition based maintenance”. There is also a

boxed called “Service” – in Banverket this is usually regarded as pre-determined maintenance.

For the distinction of service and inspection the following definitions (EN 50126 and excerpt from Ril 820.3010 of the DB AG) can be helpful:

The specified condition is to be specified according to the operational requirements and demand (speed, load) with consideration of security and availability as well as costs and use.

Maintenance

The combination of all technical and administrative actions, including supervision actions, intended to retain a product in, or restore it to, a state in which it can perform a required function.

Preventive maintenance

The maintenance carried out at pre-determined intervals or according to prescribed criteria and intended to reduce the probability of failure or the degradation of the functioning of an item.

Corrective Maintenance

Corrective maintenance is carried out to repair a failure or defect in the “system”, which occurred randomize, before detected and corrected during preventive maintenance – or passed unnoticed at inspection or planed maintenance. Also falling in this category are maintenance measures necessary as a consequence of a failure in and other system having caused damage (example in case of rail infrastructure: derailment due to vehicle failure). Prescribed procedures and technical skill levels are also applied, at least for certain “standard cases”.

Inspection

Check for conformity by measuring, observing, testing or gauging the relevant characteristics of an item. NOTE: Generally inspection can be carried out on before, during or after other maintenance activity [EN 13306:2001].

Service

Service covers measures for retaining the specified condition. Actions that prevent an accelerated degradation by removing dirt, water, snow and other debris without restoring the actual function of the asset.

3.2. Definition of LCC-methodology and RAMS-technology

The decision tree, shown in **Figure 6** highlights the main steps which have to be carried out and the related results.

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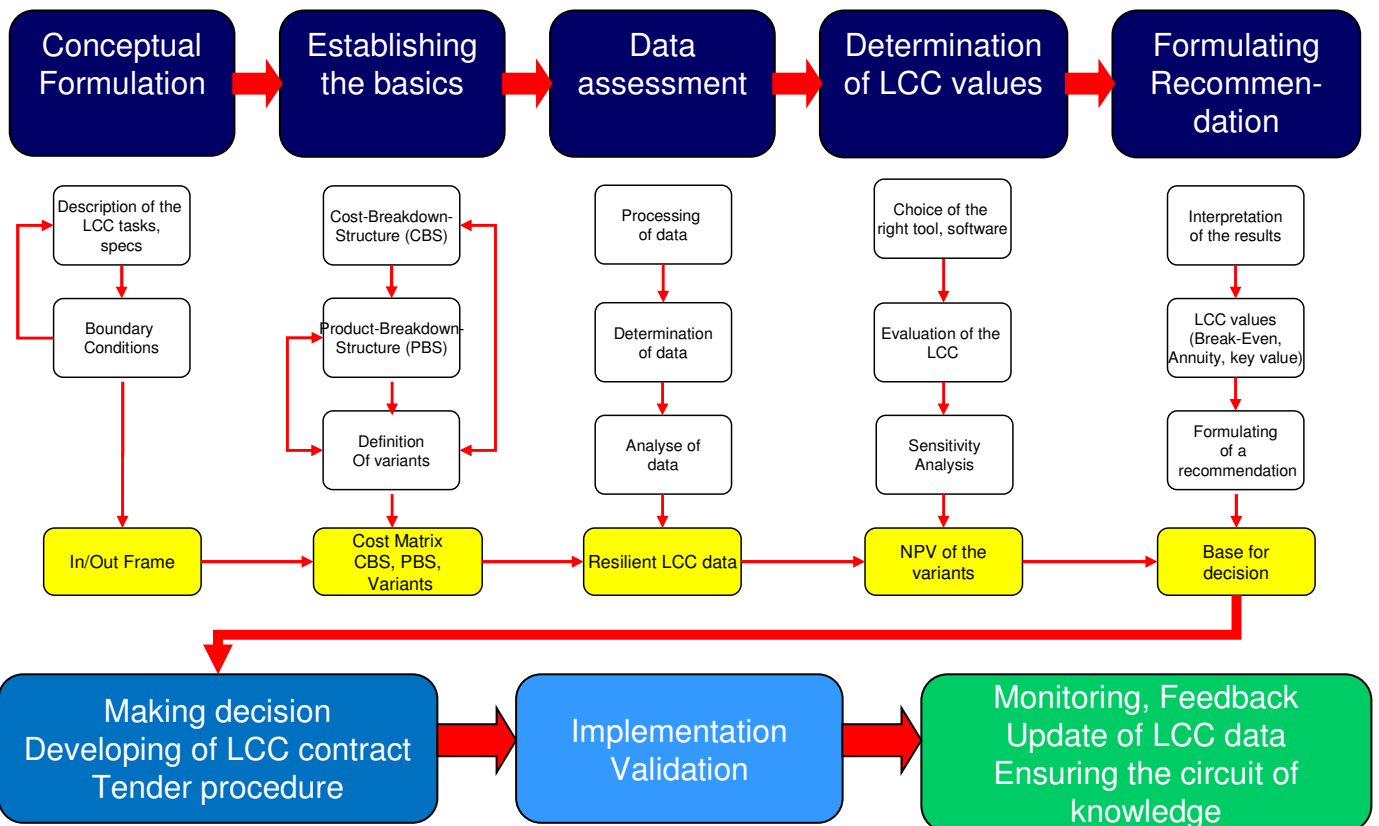
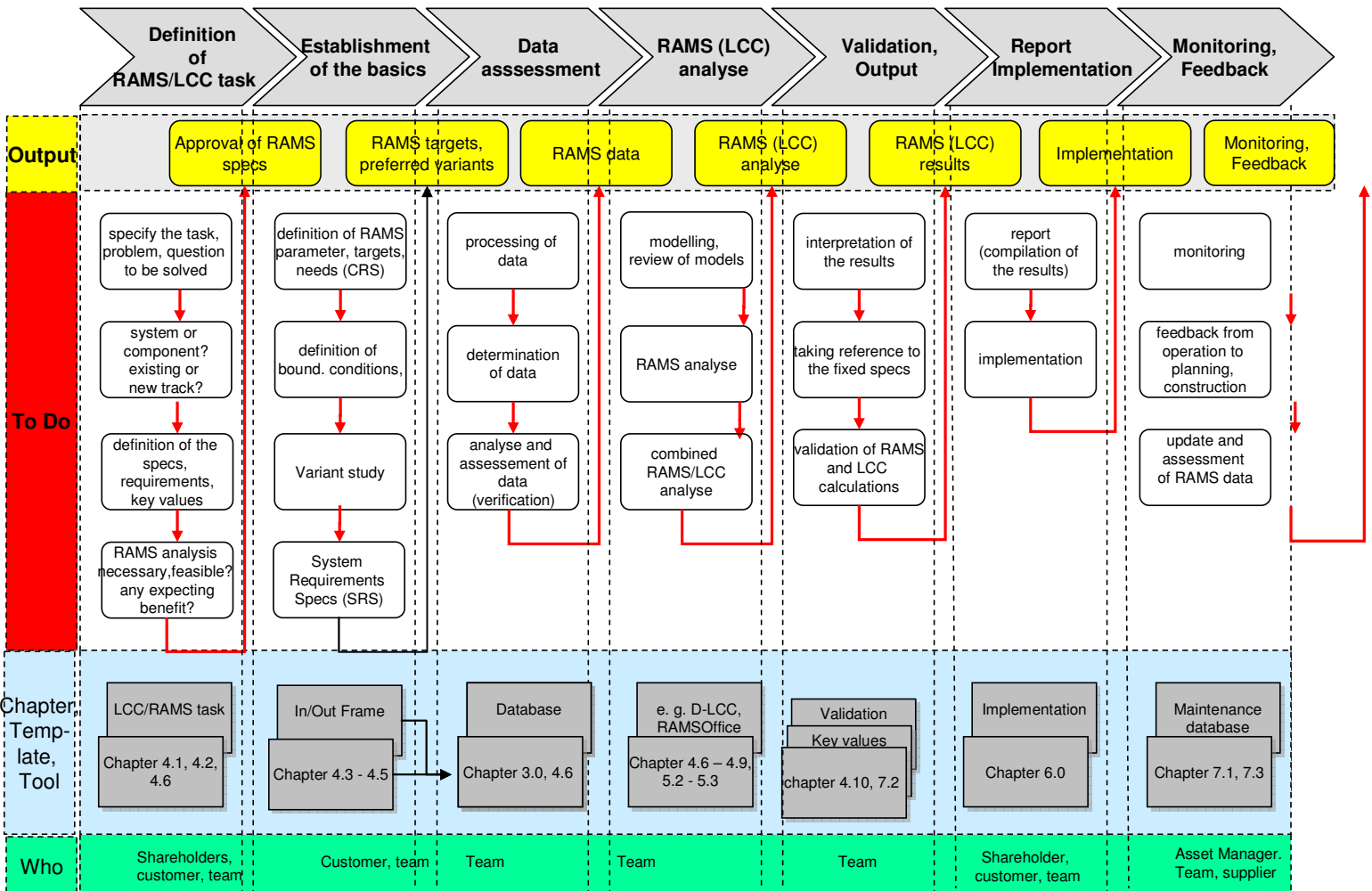


Figure 6: Decision tree for LCC

The following Figure 7 shows the needed steps for RAMS (combined with LCC) analysis.



according to the LCC procedure of WMP from DB (dated: 05.09.2006)

Figure 7: Decision tree LCC and RAM

3.2.1. LCC Methodology

Why the LCC and RAMS analysis is important for decision making during the procurement process and investment projects respectively?

Every day you make decisions: we make investments for infrastructure and vehicles, we change the supplier, we want to stretch the maintenance interval or we even want to remain everything constant. Every of these decisions are cost related. The customer demands today not only for the best technical-operating but also for the most economic solution. Because the decisions now have effects over centuries in railway sectors, you need a feeling for the cost impact of your decision and a supporting method for professional decision making.

In this regard LCC and RAMS are the appropriate methods. LCC analysis is primary a method for decision making through economic assessment and comparison of alternative strategies and design.

A life cycle cost analysis calculates the cost of a system or product over its entire life span. The method is one of the most recommended for investment projects, assessment of different solutions over the whole life cycle and comparison of various strategy options.

The classic LCC phases are:

- Concept and definition
- design and development
- production
- installation
- operation and maintenance
- disposal

For operator another diversification is useful, because the phases are more orientated on producers. As purchasers the R&D costs are part of the purchasing costs and the IM's start with the installation. DB developed thus a cost block structure to allocate the overall cost to the important phases, explained in the following chapter.

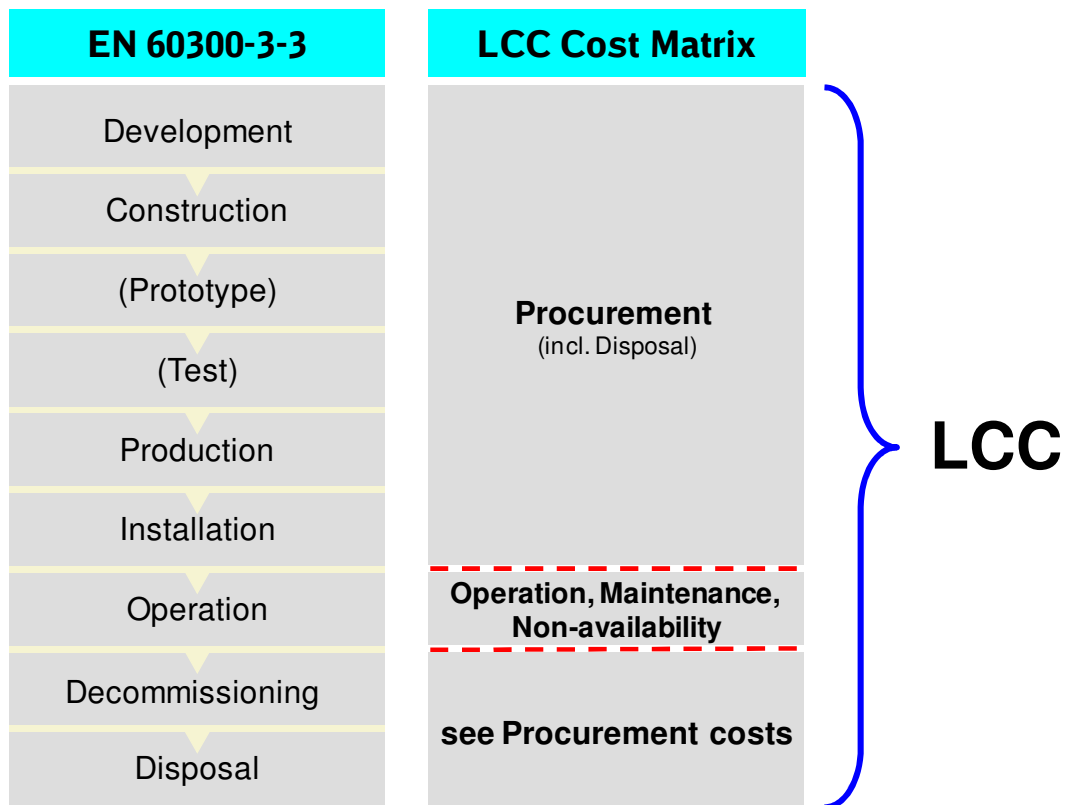


Figure 8: Life cycle phases according EN 60300-3-3

The standard IEC 300-3-3 [2] as guideline for application of reliability management straightens out in the section 3 that the LCC analysis is an integral part of the reliability management, if the approach of achieving the optimum in terms of product properties and costs is aimed. In the next section the definitions, items and used LCC method will be explained.

3.2.2. LCC Cost elements

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Life cycle cost analysis (LCCA) is a structured method to assess all costs incurred within a given system along the technical life cycle considered for this system. Major phases of the system life cycle must be included in the analysis (i.e. concept and definition, design and development, manufacturing, installation, operation and maintenance and disposal phases). As it can be derived from **Figure 8** the LCC models consist of a 3 dimensional matrix that includes:

- a breakdown of the product to lower indenture levels (PBS),
- a cost categorisation of applicable resources such as labour, materials, equipment, etc. (CBS) and

a time axis or life cycle phases where each work or activity performed is allocated to each cost element (see **Figure 9**).

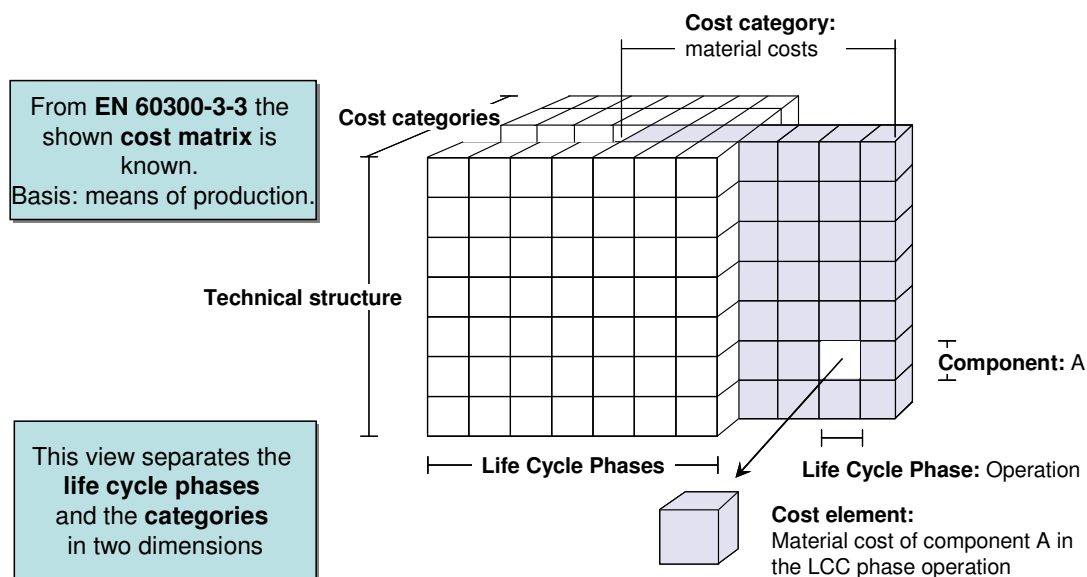


Figure 9: 3-Dimensional cost matrix of LCC (cost element concept)

The CBS is a tree structure of the duty and costs that occur along the entire life cycle of a product. The PBS is a hierarchical tree structure of components that make up a product that can help clarify what is to be delivered by the project and can help build a work breakdown structure (WBS).

With different projects the typical EN 50126 the structure was changed to the cost matrix shown in **Figure 9**, which fits to all mean products. This standardised cost matrix for LCC is used as the basis for assessment and describes all costs. The main focus was hereby on the unification of the used terms. This definition allows the comparison of each cost blocks of different calculations independent of the analyst. Also an important point is the standardized form of the useful explanations of the LCC, taking into account the data and uncertainties. The life cycle costing is carried out on the basis of the defined cost matrix with predefined cost items.

All the ongoing discussion within the InnoTrack project has been based on this cost structure. Necessary modifications because of different definitions for all partners could be included. That means only to add items, e. g. economy costs, or to shift items

- only direct costs
- indirect costs should not be part of the LCCA (indirect cost, e.g. depreciation)

Cost matrix – top level

I. Procurement	II. Operation	III. Maintenance	IV. Non Availability
I.1 Preparation - one-time I.2 Preparation recurrent project-specific I.3 Investment I.4 Imputed residual value I.5 Decommissioning / retraction / sale / removal (tasks) I.6 Disposal / recycling I.10 Other costs	II.1 Service II.1.2 Energy II.10 Other costs	III.1 Inspection and service (track) III.2 Maintenance –preventive III.4 Maintenance - corrective III.7 Design and system support III.10 Other costs	IV.1 Planned IV.1.1 Malfunctions IV.1.2 Delays IV.1.3 Serviceability IV.2 Unplanned IV.2.1 Malfunctions IV.2.2 Delays IV.2.3 Serviceability IV.10 Other costs
V. Social Economics			
V.1 Energy consumption V.2 Environment		V.3 Delay V.10 Other costs	

Figure 10: LCC cost matrix for railway infrastructure analysis

3.2.3. Discounted cash flow or present value method

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Costs and cost drivers have to be identified. Therefore the cash flow is very important for planning or controlling and for checking the financial budget. But the cash flow method is the one to take into account, that there are other opportunities to spend the money. Future cash flows have to be discounted to the starting point of the study period, the time before (time to market) could be escalated to compare different alternatives.

Multiple this factors with the annual costs for each year are the discounted cash flows. The result of accumulated costs is the Net Present Value (NPV) for each alternative. Within a LCC analysis all payments – also future payments – will be referred to a reference date using the discount rate i . The exponent means the respective year, in which the costs incurred (see **Figure 11**).

As it can be deduced from the formula on Figure 11, the value of the discount rate has a serious impact on the decision making process of a cost benefit or LCCA.

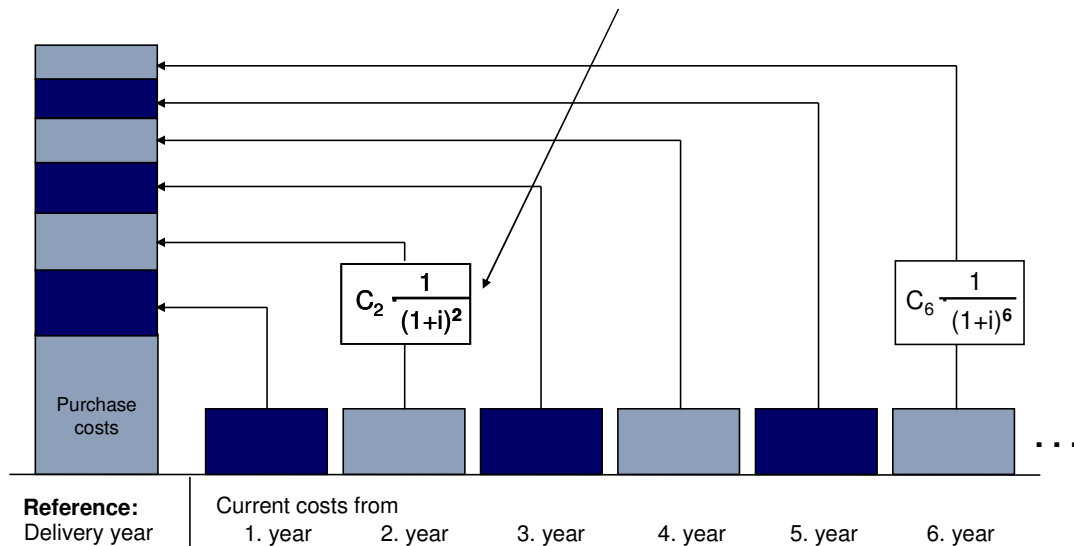


Figure 11: Annual costs

The mentioned effect of the discount rate on the net present value is shown in Figure 12. For the selected effective rates of interests of 6 and 3%, a payment of 1000€ in year 20 results in a NPV of 554 € and 312 € respectively. A payment in the first year will be not discounted and has therefore an important impact on the LCC.

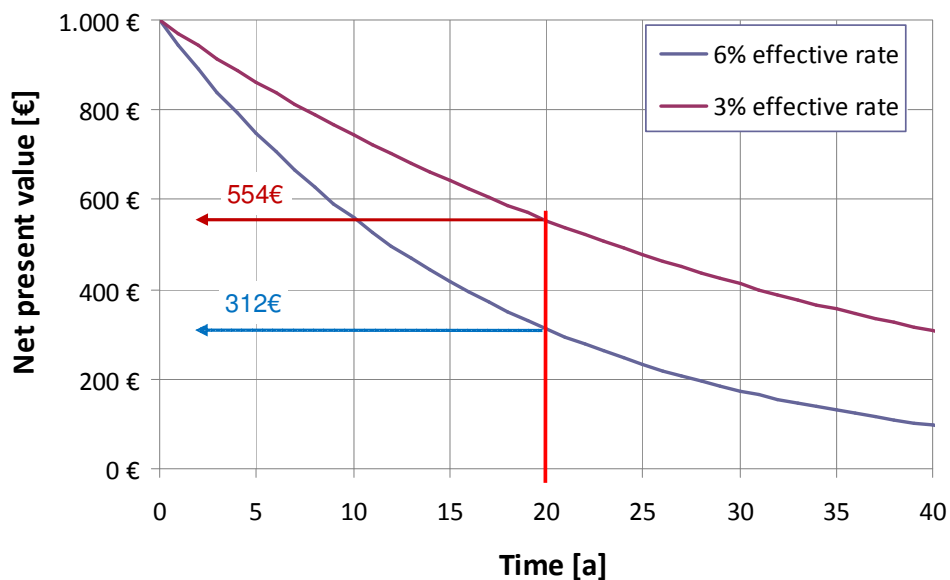


Figure 12: Effect of discount rate on discounted value

Calculating the yearly potential means to calculate the NPV for all alternatives, subtract the value standard to alternative and calculate the annuity. One benefit of the LCC as not complete financial assess-

ment could be: if for both the alternative and reference the dimension time and costs are equal, the cost blocks could be eliminated. If all the annual costs should be used for budget planning, the simplifying is not allowed.

In the case of comparison of two alternatives with larger differences in the first investment the selected discount rate is mostly the key for the decision. Only in the case of major reduction of maintenance cost in the *first years* the higher investment will be balanced (see **Figure 13**).

In this case even for an effective discount rate of 5.9% the red marked variant in Figure 13 is despite higher investment costs favourable over life cycle!

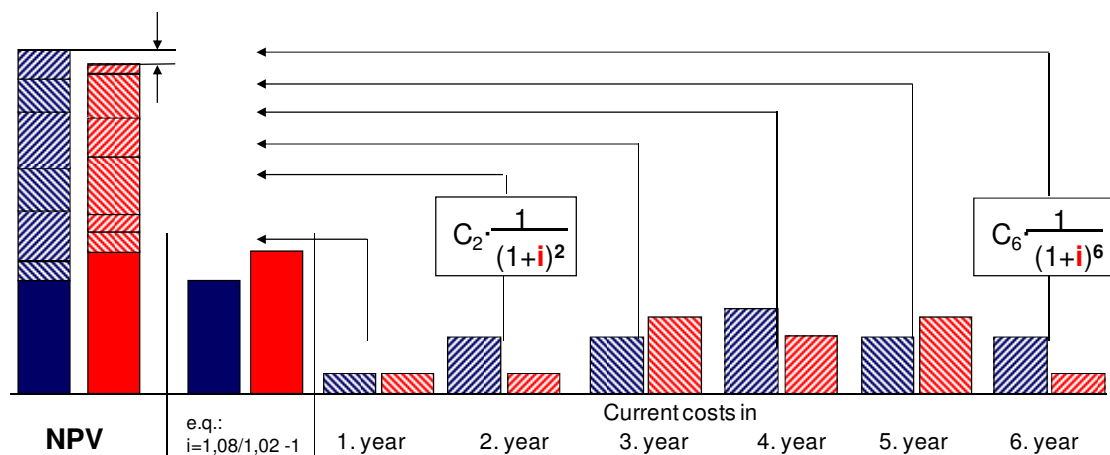


Figure 13: Annual costs for two alternatives, discounted with 5.9%

The next section tries to answer the question:.

How to choose an appropriate discount rate for the NPV calculation?

3.2.4. Discount rate and time horizon

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Within a LCC analysis all payments – also future payments – will be referred to a reference date using the discount rate. The question within the InnoTrack project was which discount rate and study period for the LCC calculation had to be taken into account and had to be fixed. For instance NR takes 6.5 % as effective discount rate for infrastructure, DB 5.9%. In order to use a common discount rate and agreed study period for the LCC calculation, an evaluation needed to be done.

Economical boundary conditions are key factors on the results provided through LCCA. An in-depth evaluation of current practices concerning the discount rate and the time horizon on infrastructure project appraisal was performed. Most recent bibliography on the subject shows that, among the diversity of criteria and values adopted, there is a tendency to use reduced values for discounting combined with large periods of consideration. Based on a detailed theoretic analysis performed towards the definition of a unique criterion for discounting and the time horizon of LCCA has driven to the following decisions for the InnoTrack project:

to consider a variation of 3% to 5% for the discount rate, with a reference value of 4%

to consider a range of 30 to 40 years as time horizon, with 40 years as recommended upper bound for large investments on ballasted tracks assessed through LCCA (closely linked with an accurate estimation of the alternatives residual value).

BV	4.0 %	
DB	5.9 %	For infrastructure
NR	6.5 %	
ProRail	4.0 %	
Public investor	≅ 4.0 %	
Private investor	5.0 % ++	Depending on risk
InnoTrack	≅ 4-5 %	For comparison

Figure 14: Discount rates depending on investors and IM's

It's inevitable to discuss and to agree on the selection of appropriate discount rate and time horizon discount rate to be valid for a given country, a firm or other special conditions.

As a change of the discount rate changes the decision, we have to think about the right value of discount rate, in order not to kill innovations. Taking into account the long service life of the railway infrastructure and the fact that investments risks in the infrastructure are low, a discount rate that depends on the service life of asset is proposed. **Figure 15** shows as an example the discount rate as a function of the service life of the asset. In general the LCCA will be done with a constant rate for all components of the analysis. The use of different rates for components with different service life is also possible, but will increase the complexity of calculation and documentation.

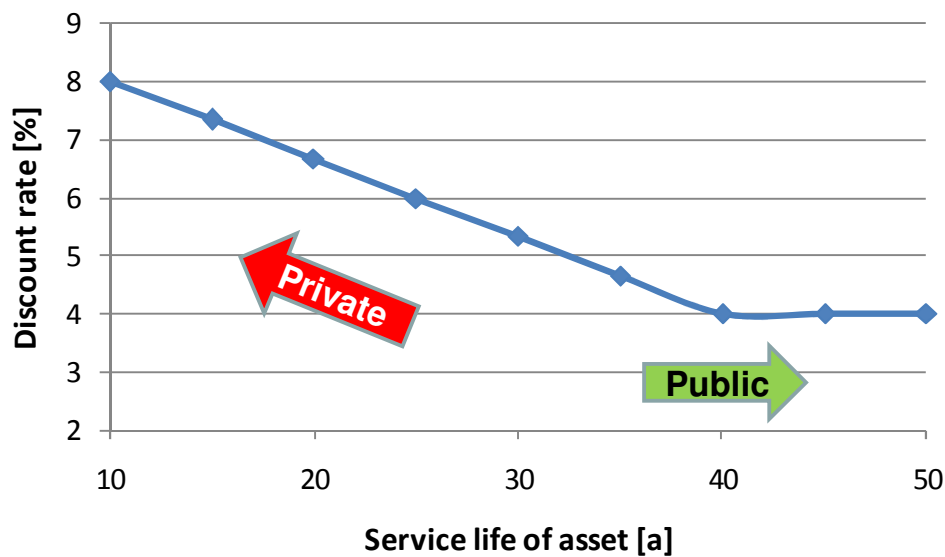


Figure 15: Proposed discount rate as a function of asset life

The accuracy of an economical evaluation is of course extremely bound up with the accuracy of the cost estimation techniques (for both investment and operational costs): the improvement and homogenization of those techniques (e.g. at a European level) would bring further confidence on the results obtained. However those are not the only aspects where attention should be focused when preparing an economical analysis. Current experience in European infrastructure projects appraisal has shown that there are three other important key issues requiring particular attention, given that they strongly affect the results obtained. Those are (EC, 2002):

- The selection of appropriate discount rate (financial and social)
- The definition of time horizon for the project
- The evaluation of the residual value of the investment

The right choice of the discount rate calculating the LCC can have a big impact on the LCC results and the decision making process of a LCCA. Adopting either a 3% discount rate against an 8% or 10% rate (all common values) can suppose a drastic change on:

the profitability of a given project (move from negative to positive NPV) and/or

the choice of an investment over an alternative one (move from inferior to superior NPV of a project over the other).

In Life Cycle Cost Analysis, theoretically applying a high discount rate will tend to favour investment alternatives with low capital costs, short life cycle and high recurring costs. On the other hand, low discount rates will tend to favour high capital costs, long life cycle and low recurring costs. Due to a fact that also after an improvement the income will not increase in general the implementation of innovation is **impossible** at high discount rate. Therefore, an appropriate selection of discount rate is crucial. **Figure 16** summarizes the results of an LCC analysis taking into account different effective discount rates. A break-even point between the reference and the innovation is given for an effective discount rate equal or less 4%. For higher discount rates the higher investment cost for the innovation leads to an increasing gap to the reference.

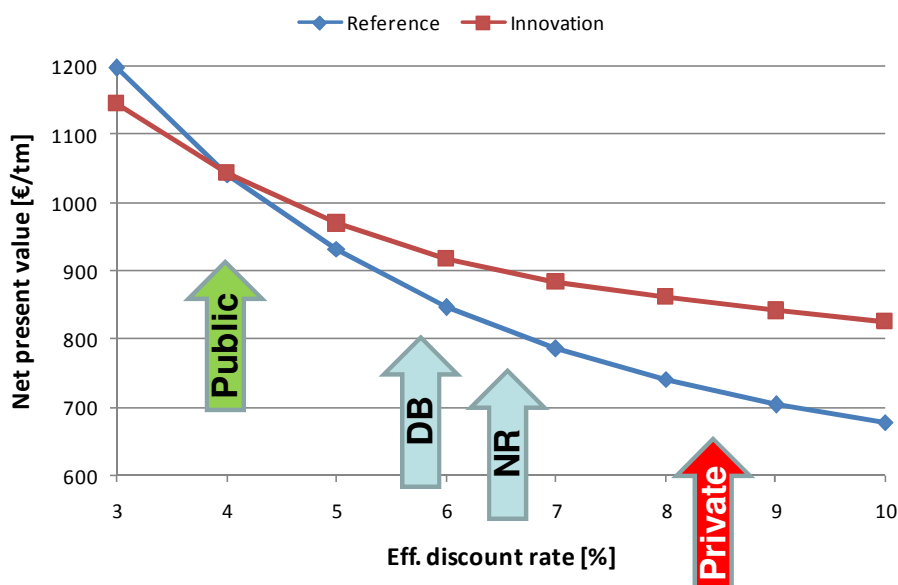


Figure 16: Influence of discount rate on NPV

The discount rate of 4% for a long lasting investment will ensure profit over the whole period and will give the innovation the chance to change the railway in a positive way and to increase the image.

In the same way as for the rate of return, the choice of a correct period of consideration also highly affects the results of NPV calculation: depending on the cash-flows distribution, a project can move from negative to positive NPV just by changing the project time horizon. On the same way, a project can become inferior or superior to another alternative simply by adjusting a different period of consideration. Also in the case of this factor, important differences can be found over similar infrastructural projects.

Accordingly, suggestions from many authors tend to favour the use of internationally accepted practices for the selection of time horizon, depending on the sector.

The consideration of the residual value of the investments is a key issue to avoid distortions due to different time horizon criteria. According to cost-benefit guidelines, residual value is considered as a liquidation value of the project and should include the discounted value of all expected net revenues after time horizon. Therefore it should be calculated in two ways (Florio et al., 2003):

Considering the residual market value of fixed assets, as if it were to be sold at the end of the time horizon considered – includes future net incomes generated by the project.

Considering the residual value of any other current assets and liabilities

Figure 17 illustrates an appropriate calculation of the residual value for two alternatives. The time horizon for the LCCA is 40 years. The technical life time of alternative A is 50 years and for Alternative B 40 years. The financial value of the assets will be linear depreciated over their technical lifetime. The residual value of the assets will be calculated according equation (3-1)

$$RV = V_{Asset} \frac{TLT - TH}{TLT} = V_{Asset} \left(1 - \frac{TH}{TLT} \right) \quad (3-1)$$

In this equation RV means the residual value and V_{Asset} the value of a new asset (normally the value of the asset at time t_0)

In case of variant A the residual value is 1/5 of the asset value and in case B only the scrap value and the cost for disposal have to be taken into account.

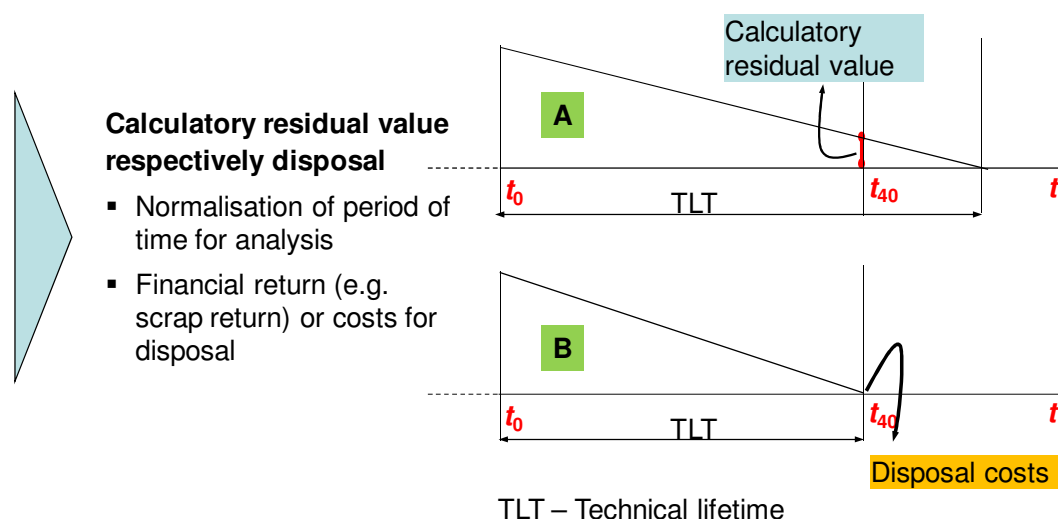


Figure 17: Residual value – principal approach; alternatives with different life times

3.2.5. Documentation of input data and boundary conditions

A clear and standardized documentation of all assumptions and parameters is absolutely essential for a traceable analysis and for comparable results. .

The following subsections give some recommendations about the documentation of the boundary conditions and technical and economical parameter, which are relevant for LCCA. A filled documentation can be found in the appendix.

In/Out Frame

The definition of the impact of each innovation should refer to what is new (general description) and an identification of which specific cost elements does the innovation affect (including the breakdown of this effect) within a reference cost matrix.

The result can be visualized in an *In/Out Frame* (**Figure 18**) where one can identify those cost elements that will be part of the LCC calculation and, as a result, will require a detailed clarification and possible breakdown (if applicable).

The *In/Out Frame* assures that the appropriate boundary conditions are fixed and the question what is within the calculation and what is not are made clear. A filled In/out Frame is shown in the appendix. The In/Out Frame also gives the possibility to put some fields on the

frame, which need to be clarified during the LCC analysis and required as essential input for the LCC calculation.

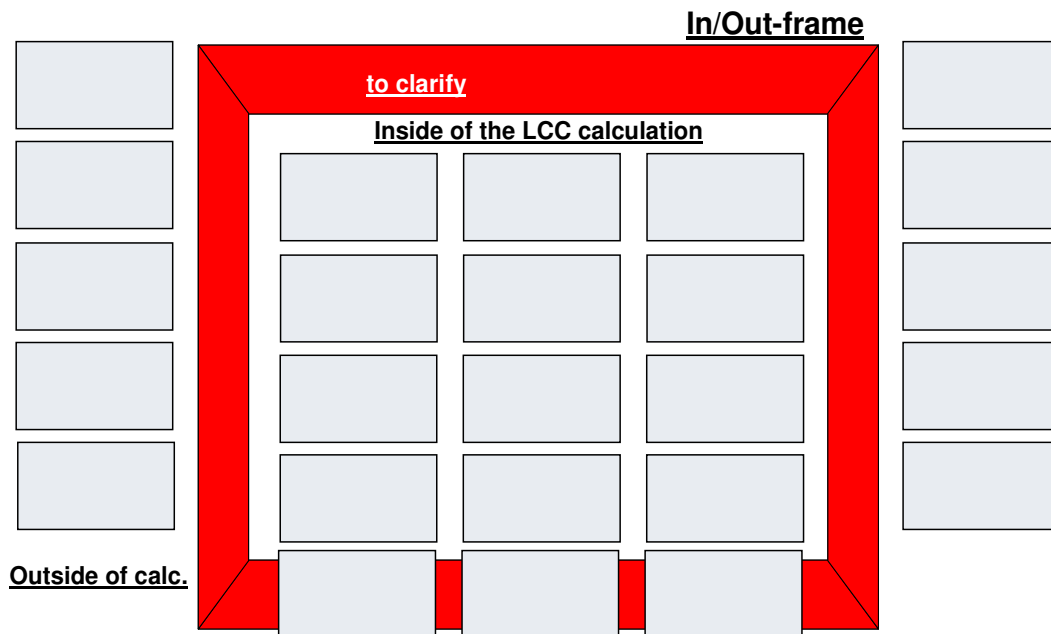


Figure 18: In/Out Frame for documentation of boundary conditions

Used cost elements

Beside the boundary conditions which are documented in the In/Out-Frame the used cost elements should be marked at least at the top level of the cost matrix to visualize the scope of the LCCA (**Figure 19**).

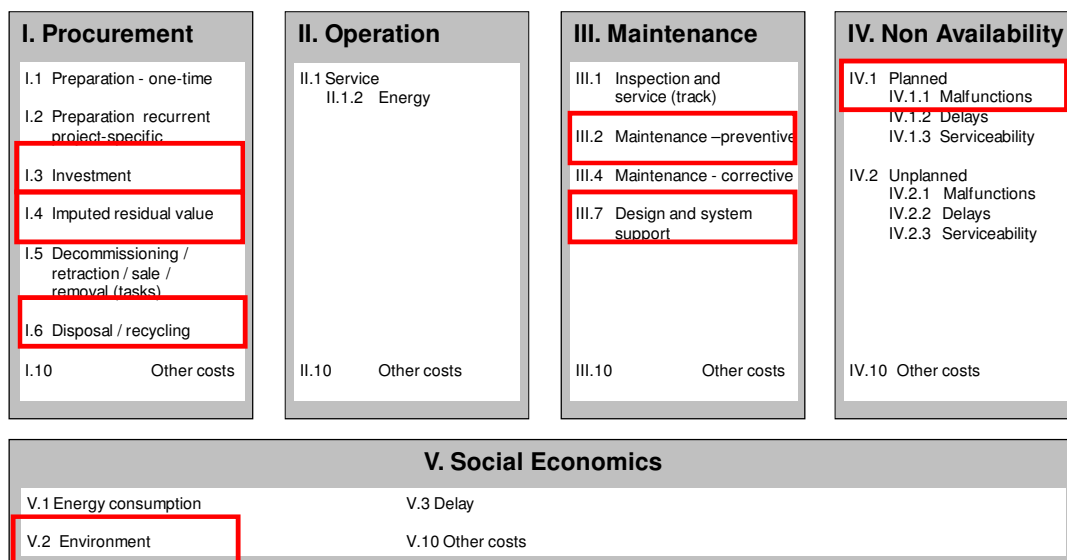


Figure 19: Visualization of used cost elements – top level

Important technical parameter

The technical parameters, which are relevant for the analysis in relation to technical performance and related to costs, should be documented in a table like shown in **Figure 20**. This documentation also includes details about the rates and the time horizon.

Parameter	Reference case	Innovation A
Technical Parameter 1		
Technical Parameter 2		
Technical Parameter 3		
Technical Parameter ...		
Technical Parameter n		
Remarks		
<ul style="list-style-type: none"> ■ Nom. discount rate: ___ % <i>The nominal discount rate should be based on asset life</i> ■ Mean inflation rate: ___ % <i>The inflation rate should be estimated from the last years</i> ■ Effective rate: ___ % ■ Time horizon: ___ years: 		

Figure 20: Documentation of relevant technical parameter

Important economical parameter

The economical parameters, which are relevant for the LCCA, should include details about the costs, cycle of payments, the source and quality. An example for the documentation is given in **Figure 21**.

Cost block	Data structure	Reference case	Innovation A
Investment	Euro Cycle Source Quality		
Operation	Euro Cycle Source Quality		
Maintenance Activity A	Euro Cycle Source Quality		
Maintenance Activity B	Euro Cycle Source Quality		
Maintenance Activity C	Euro Cycle Source Quality		

Figure 21: Documentation of relevant economical parameter

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3.2.6. Processing and determination of LCC data

The most important part of a LCC calculation is the processing and determination of LCC data. DB has defined the Milestones for a LCC analysis which is shown on the following **Figure 22**.

The first step of starting a LCC and RAMS analysis is to define the question or problem to be solved, to fix the boundary conditions and to formulate the goals/requirements of the analysis as a conceptual formulation. Thus the task, scope and the boundary conditions of the present LCC application are to be defined in order to establish the basics for the LCCA. A LCC calculation is as good as all the relevant boundary conditions and the LCC aspects are considered and documented accurately. In the same way is to be proceeded with the next step of processing and determination of (LCC) data. Data quality and data availability are the major problems in achieving the LCC and RAMS targets. The identification of the RAMS parameters is the core of a RAMS analysis. Additionally to the definition and assessment of the RAMS parameters the data collection and data processing are the most important part of RAMS and LCC analysis. But it is also important that besides the input data collection the LCC and RAMS data are followed up.



Figure 22: Defined milestones of a LCCA at DB

Generating the LCC model based on the CBS and PBS the calculation and the evaluation of the alternatives can be done by using the obtained data. The NPV, the Annuity and the Break-Even-Point as the primary key values for the decision making process are the first results and the base for formulating a recommendation. The manufacturers and contractors could only be accountable for their product if the RAMS and LCC specifications are clearly defined and fixed in contracts with them. Therefore a contract implying obligatory LCC aspects is recommendable because this makes the producer and supplier being accountable for their delivered product. The monitoring and verification of the implementation of the LCC results should not be neglected because they are also very essential parts of LCC and RAMS analysis which ensure the circuit of knowledge.

In the frame of INNOTRACK the methods of Life Cycle Costing (LCC) and RAMS technology are defined and implemented for the infrastructure. The established harmonized LCC calculation method at European level enables to identify cost drivers, assess the track components/modules and to make cross-country comparison. LCC calculations based on these models for references & innovations are carried out before the innovative solution could be validated in technical and economical terms. The generated structures and the modular LCC models are a good base for further development in terms of LCC and RAMS analysis with focus on application and benefit of the methods. Basically a better – common - understanding of LCC and RAMS between IM's and industry has been achieved.

The state of the art and the InnoTrack project show that firstly, the analysis of existing knowledge and the practise of infrastructure managers regarding LCC and RAMS are rarely used for decision making during the procurement process. Secondly, the decision makers (technician, controller) are not aware of the matter that especially decisions in the early phases of the product life are very important. Operators start with the initial phase purchasing the product. All the costs that could be affected (e.g. by maintenance measures) throughout this life phases are defined in the earlier phases of the product life cycle; the literature mentions a range between 80 – 90%.

RAMS and LCC is not carried out in all the life cycle phases. It's mostly done in the investment and operation and maintenance phase. As a consequence of this fact the potential LCC savings are not so much as in the earlier phase like construction and planning phase.

We need to notice the fact that the significant part of LCC is fixed before the installation phase, where is the highest potential for savings. Thus the focus should be on the design and production phases when we want reduce the operational costs. The following Figure 23 shows the key phase for the life cycle costs.

In general the suppliers of components or systems do not operate their products. Because they therefore do not know details about the technical behaviour of their products a feedback of the operators to the supplier is essential for a fast optimization.

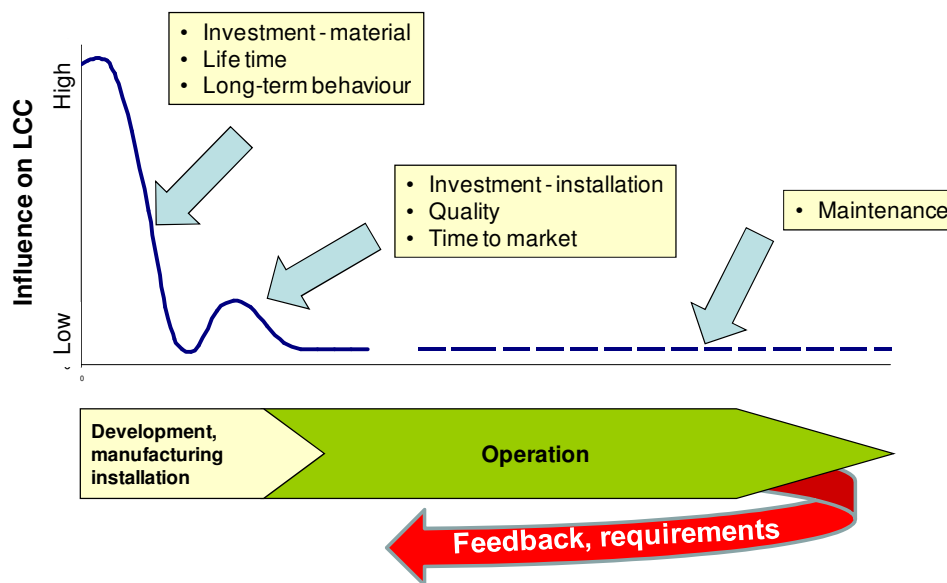


Figure 23: Key phases for reduced LCC

3.2.7. Increasing load

A LCC analysis should take into account and evaluate a system not only in terms of economic effects but also with the capability for significant improvement to future needs. Future requirements like the prognoses of increasing load in the near future have to be part of the decision making process.

The calculation is starting at the operation time for specific conditions. Load is basically responsible for intervals. Increased reliability means increased maintenance intervals as part of the LCC model. The planner/ decision maker for a system has to take into account that the final solution lasts for a long period, in many cases 24 years. For already existing systems it is the same procedure. The standard recommends technical solutions; the selection has to handle the prognosis of increasing load, speed, etc.

For example in the frame of InnoTrack project the increasing load and environmental effects have been taken into account in the LCC analysis. The influence of track loading on LCC could be demonstrated on the embedded rail slab track (BBERS). For higher loading, the LCC of slab track is relevant lower than for ballasted track.

3.2.8. Uncertainty of parameters – sensitivity analysis

Not all the necessary parameters are well known. Even uncertainties are part for future cash flows, which have to be estimated at the beginning. There are different kinds of uncertainties like

1. not well known values of parameters due to missing data for existing systems,
2. uncertain values of parameters by reason of missing experiences for new components or systems or
3. parameters like life time of components, failure rates or maintenance intervals are not constant but described by probability density functions (PDF) (see also Figure 2)

For the first two cases of not well known values of parameters a *sensitivity analysis* helps to identify the impact of the uncertainty and to focus on further analysis.

The idea is to vary the input parameters for the LCC analysis and to compare the results in relation to the input. **Figure 24** shows as an example the change of NPV as a function of the variation of the input parameters. The NPV and the variation of the input parameter are plotted in percentage of their nominal values (100%).

In this example the investment cost and the maintenance interval have an important impact on the predicted life cycle costs. By contrast the unknown lifetime of the component has a negligible influence on the results in the analysed range of uncertainty.

These results indicate that more analyses are necessary to reduce the uncertainty of unknown values – in our example the investment costs and the maintenance interval. If it is not possible to achieve better input values for the LCCA a set of calculations are necessary within the specified range of the values.

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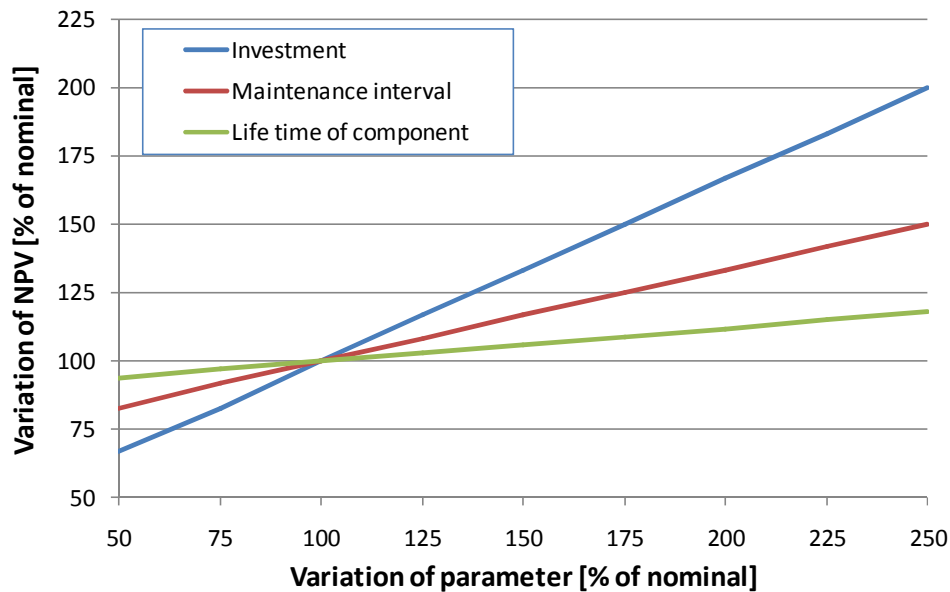


Figure 24: Example of sensitivity analysis for a specified maintenance parameter

This kind of calculation is also necessary if the values of the parameters could not be described satisfactory by mean values. In general maintenance activities or re-investments are necessary if a failure occur. If the failure rate is described by a PDF the maintenance activities and hence the related costs could also be specified by the PDF. If the model contains more than one uncertain parameter that is described by a PDF a Monte-Carlo-Simulation provides beside the life cycle cost the probability of the results.

A short overview of the Monte-Carlo simulation in relation to LCCA is given in the next chapter.

3.2.9. Probabilistic approach - Monte-Carlo simulation

S The Monte-Carlo is very powerful to manage uncertainties on the values of the input parameters of the LCCA like

RAM parameter (MTBF, MTTR) or
Unit cost value.

Implementation steps

In the *first step* the technical and economical uncertainties have to be identified using expert estimations.

In the *second step* the impact on the predicted LCC should be analysed by using a simple sensitivity analysis like shown in Figure 24. This results of this analysis helps to focus further work on relevant parameter.

In the *third step* the probability density functions or probability distributions which represent the possible values and their probability of occurrence. For the functions different approaches are possible like triangular distribution, normal distribution, lognormal distribution, uniform distribution or Weibull distributions (**Figure 25**).

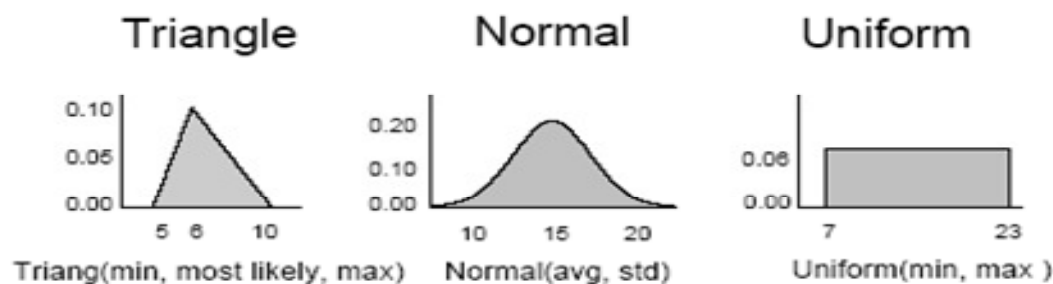


Figure 25: Probability density functions

Especially the continuous Weibull distribution enables nearly all distributions by the control of parameters.

The definition of the distribution functions should be done on the basis of a RAM(S) analysis, data bases or by expert estimations.

The *fourth step* is now to run the Monte-Carlo simulation with appropriate LCC tools like D-LCC. Figure 26 shows a schematic of Monte-Carlo simulation including the third step.

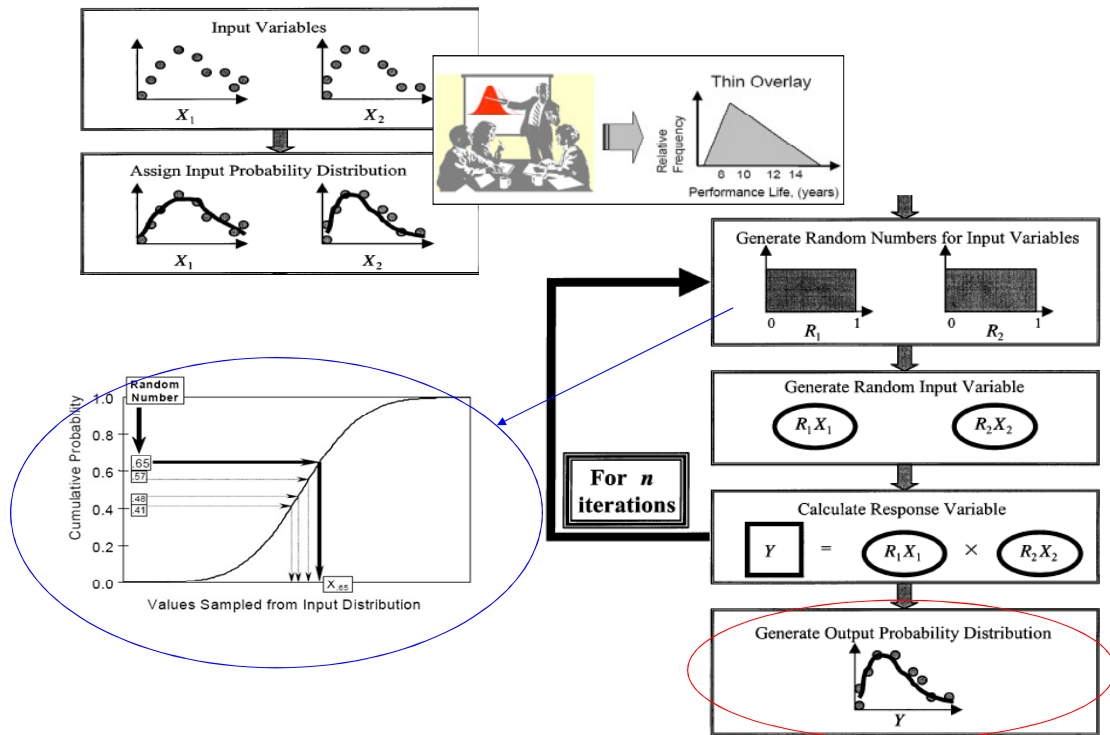


Figure 26: Schematic of Monte-Carlo simulation

The fifth and last step is the interpretation of the calculated results (Figure 27). The results can be plotted in different views like

- probability distribution function of NPV for the different alternatives or
- cumulative probability distribution of NPV for the alternative.

As you can see in Figure 27 all variables of the calculation including the discount rate can be described with a PDF.

Depending on the PDF of the different technical and economical variables in the LCCA the PDF of the resulting NPV differs for the alternatives. The probabilistic approach identifies risks and chances and also helps to focus on further data analyses or technical improvements.

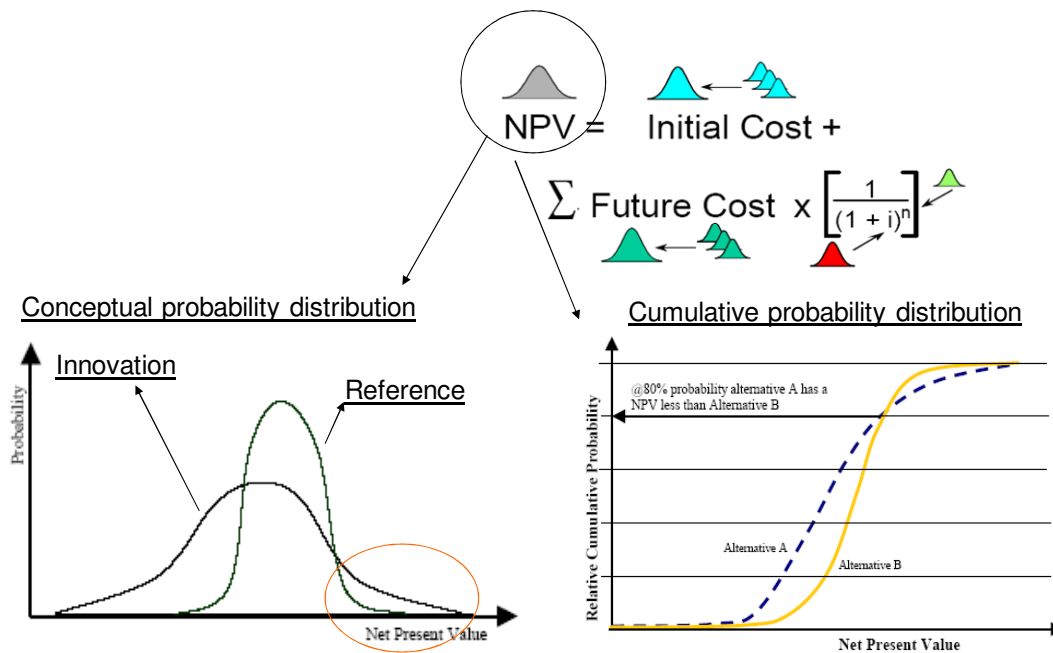


Figure 27: Schematic - interpretation of results of Monte-Carlo simulation

3.2.10. RAMS Technology

RAMS technology is a management and engineering discipline for the purpose to predict the specified functionality of a product over its' complete life cycle. RAMS technology keeps the operation, maintenance and disposal costs at a predefined accepted level, by establishing the relevant performance characteristics at the beginning of the procurement cycle and by monitoring and controlling their implementation throughout all project phases. The RAMS characteristics determine essential parameters of the system such as the usability and acceptability of the system, the operation and maintenance costs, and the users' safety and health risk when operating the system.

RAMS according to EN 50126 is an abbreviation describing a combination of Reliability (R), Availability (A), Maintainability (M) and Safety (S):

- Reliability is defined as the probability that an item can perform a required function under given conditions for a given time interval.
- Availability: the availability of an object being in a condition in order to fulfil a required function under given terms and given

period or during an alleged span of time provided that the required auxiliary materials/external tools are available.

- **Maintainability:** the feasibility that a certain maintenance measure could be executed for a component under existing boundary conditions within a defined span of time, if the maintenance will be made under defined conditions and defined process and auxiliary materials will be used.
- **Safety:** the non-existence of an unacceptable damage risk.

The EN 50126 (Specification and the proof of the reliability, availability, maintainability and safety (RAMS) of rail applications) is issued by the CENELEC. The standard describes the engineering, construction, use and demolition of a railway system from the perspective of RAMS. Rail infra projects executed by Infra Managers must meet standard EN 50126.

3.2.11. V-Model according EN 50126

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The V-Model (or VEE model) is a systems development model designed to simplify the understanding of the complexity associated with developing systems. In systems engineering it is used to define a uniform procedure for product or project development.

The V-model is a graphical representation of the systems development lifecycle. It summarizes the main steps to be taken in conjunction with the corresponding deliverables within computerized system validation framework. The downward line of the V-Model implies the project definition, a constant interchange of user and functional requirements, configuration and technical specifications. This is a decomposition from the global level until a detailed design is eventually generated. The upward line reverses the sequence of project test and integration (installation, validation and acceptance of the system including the acceptance by the maintenance department). Going on with monitoring of the systems performance and the modification, the model ends up with the disposal after the end of the time life of the system.

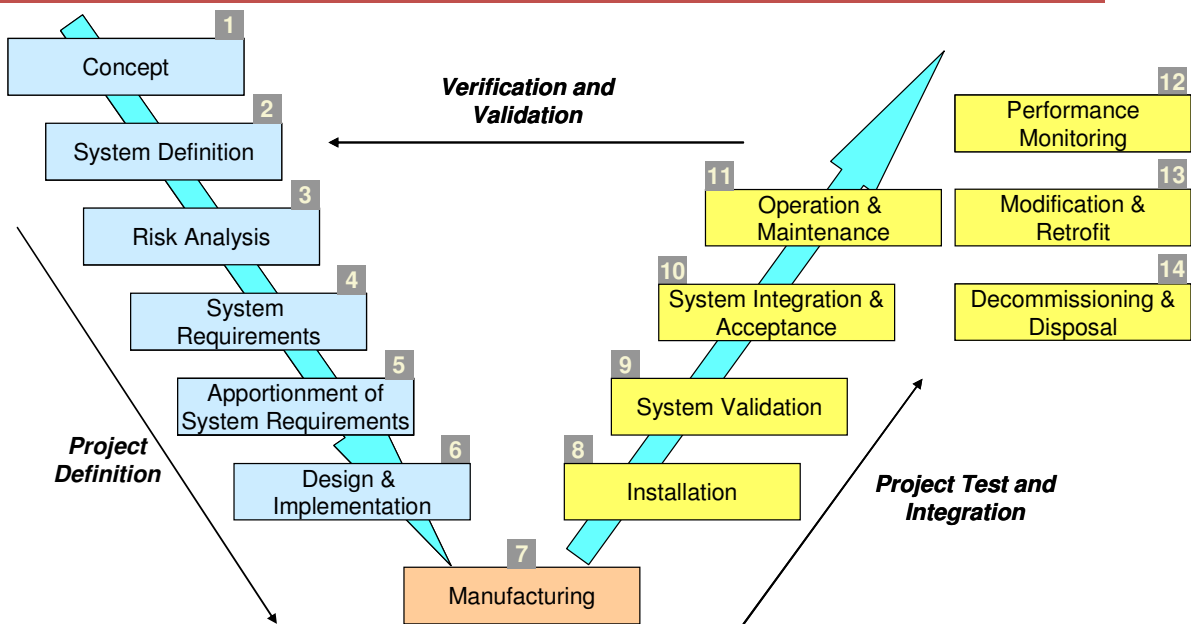


Figure 28: V-Model according EN 50126

Definition and approval of RAMS parameter/specifications is important

The questions before starting a RAMS analysis probably are: what question has to be answered with a RAMS & LCC analysis? Or what questions have to be solved and how they could be to solved?

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In general, the target of the RAMS analysis consists in

- prediction of reliability by failure rate analysis and
- prediction of serviceability and availability by maintainability analysis

The components determining the system functionality are defined by the requirements of the customers, which on the other hand are described by the RAMS parameter (reliability, availability, maintainability and safety) and affect the system reliability and total performance according to EN50126. In a narrower sense, all requirements are greatly influenced by the reliability. It's essential to define clearly the RAMS and LCC specifications and to fix those in the contracts with manufacturers and contractors as far as possible.

So a project starts with a set of functional requirements. The right key parameters have to be described and identified. The defined specifications and the key parameters are project specific and serve to solve the questions of the concerned project, e. g. to predict the fu-

ture performance and costs or to select the variant which meet the requirements/needs of the shareholders/project.

The background of the definition of the specifications is to solve the problem to be faced with. A procedure could be to answer the overall questions: which RAMS parameters are taken as a basis and which goals should be achieved by the RAMS analysis? could be:

first to find out how to get the RAMS specifications
then to define RAMS specifications at top level as starting base
detailed specifications with each ongoing phase

More indication on this issue see chapter 4.4.

By determination of RAMS goals the parameters taken from the system requirements/specifications have to be stated more precisely. Usually parameters are generated as requirements in reference to Mean Time Between Failure (MTBF) and availability parameter (measured in train delays in hours). If there are no detailed specifications regarding the RAMS parameters, the following indications and questions respectively to be solved by a RAMS analysis could be helpful, as described in the following:

- Availability: according to the question in what extent is the system/track available for the operation/use? ⇒ guarantee of availability of the track without traffic interruptions, i. e. the maintenance activities are carried out beyond the operating time
- Reliability: according to the question what kind of failures and how often do they occur? ⇒ knowledge of the system/track behaviour to be analysed regarding the failure rate and wear implying the impact on operation and lifetime of a system/product/component
- Maintainability: according to the question how good and how bad is the system/track maintained? ⇒ to identify an approach of an optimal maintenance strategy
- Safety: according to the question what consequences do the failures have? --> identification of security relevant functions

At the end of the analysis a reference should be taken to the specifications fixed before the analysis. For the example the reference for the above described could be:

- Availability: the availability of the system/track is assured, because there are no operational disturbances which cause limitation of the track operation
- Reliability: the amount and the locality of the failures are identified, based on this results further conclusions regarding the failure and wear behaviour could be driven
- Maintainability: an approach for an optimal maintenance strategy could be an indication concerning the grinding interval
- Safety: the focus is not on safety issue but for LCC and RAM analysis, because we act on the assumption that the railway company use suitable and safe devices for their application

In the next section there is a summary of common used parameters for RAMS specifications.

Parameters for Reliability

Parameters in use are failure rate (λ), Mean Time Between Failure (MTBF), Number of failures in the system per month/per year and Number of train influencing failures.

Failure rate (λ)

The probability of failure per unit of time of items in operation; sometimes estimated as a ratio of the number of failures to the accumulated operating time for the items. Failure rate is usually time dependent, and thus the rates change over time versus the expected life cycle of a system.

$$\lambda(t) = \text{Failures} / \text{time unit}$$

Failure rate is the frequency with which an engineered system or component fails, expressed for example in failures per hour. In the special case when the likelihood of failure remains constant with respect to time (for example, in some product like a brick or protected steel beam), failure rate is simply the inverse of the Mean Time Between Failure (MTBF), expressed for example in hours per failure.

Mean Time between Failure (MTBF)

Mean Time between Failures, is a basic measure of a system's reliability. It is typically represented in units of hours. The higher the MTBF number is, the higher the reliability of the product.

Further reliability parameters are MTTF (Mean Time To Failure), MTBM (Mean Time Between Maintenance for preventive Maintenance), MTFE (Mean Time to First Failure) and Train delaying failures.

Parameters for Availability

Every IM has its own key performance indicators regarding the availability. It is a fact that it is still very difficult to raise non-availability costs. There are also differences in each nation in raising the costs related to non-availability. Therefore it's a difficult issue, because besides the economic factors it depends on the way of thinking and the philosophy respectively to deal with it.

The availability could be measured for example in train delay (hours), total train delay, train delay caused by infrastructure, train delay caused by a specified infrastructure asset and punctuality of passenger and freight train. There is also a code for what caused the train delay.

A definition of train delay could be: if the train is more than 5 minutes late. A primary delay to a train is a delay that directly affects the train. A secondary delay is a delay caused by a primary delayed train, the terms knock-on delay and cascading delay are used synonymously.

It's a question how the availability parameters (the method) are calculated? How the cost due to down time, unavailability, train delay caused by infrastructure, traffic disruption, penalty etc. is calculated in the LCC model?

Parameters for Maintainability

Parameters in use are: Mean Time To Repair (MTTR), Mean Time Between Maintenance (MTBM), Mean Time Between Repair (MTBR), Mean Maintenance Hours (MMH), MDT (Mean Down Time) as well as Mean Logistic Delay Time.

Mean Time Between Maintenance (MTBM)

MTBM is the average time between all system maintenance actions. Maintenance actions may be for both, preventive purpose or repair.

Mean Time Between Repair (MTBR)

The average time between corrective maintenance actions, which require removal or replacement of a subsystem.

Mean Time To Repair (MTTR)

The sum of corrective maintenance times divided by the total number of repairs within an item. That indicates the average time to fully repair a failed system – it includes detection of failure(s) removal and replacement of the failed component(s) and final check.

MTBM, MTBR and MTTR are basic measures of maintainability. Complex systems, like railway track (or railway infrastructure as a whole) would need combination of the basic measure and other means of evaluation.

Parameters for Safety

Parameters in use are Hazard rate, Number of accidents, Number of derailments, Number of accidents due to external sources, Number of accidents due to internal sources and incidents that could have led to accidents/damage.

A quantitative analysis produces a quantitative pronouncement on the safety level in terms of personal hazard (i.e. risk of fatality per time unit or per train kilometres for various risk-bearers) and/or social hazards (e.g. total number of fatalities per year or frequency of major accidents).

The safety aspect is not studied since it is not the focus of this guideline. We assume that the railway companies use suitable and safe devices for their applications. Nevertheless, the safety aspect needs to be considered in specifications for components and equipment.

If a safety analysis is required, see details chapter 4.6.5 of this Guideline.

Definition of boundary conditions

The identification and definition of the boundary conditions that will affect the chosen RAMS parameters (e. g. the reliability of components/ system) are very important.

The environmental conditions in which the equipment is to be operated, such as temperature, humidity, dust, maintenance facilities, maintenance and operation personnel training etc. often have considerable influence on the product reliability characteristics and thereby on the maintenance and product support requirement. During the operation phase, manufacturers can benefit from obtaining information about the product's technical health as well as conformance and deviations from the expected performance targets.

As described in the previous chapter the result of defined boundary conditions can be visualized as an In/Out Frame. This is the best way to make clear the range and define the base of the boundary conditions to be analysed within the LCC and RAMS analysis. The clearly and accurately the boundary conditions are defined and documented the better is the LCCA.

The identification of the RAMS parameters is the core of a RAMS analysis. In addition to the definition and assessment of the RAMS parameters the data collection and data processing are the most important part of RAMS and LCC analysis. But it is also important that the RAMS data are followed up.

Regarding the key values for analysis and minimum quality of data see section 4.5. Indication of key values and quality of data needed for the analysis, conjunction to the paragraph effort vs. benefit.

The analysis within the InnoTrack project confirms that the use of key values for LCC and RAMS is in a development phase and that there is a need to develop measurable key values for RAMS and LCC.

Current state of RAMS practice

Today we can say that RAMS in railway infrastructure is in a very early stage of development and there is more basic development necessary.

The use of RAMS analysis in the railway infrastructure is limited and where it occurs it is in an early stage, especially in the track and civil

engineering sector. This is in contrast e.g. to the signalling sector where the use of RAMS is more used. The reason is the complexity of the railway system and the tradition of the track and civil engineering system. The complexity stems from several sources. One is the interaction of several railway areas (track, S&C, catenary and signalling, etc.). A second complication is the vast need of data for RAMS analysis. This data is often hard to define and scattered between different databases and organisations. In other words, there exists a lot of measured data in the track sector, but this data is seldom easy to obtain and often difficult to compare between railways since they are defined/measured in different manners. Furthermore it is not obvious which data is relevant for RAMS analysis. Additionally, geographical distribution of assets and various influences of the environment increase the complexity.

More basic development is necessary before RAMS analysis can become fully functional in the railway community.

Results from the analysis carried out within InnoTrack show that there are several development areas. Although it is necessary to keep in mind that most papers in the literature review do not consider the environment for the “outdoor” infrastructure systems. This means that the system is more affected by the operational conditions than in an in-house plant. Other parameters that make it difficult to define or put up key values for RAMS and LCC for infrastructure are that there is a third part operating the track (traffic companies) and also that maintenance often can be outsourced.

3.3. Description of the economic benefits from RAMS and LCC analysis

Efficient asset and life cycle management of both infrastructure and rolling stock are one of the ways to stay ahead of competition. New investments require a critical and thorough analysis of the additional costs for maintenance, repair, overhaul and utility in a sector where high demands on reliability, availability, maintainability, safety, health and environment are imperative. This results in a different tendering process, new financing methods, a change in business agreements and chances for innovative technology & engineering. The decision-making process regarding infrastructural choices must always include the RAMS / LCC impact of the finished product. The InnoTrack project has managed to define and implement a harmo-

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nized LCC and RAMS technology for the infrastructure at European level including the development of general definitions, requirements for LCC and RAMS analysis and an applicable LCC tool. The established LCC calculation method enables to continue the analysis of cost drivers.

Basis of RAMS/LCC technology

Holistic approach

Information logistics with following principles:

The determination of relevant data for RAMS and LCC analysis in a appropriate quality, appropriate quantity and accurate form. The aim must be to merge the various data sources in a consolidated database system by theme clustered, time-related and permanent collection (continuous data flow over the total life cycle) of data for assessment and decision support of the management.

Mapping of the reality with appropriate modelling

Experts with knowledge and experience in the field of RAMS and LCC

Most of these needed works are implemented in the control loop of reliability management, illustrated in Figure 29.

Control loop of Reliability Management:

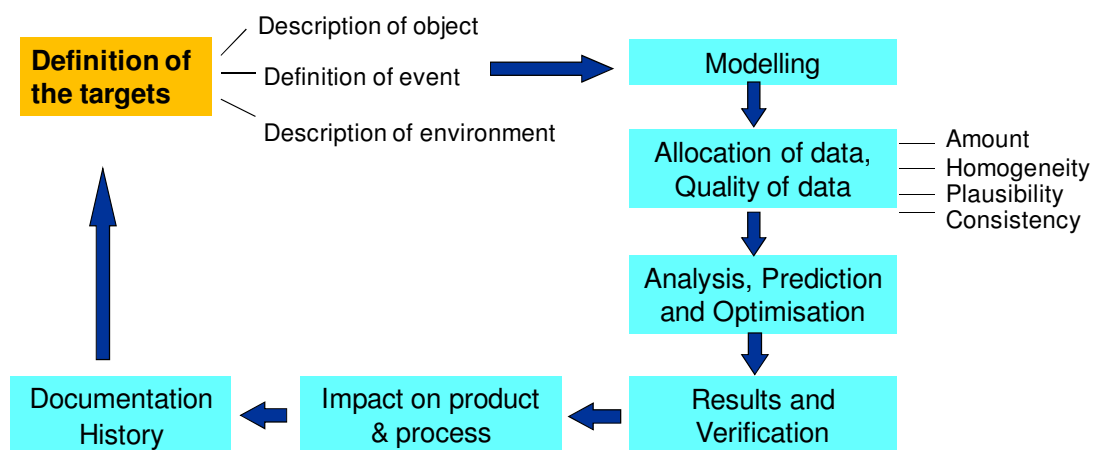


Figure 29: Schematic representation of the control loop for reliability management

Targets of RAMS/LCC technology

assessment of different solutions and prediction of costs over the whole life cycle as well as comparison of various strategy options

Ensuring and increase of business success through quality and customer satisfaction

Optimisation of reliability and availability costs by ensuring of quality at the same time

Cost guarantee, planning reliability and benefit certainty

Benefits of RAMS and LCC

assessment and comparison of alternative strategies and design

Transparency of the costs

Security of the decision making

Exploitation of life time reserve

Reduction of Life cycle costs through reliability related process planning

Optimisation of reliability, availability and security

Strengthening the business case

Preconditions for RAMS and LCC analysis are

Knowledge of the reliability of system and process

adapted organisational structure and workflows

Systematisation

Expertise

Appropriate tools

Holistic approach

Motivation and staying power

One of the major benefits of RAMS and LCC analysis is to optimise maintenance strategy and taking decision on maintenance with the regulators.

Relation between effort and benefits

A project starts with a set of functional requirements. In the investigation phase all the possible variants to meet the specifications has to be listed. The right and feasible variants have to be identified, because many variants are addressed but not all are feasible. At the end of the investigation phase (variant study) only the variants with the highest potential are chosen to be investigated in the next phase. In the variant study only 2 or 3 variants are further investigated.

LCC is an appropriate method to identify cost driver and to gather the costs of a system/module/component over its whole life time. Different views and evaluations allow the comparison of different systems/alternatives and delivers necessary information for technical and economical decisions. Especially decisions in the early phases of the product life are very important.

Therefore a LCC and RAMS analysis should be done with a cost-benefit analysis which is naturally project specific. The task is to identify the potential savings during the analysis: if the potential benefits are less but linked with high costs, there is no use to continue with the analysis.

The next step to be checked is: do we have the base to carry out the analysis with a justifiable investment or not? This question has also to be answered before starting with the analysis, that could be linked with a huge effort and costs but without resulting any potential benefit.

For example - RAMS analysis of switches:

First step could be to identify the root causes of the problems and to find out what are the causes for the occurred failures. Before starting with a LCC and RAMS analysis it's important to evaluate whether it's worth to do and to identify the impact of such an analysis. This helps to minimise effort and money for a carried out analysis because it would not be necessary or because of the minor the impact or because of the less benefits potential.

In order to minimise effort and money it may be sufficient for the first analysis to take only a representative amount (panels = representative panels means the selection of technical places) instead of

taking all the existing switches in the existing net into consideration. Based on the selected panels the analysis can be carried out.

Regarding the key values for analysis and minimum quality of data see section 4.5.

3.4. Relation between LCC and RAMS

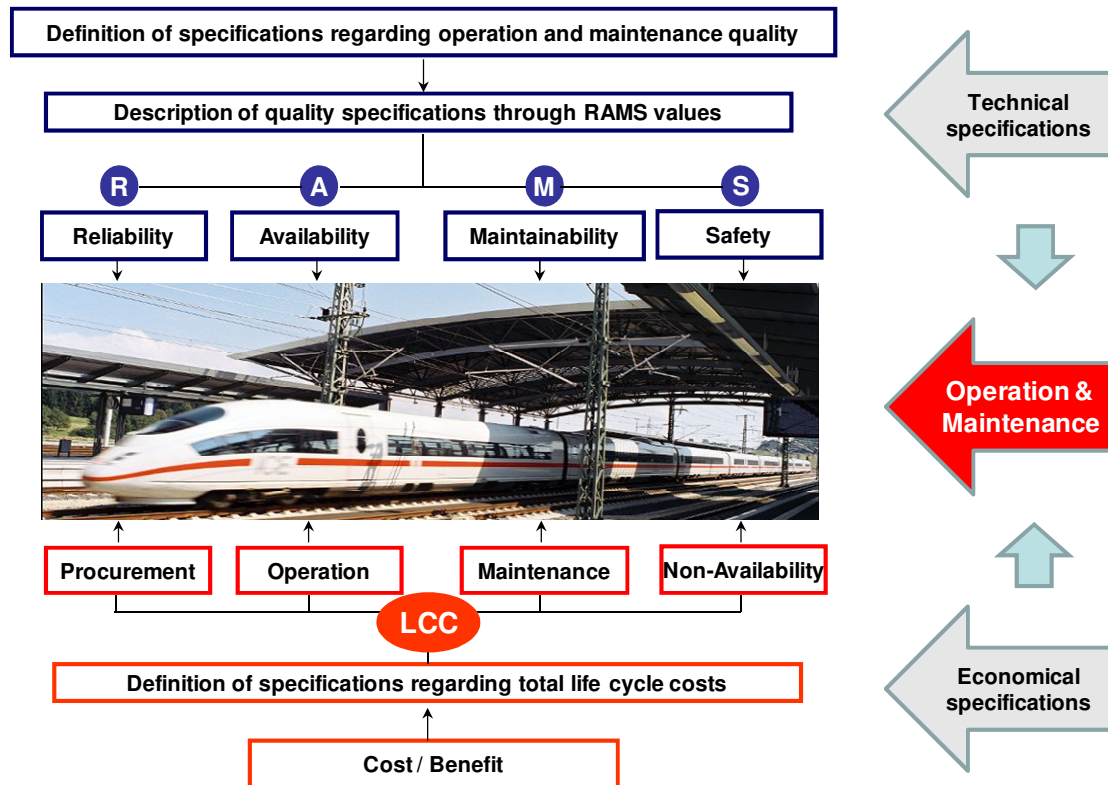


Figure 30: Conjunction between RAMS and LCC

Life Cycle Costs are one of the most important decision criteria for the procurement or development of new products. Often the technicians decide on the basis of the technical behaviour of a product and the controller on the basis of short-term costs. But primary the combination of the procurement cost, the maintenance and non-availability costs, strongly influenced by the technical performance of the product as well as the disposal and recycling costs, result in the total costs of the product and should be basis for decision. Although Life Cycle Costing is a standard method the technicians and the controllers are not aware of the influences of the different cost items on the economy of the product. The standard IEC 300-3-3 [2] as guideline for application of reliability management straightens out the LCC analysis an integral part of the reliability management, if the approach of achieving the optimum in terms of product properties and

costs is aimed. The balance between technical and economical aspects is considered by the life cycle costs.

A good insight in and control of the total lifecycle costs of rail assets is crucial in order to obtain and maintain competitive advantage. In this process it is imperative to secure or preferably increase reliability, maintainability, availability and safety when looking for ways to reduce the life cycle costs.

It is fact that the technical performance of a system influences the LCC. Therefore not only the technical parameter but also the follow-up costs over the life time of a system or component like maintenance costs should be taken into consideration. In general, the technical performance such as lifetime or maintenance and cost are known for the base case but unknown for the innovation. Because the technical performance of a system or component strongly influences the life cycle costs, these parameters have to be verified very carefully for innovation.

The RAMS analysis is the base for LCC assessment and an important part/element to optimise the costs of a product over the total life time of a product/system.

The decision-making process regarding infrastructural choices must always include the RAMS / LCC impact of the finished product. If the impact is significant the RAMS / LCC analysis will be given a greater degree of detail than if the impact is minor. The Infra Manager has to decide not to conduct explicit RAMS analyses of projects that have only a minor impact on the RAMS / LCC performance. However, RAMS / LCC specification will always be requested for the next phase, but the specification will also differ for each project in terms of detail and scope. The achievable RAMS targets should be defined and to obtain those targets a procedure should be elaborated.

This means that the detailing of the RAMS / LCC analysis will differ for each project type and phase.

4. RAMS and LCC Analysis

4.1. *Necessity and criteria for RAMS & LCC analysis*

To check whether a LCC or RAMS analysis is necessary through a cost-benefit analysis. What question has to be answered with RAMS & LCC analysis?

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When is a detailed analysis necessary? E.g. short life time of components, short maintenance intervals, estimated maintenance costs are more than x percent of investment, high non-availability costs, service life of components differs strongly, strong increase of requirements, new regulations.

4.2. *Description of the system and boundary conditions*

The railway infrastructure is a vital part in the railway system, as shown in **Figure 31**. The other vital part is the rolling stock. The interaction between infrastructure and rolling stock is operated by traffic control centres.

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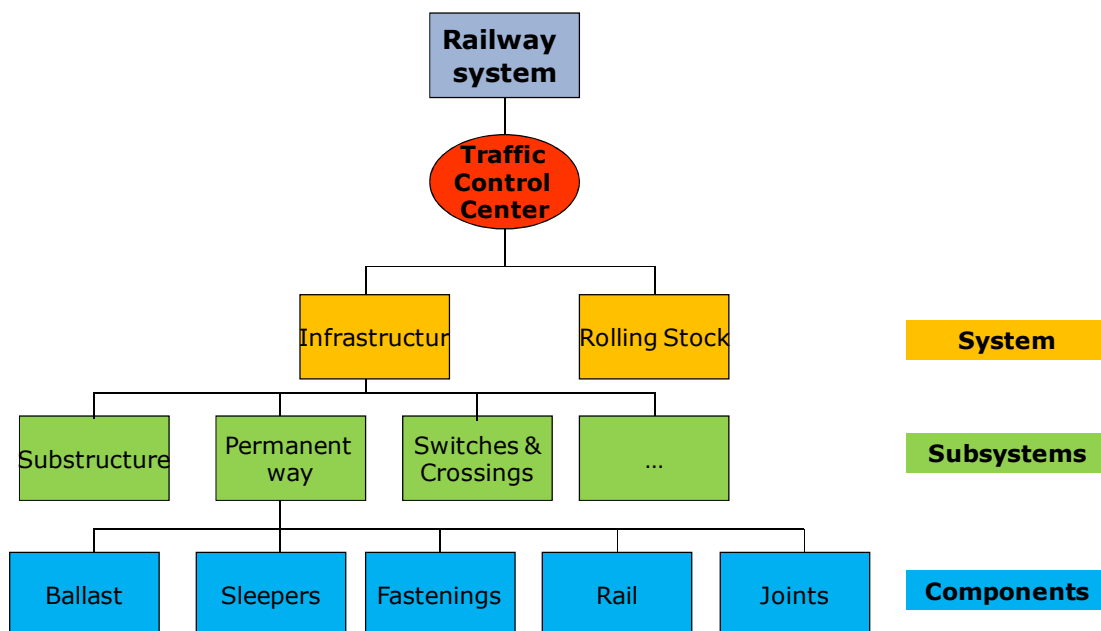


Figure 31: The Railway system

The railway infrastructure can be divided in subsystems, e.g. substructure, permanent way, switches and crossings and so on. The

Subsystem may in turn be divided in components, e.g. such as ballast, sleepers, fastenings, rails and joints.

The complexity is further enhanced by the amount (density) of asset. Increased amounts of track (single, double), switches and crossings, etc., in order to increase capacity or/end redundancy, requires, among other things, more planning and control.

In an ideal situation the infrastructure assets are fortunate in verifiable conditions, i.e. we know how the assets are used and how they break down. This means that we have control and knowledge of the traffic operating the track and degenerate the track. We also have control over the environment in which the facility is located, namely that it is not adversely affected by e.g. corrosion, weather, sabotage.

In reality, however, both unwanted and unexpected events occurs that affect the system and causes adverse and undesirable output e.g. train delays, see **Figure 32**. These events can also be called negative boundary condition, and will affect the reliability and availability of the system.

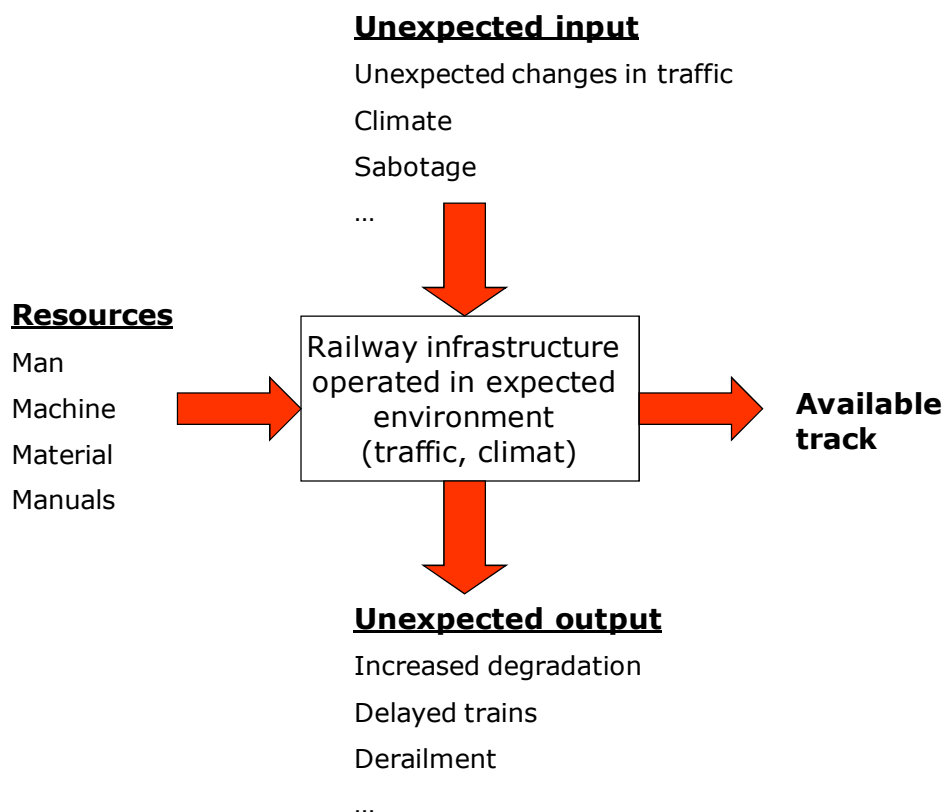


Figure 32: Unexpected input/output affecting the reliability and availability

Boundary conditions are those factors that might change the planning or the contract commitments, beyond what the planner/contractors are able to influence over. For the documentation the In/Out Frame shown in Figure 18 can be use.

Such factors are:

- Traffic:
 - type of train and their maintenance standard – yaw stiffness/wheel profiles.
 - axle weight
 - speed
 - traffic volume (amount of trains, MGT, mix of traffic)
- Track related:
 - track quality
 - structure beneath substructure
- How to establish maintenance logistic (logistic time)
- Climate (cold weather, storms, flooding)
- Unwanted objects in the track (animals, tractors, etc.)
- Sabotage

These boundary factors needs to be continuous monitored. There is a need to develop methods for vehicle classification and monitoring of their maintenance condition and how their condition affects the degradation on the infrastructure assets. There is also need to improve ways of getting feedback of how the track is operated, amount of trains, mix of trains. Risk assessments for unwanted events must be included as early as possible in the planning phase.

Note that if other assets or systems are considered, e.g. signalling system, there might be other boundary conditions to consider.

4.3. Investigation of different variants

A project starts with a (set of) functional requirement(s), such as:

*Functional requirement in investigation phase:
The travel time for passenger trains between Berlin and Paris must decrease with 45 minutes.*

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In the investigation phase all the possible variants to meet the specs are listed:

- Less stops
- Shorten en straighten the track
- Using high speed switches
- Faster trains on existing track
- High speed trains on new track
- ...

Many variants are addressed but not all are feasible. At the end of the investigation phase only the variants with the highest potential are chosen to be investigated in the next phase: Variant study.

*Example of a subject in variant study:
In the variant study we choose between a tunnel and a bridge*

In the variant study only 2 or 3 variants are further investigated. One of the issues to compare the variants can be the RAMS / LCC performance. In that case a RAMS / LCC analyses can be part of the Variant study. It depends on the type of project what questions the project manager wants to be answered by the RAMS / LCC analyses.

The choice for one of the variants can be based on politics, RAMS, LCC, functionality, etc.. At the end of the Variant study one of the variants is preferred. This preferred alternative is worked out in the next phase: Preferred Variant study.

*Example of a subject in preferred variant study:
In the preferred variant study we choose between a concrete and steel bridge*

In the Preferred Variant study the preferred variant is designed in more detail. There is more knowledge of the future infra. The RAMS / LCC study is more detailed. Where needed the RAMS / LCC can be used to make a decision between different options of the preferred variant? But RAMS / LCC must also be used to predict the future performance RAMS performance and LCC costs. This prediction is used in the next phase: Realisation

*Example of a subject in realisation phase:
In the realisation phase we make a choice between paint on the bridge or galvanising treatment of the steel base material*

In the realisation phase the final choices are made. The final requirements are written in the Specifications for contract. When needed different contracts are used for the different (sub) contractors.

4.4. *Definition and approval of RAMS parameters and specifications*

Projects for the development of a new system (e.g. a switch) or a new piece of track (e.g. from Lelystad to Zwolle in the Netherlands) have many different shareholders. The maintenance department is one of the shareholders. All the shareholders have different needs.

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The reasons we need specifications of the new system or new piece of track are:

- Verification if the design meets needs of the shareholders.
- Specifications help making a choice between the various alternatives.
- Using systems that meets the regulations of the Infra Manager is not a guarantee for a good RAMS performance of a new piece of track.
- Not everything that is designed has a good RAMS performance.
- When the maintenance department does not bring its needs early in the project maintenance is not a key design parameter. This can lead to sub optimization of the project. Prior to delivery the maintenance department is then confronted with a design that can only be maintained at a higher cost.
- When the RAMS performance is not specified is it impossible for the maintenance department to make a proper maintenance plan.

The needs of the all the shareholders are written down in the Client Requirement Specifications (CRS). Based on the CRS and preliminary designs the System Requirements Specifications (SRS) are generated. In the SRS the project team writes what they will deliver to the “client”.

The Specification for contract contains what is specified for the various (sub) contractors. Be aware that the specifications in all the (sub) contracts must lead to realisation of the top specifications of the whole project. Always make sure the RAMS analyses also combines

all the (sub) contracts and validates whether the top specifications can be realised by the chosen variant.

The relationship between the steps in the V model of EN 50126, the project phasing and the deliverables are illustrated in the **Figure 33**.

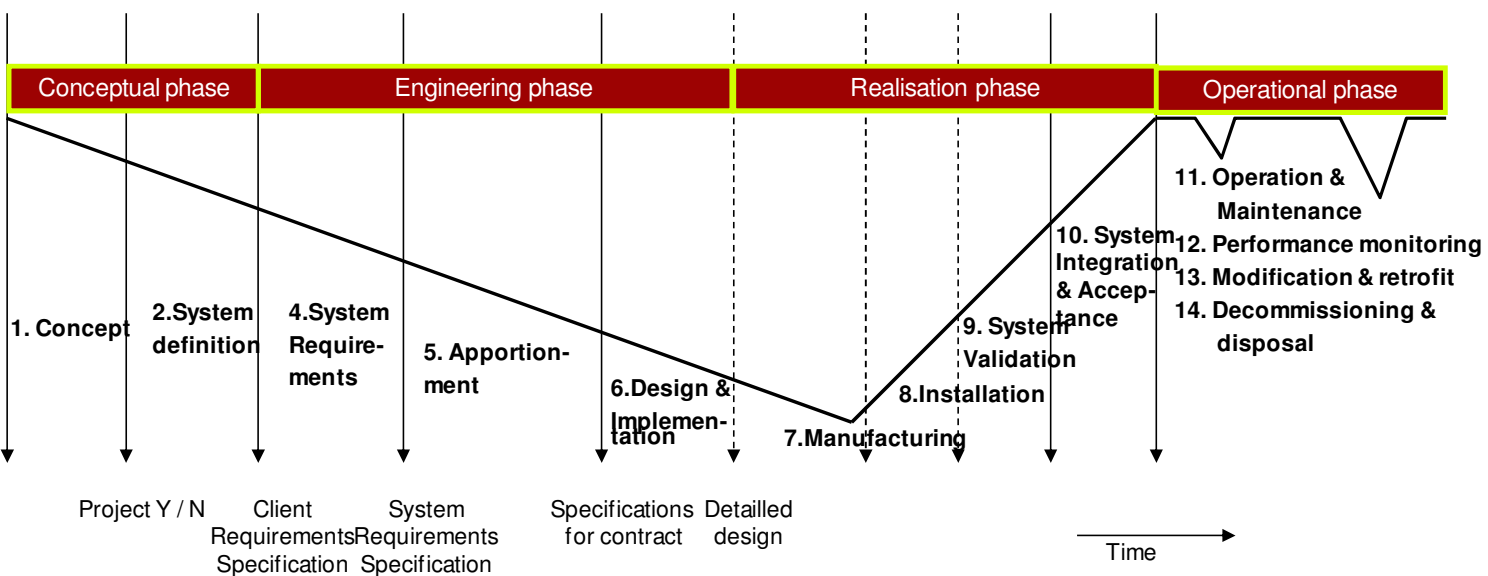


Figure 33: The V model according EN 50126

The EN 50126 (Specification and the proof of the reliability, availability, maintainability and safety (RAMS) of rail applications) is issued by the CENELEC. The standard describes the engineering, construction, use and demolition of a railway system from the perspective of RAMS. Rail infra projects executed by Infra Managers must meet standard EN 50126.

The downward line involves a constant interchange of specification, design and consideration – a decomposition from the global level until a detailed design is eventually generated.

The upward line reverses the sequence – integration of individual systems until and including the final system acceptance (delivery). Acceptance by the maintenance department takes place in phase 10, possibly after approval by a Safety Authority.

The RAMS specifications are called “aspect requirements”. The following items can be part of the aspect requirements:

- Reliability & Availability
- Lifetime
- Maintenance
 - Maintainability
 - Cost for maintenance
 - Accessibility of rail infrastructure
- Safety
 - System
 - Occupational safety
 - Social safety
- Health
- Environment
- Sustainability

A set of generic specifications can be used as a base. But for each project these specifications must be made project specific. This means that not all the generic specifications are needed to describe the needs of the stakeholders. The generic specifications must be quantified for the project. Due to specific items in the project new specifications can be introduced.

4.5. Key values for analysis and minimum quality of data

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The key values required for RAMS analysis will depend greatly on the specific analysis being carried out and specific national requirements. For example if the RAMS data is to be used for a simple life cycle cost calculation where costs of delays and interruption to traffic are not considered then 'Mean Time Between Failure' and the cost to repair and maintain, will be the key RAMS value. However, if the purpose of your RAMS calculation is to consider availability of a line and the impact of delays, then 'Mean Time Between Service Affecting Failure', 'Mean Time to Repair' and 'Mean Time to Maintain' become the critical RAMS values.

However, infrastructure managers should collect a standardized set of RAMS data and build up and maintain a database of these values, therefore it important to standardize on a set of key values which can be utilized; D6.4.1 identified the following key values for RAMS and LCC.

Table 1: Key values for RAMS and LCC

Reliability	Availability	Maintainability	Safety
<i>MTBF</i> , Mean Time Between Failure for corrective maintenance	Train delay hours	<i>MTTR</i> or <i>MART</i> , Mean Time to Repair or Mean Active	Hazard Rate
<i>MTBM</i> , Mean Time Between Maintenance for preventive maintenance	<i>PPM</i> , Passenger Performance Measure	Repair Time	Number of derailment due to asset
<i>MTBCF</i> , Mean Time Between Critical Failure		<i>MTTM</i> , Mean Time to Maintain	Number of accidents
<i>MTBSAF</i> , Mean Time Between Service Affecting Failure		<i>MDT</i> , Mean Down Time	

4.5.1. Data sources

The key sources of data for RAMS parameters are:

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- Infrastructure manager's or contractor's maintenance databases, records and asset registers
- Models and simulations
- Laboratory/test data
- Manufacturer's data
- Generic component reliability data
- Expert estimation

The source of data used for RAMS data depends mainly upon the availability of the data. The most reliable source of data is that which is collected from maintenance databases and records that truly reflect the performance of the equipment or infrastructure. However, this is not always possible; for example in the case of assessing a new technology where there is no actual historical data available. In this case models and simulations, test or laboratory data, manufacturers data from other installations and/or generic component reliability data can be used build up an overall probability of failure.

Key to the interpretation and use of this RAMS data is the understanding of the reliability of the data and the distribution and causes of the failures. Incidents can be classified as having either operational or technical causes and the incidents with causes such as wear should be related to the traffic type and MGT, rather than time alone. For other equipment such as switch motors the wear will be dependant upon cycles as well time and for other components reliability can be dependant upon time, cycles and load. Therefore, to provide useful data it is essential to categorize the equipment based on equipment type, model and operating conditions which could include line type (mixed, passenger only, freight only), gross tonnes per year, region etc. The RAMS data collected can then be defined for specific categories or a relationship can be developed to relate MTBF to MGT or cycles.

Table 2: Technical and operational incidents

<i>Technical incidents includes those caused by</i>	<i>Operational incidents include those caused by</i>
<ul style="list-style-type: none"> • physical defects and wear; • equipment/components being out of adjustment/tolerance; • No Fault Found (NFF), restored by reset, tested OK on arrival, etc, i.e. all spurious causes. 	<ul style="list-style-type: none"> • factors external to the equipment and outside its specification, e.g. water/condensation, vibration, settlement/subsidence, overgrown vegetation, damage, vandalism; • operational or maintenance activities on the equipment itself; • operational and maintenance activities on other system/equipment which affect the equipment under observation

Reliability can also vary over the age of complex systems, for example with a motor vehicle the MTBF decreases as the vehicle gets older, or in some cases there can be a very short MTBF in the early life of a system due to initial teething problems or early component failure. Models such as the Duane model should, where appropriate, be used to relate MTBF to the age of the component or system. Other systems will have a constant MTBF.

Duane Model: $MTBF = \frac{T^\alpha}{\lambda}$

Where α is a growth factor, λ is a constant and T is cumulative time.

RAMS data collected from maintenance records is a statistical sample and can therefore be fitted to a statistical distribution such as a X^2 distribution allowing upper and lower limits to be calculated within confidence limits, for values such as MTBF, MTTR and MTBM. However, as maintenance is generally carried out at fixed cycles, MTBM will generally be fixed and any variation will be a result of scheduling. The statistical distribution can be applied directly within an LCC calculation where a Monte Carlo simulation can be used, or the upper

and lower confidence limits can allow for the calculation of best case and worse case scenarios.

RAMS values should be continually reassessed and updated, the greater the sample of data the greater the confidence of the results; additional new data will also help to identify if there has been any major shift in reliability and can help to identify emerging problems or if external factors are affecting particular items of equipment and again statistic tests such as ANOVA test can identify if a new sample of data is significantly different from an existing set data.

RAMS data should also be validated in the case of new or innovative equipment being installed; initial failure rates may have been calculated from finite element models for wear and fatigue and generic failure rates for motors and other components, however, these values should be validated with actual failure data from operation as it is acquired which will also increase confidence in these new values.

4.6. *R, A, M, S analysis*

This chapter clarifies the differences between the different RAMS / LCC analyses. In principle, the analyses relate to the operational phase, but availability and safety aspects are also relevant in the building period. Consider the planning of train free periods and the impact on adjacent operational track zones. So these aspects must be considered at an early stage.

The analyses relating to the building phase and the operational phase must be included separately in the RAMS / LCC analyses and the RAMS dossier.

A RAMS / LCC analysis consists of several analyses, which are indicated on the vertical axis of the **Figure 34**. The guideline provides an aid for the project manager to always clarify the following items per project phase and per analysis method:

What question(s) must be answered with the RAMS / LCC analysis?

What input can be used and where is it available?

What output for the analysis must be delivered for the analysis as a minimum?

What preferred method, models and software must be used for this?

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As an example the matrix of ProRail (see also ref. (1)) is shown in Figure 34.

Analyse	1 Investigation	2A Varianten Study	2B Preferred Variant Study	3 Realisation
RA				
M				
S				
LCC				
RAMS / LCC				
Social Cost and Benefit analyses				
RAMS / LCC spec				
Example of degree of detail	Faster from A → B	Tunnel or bridge	Concrete or steel	Galvanizing or paint

Figure 34: Matrix of ProRail

The guideline describes all analysis methods for a phase. An Infra Manager must specify the contents of the different analysis in every phase of a project. The description is always divided into a question, the input, the method and the output. One question is specified per analysis and per phase. Refer for more ProRail examples to the appendix.

To finish each phase the RAMS / LCC specification must be further detailed in order to function as the basis of the next phase. This means that the results of the various analyses can always be compared with the specification. Effective analysis is not possible without specifications!

In the next paragraphs the ProRail (see ref. 1) implementation is shown of all analyses for a project in phase 2B (Preferred Variant study).

4.6.1. Process description RA, M, S, LCC, SCBA

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This process description relates to all analyses and not only to the RAMS / LCC analysis. The idea behind it is that the results of the RA, M, S and LCC analyses will eventually produce an integrated RAMS / LCC analysis that part of the social cost benefit analysis.

In every phase of the project the result of the previous phase is studied in more detail in order to prepare for the realisation phase. Depending on the type of project RAMS / LCC considerations may play a role in the decision-making process relating to the different options that remain in the variant for infrastructural solution concept (called “variant”).

The procedure described below must be followed in order to execute a complete analysis of the preferred variant for the decision-making process. For every phase in a project the process can be made more specific:

1. Study the results of RAMS / LCC from the previous phase.
Explanation 1: if analyses or specifications were executed or formulated in previous phase(s), the subsequent phases will use them. Certain activities that specified in the following procedure do not need to be executed again, but only checked against and adapted to the current situation. The results of the prior phase are recorded and added to the RAMS / LCC dossier.
Explanation 2: the process owner of the RAMS / LCC dossier must also be succeeded when another department becomes responsible.
2. The project manager must determine which analyses are regarded as necessary in order to support his project. If no separate RAMS / LCC analyses are executed this is also stated in the RAMS / LCC dossier.
3. Give an overview of the current situation with the aid of current RAMS / LCC performance indicators
Explanation 3: In addition a RAMS / LCC counter must be available where the current state of affairs relating to RAMS / LCC performance indicators can be requested.
Explanation 4: In the case of complete new rail infrastructure a comparable situation will have to serve as a reference.
4. Ascertain what the most important changes for rail infra would be for the variant.
Explanation 5: In this phase the variant is worked out in more detail. So we get a better view on the difference between the variant and the current situation.
Explanation 6: analysis of the variant could lead to different options that must be compared in terms of RAMS / LCC aspects.

5. Determine the impact of the most important changes on the RAMS / LCC indicators. Based on the results of this phase a more accurate estimation of the RAMS performance can be made of the infrastructural concept.
 Explanation 7: it is important that the Infra Manager has global RAMS indicators as well as global LCC indicators.
 Explanation 8: Make use of expert opinions (e.g. knowledge of the systems, the specific venue or traffic control)
 Explanation 9: Ensure that the interfaces between RAM and S are given attention and clarified.
 Explanation 10: In every next phase the bandwidth must become smaller.
6. Investigate whether the options within the variant have significant differences
 Explanation 11: if this is not the case, RAMS / LCC will not play a role in the decision regarding the choice between the options, but it is important to communicate the RAMS / LCC estimates for the rest of the project.
7. Estimate the total life cycle costs (LCC) of the variant that will be further examined in the next phase. Here, the focus is particularly on investments and the maintenance costs to be expected.
8. Formulate the RAMS / LCC performance requirements and tighten the requirements in relation to the previous phase on the basis of newly obtained information.
9. Update the RAMS / LCC dossier, which include the most recent Social cost benefit analysis. The RAMS / LCC dossier contains references from specific RAMS / LCC analyses that have played or will play a role in the decision-making process.

4.6.2. Differentiation of projects

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Each project has a unique character. One project must be thoroughly underpinned on the basis of RAMS / LCC in order to arrive at a choice. In other projects the RAMS / LCC performance is not a significant factor in the selection of alternatives. In order to prevent the need for complete RAMS / LCC analyses for every project the projects have been divided into 3 types:

Type 1: project has high impact on RAMS / LCC performance. A detailed RAMS study is needed.

Type 2: project has a medium impact on RAMS / LCC performance. Not all the analyses of this guideline need to be used.

Type 3: Project has no or minor impact on RAMS / LCC performance. Only a limited RAMS / LCC study is needed.

The typing of each project is merely indicative and may change in relation to RAMS / LCC during the project.

Example:

We expect that a project will have a major impact on the RAMS / LCC. It will be regarded as type 1 in the variants study (2A). However, as it becomes clearer which infra issues must be resolved the type may change to 2.

The decision-making process regarding infrastructural choices must always include the RAMS / LCC impact of the finished product. If the impact is significant the RAMS / LCC analysis will be given a greater degree of detail than if the impact is minor. The Infra Manager has to decide not to conduct explicit RAMS analyses of projects that have only a minor impact on the RAMS / LCC performance. However, RAMS / LCC specification will always be requested for the next phase, but the specification will also differ for each project in terms of detail and scope.

This means that the detailing of the RAMS / LCC analysis will differ for each project type and phase.

If no separate RAMS / LCC analyses are executed this is reported in the RAMS / LCC dossier.

4.6.3. Reliability and Availability analysis - operational reliability analysis

The function of an infra system (for example as emplacement or corridor) is the facilitation of rail traffic on the basis of a production model. In principle, an RA analysis can be used to calculate how often the production model cannot be achieved and how long the situation will last. It is important to define clear failure criteria: when does the system no longer function? Depending on the aim of the analysis a

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choice can be made for failure as a consequence of technology, processes, weather, third parties or a combination of these.

The RA analysis starts with the determination of the failure frequency and the non availability of the technical systems. These operational reliability figures are linked to the function (or functions) of the system. The output of the RA analysis for systems consists of a comparison of the existing and the new situation, expressed in disruptions and timetable affecting errors per infra system. Whether a disruption becomes a timetable affecting error depends on the implementation form, redundancy, timetables, etc.

Overall target values can also be included, depending on the nature of the RAMS study.

A more refined analysis will differentiate the various functionalities in the production model. This should make it possible to create different train routes. We must point out that a train connection between A and B can be created via various train routes in a robust infrastructure.

RA analyses of each system must be used as the basis of an RA analysis of each intended train route. Account must be taken of the options for guidance by traffic control. A fault tree analysis is an excellent analysis tool for complex function changes. The output of the RA analysis for each intended train path consists of a comparison of the existing and the new situation, expressed in:

- Disruptions and timetable affecting errors (quantity and function recovery time)

- Non availability per train route in hours

- Number of cancelled and delayed trains (modelling or estimation by traffic control)

Some Infra Managers have specific Key Performance Indicators (KPI) for the reliability and availability. It is necessary to gain a clear view on the effect of new system or the function change on the KPI's at an early stage in the project. The output of the RA analysis for the KPI aspect consists of a comparison of the existing and new situation. The RA analysis is concluded with a comparison with the RA specification as included in the functional Program of Requirements and further detailed in the previous RA analysis.

Question

What change in RA performance is expected for the different options of the preferred variant in relation to the existing situation?

Input

Principle diagrams of intended infra solutions within the selected variant

Standard values (best estimate or key performance figures) of relevant infra objects / elements / systems

Intended production model in terms of train routes

Data: disruptions, timetable affecting errors, function recovery time

Utilisation data of switches, actual number of trains, tonnage and wheels etc..

KPI's

RA analysis previous phase

RA specification drawn up at the end of the previous phase

Method (model / technology / programme)

Prescribe the desired method (e.g. expert opinion, fault tree analysis, FMECA) needed for this specific project

Simulation model. Information from traffic control can also be used.

Sensitivity analysis, e.g. for intended production model or number of timetable affecting errors per switch

Output

RA figures per infra system per option (comparison old – new (per option))

- Disruptions and train effecting errors per infra system (depend on the implementation form, redundancy service schedule, production model etc.)

Depending of the nature of the RAMS study overall performance key figures can also be taken.

RA figures per intended train route per option, including error handling of traffic control. Comparison old – new (per option)

- Number of Timetable affecting errors and function recovery time
- Non availability per train route in hours

- Number of cancelled and delayed trains (possibly estimate traffic control)

KPI availability per option (comparison old – new (per option))

- Only study those infra systems that cause $\approx 80\%$ of the non availability
- Unplanned non availability (result RA – analysis)
- Planned non availability (Maintenance time, result M analysis)

Comparison with RA specification as included in the functional Program of Requirements or System requirements and further detailed at the end of the previous phase.

4.6.4. Maintainability analysis

AST

The M analysis as part of RAMS was originally intended to determine the functional recovery time. The M analysis must contain the following components:

Planned non - availability (= maintenance time). This provides input for the RA analysis.

Overview of maintenance activities to be expected – with frequency, required maintenance hours (preventive and corrective).

Required train free periods and other critical resources during the building phase or risks connected to this and which management measures (with associated costs) can be taken.

Required train free periods for the implementation of preventive and corrective maintenance (incl. possibilities for clustering), specific times, and with specification of special circumstances and/or causes.

Insight into the degree to which it can fit into the current maintenance schedule.

Time available for inspection of objects on the basis of the timetable.

Determine what is required in order to execute the maintenance in accordance with the applicable regulations. Within the M analysis the focus must also be on measures that simplify

maintenance, reduce downtime, reduce costs and guarantee safety, etc.

Costs (input for LCC): It is important not to make the determination of the required capacity and resources more difficult than it is. Ignore the selected contract form where possible.

Maintenance costs (preventive and corrective) per alternative. Only study the changes to the initial situation (e.g. moving of switches leads to investment costs, but for the same amount of trains using the switch there is no change in the maintenance costs).

Estimation of the life cycle costs of the applied components. It is advised to do this at the level of e.g. switches.

Maintenance concepts of systems

Overview of non available maintenance concepts for systems. The missing maintenance concepts are points of attention during the engineering phase of the project.

Plan of approach for the maintenance of the systems that are not yet included in regulations of the Infra Manager.

The following items deserve attention:

- Working safely on the Infra: single / double track out of service, distance between tracks, presence of gates, etc.
- Accessibility of locations for maintenance: roads, inspection paths, material utilisation location etc.

The M analysis is concluded with a comparison with the M specification as it is included in the functional Program of Requirements and further detailed in the previous M analysis.

Question

What change in maintenance work (hours / money) can be expected for the various options of the preferred variant in relation to the existing situation?

Input

Key figures costs data

Maintenance Documentation, maintenance schedule, train free periods needed for realisation, train free periods for maintenance

Relationship between costs, performance and maintenance activities

KPI availability (planned non availability).

M analysis previous phase

M specification drawn up at the end of the previous phase

Method (model / technology / programme):

Output

Planned non availability (= Maintenance time)

- Overview of maintenance operations to be expected, with frequency, required maintenance hours (preventive and corrective)
- Required train free periods and other critical resources during the building phase or which
- risks are attached to them and which management measures (with associated costs) can be taken
- Required train free periods for the implementation of preventive and corrective maintenance (incl. possibilities for clustering), specific times and with specification of special circumstances and/or causes
- Insight into the options for incorporation into the current maintenance schedule
- Time available for inspection of objects on the basis of the service schedule

Costs (input for LCC)

- Costs of maintenance (preventive and corrective) per option. Only study the changes (e.g. changing points does involve investment costs with the same utilisation level, but frequently does not involve any change in maintenance costs)
- Estimation of life cycle of the components used (level points, not lower)

Maintenance Documentation

- Overview of the non available maintenance documentation (= attention point for RAMS study realisation phase)

Comparison with M specification as included in the functional Program of Requirements or System requirements and further detailed at the end of the previous phase.

The following items must be included in the M analysis:

To what degree has working safely on the infra been taken into account: single/double track out of service, distance between tracks, presence of fences, etc.

Accessibility of locations for maintenance: roads, inspection paths, material deployment locations

Summary of possible adaptation to the infrastructure in order to reduce the costs and the planned non availability.

4.6.5. Safety analysis

The system and occupational safety risks for persons and groups in and around the infra system are mapped out with an S analysis (safety analysis). This analysis may be qualitative or quantitative in nature.

S

A qualitative analysis provides insight into the possible hazards for the various risk-bearers, in terms of possible accidents (derailment, collision, unsafe situations due to external party on the infra, unsafe situations due to getting on and off the trains etc.) and the causes of these accidents.

A quantitative analysis produces a quantitative pronouncement on the safety level in terms of personal hazard (i.e. risk of fatality per time unit or per train kilometres for various risk-bearers) and/or social hazards (e.g. total number of fatalities per year or frequency of major accidents).

In principle, the S analysis only relates to the situation after delivery, therefore during operation and maintenance. For the building and completion phase the project must provide an additional Safety and Health plan.

The output of the S analysis consists of a comparison of the existing and new situation, expressed in:

Early phase of project: difference values in the safety level between the different alternatives, technical lay-outs (options). The description of the safety level must comply with the safety goals for System Safety and Occupational Safety of the Infra Manager.

Building and completion phase: Safety level of the completed infra system, expressed in the Infra Managers safety goals for System Safety and Occupational Safety.

It must be established whether a safety case must be made or is already present.

The required generic application safety cases and specific application safety cases are made.

The results of a safety analysis must be compared with the safety goals of the Infra Manager. Sources for these goals include the Safety Management System of the Infra Manager, project plans (e.g. an integrated safety plan) or national policy. In many cases these safety goals are specified at transport system level, whereby factors outside the scope of the infra system also play a role. This means that information on the safety features of other parts of the transport system is required.

The project team will have to describe the safety goal in order to formulate the desired content of the S analysis.

It is important to clearly define the scope of the term 'safety'. This guideline limits the system safety to accidents involving personal injury or fatalities. Other health risks, social safety and environmental safety are outside the scope of this guideline. Although for some projects they can be essential.

The S analysis is concluded with a comparison with the S specification as included in the functional Program of Requirements and further detailed in the prior S analysis.

Question

What change in the safety of the rail system is expected with the different options of the preferred variant in relation to the existing situation?

Input

Principle diagrams of intended infra solution within the chosen variant

Description of the S performance of the different systems used

Intended production model in terms of train routes

Available Safety Cases systems

Accident register of Infra Manager

S analysis previous phase

S specification drawn up at the end of the previous phase

Method (model / technology / programme)

Risk analysis with FTA (fault tree analysis) and/or ETA (event tree analysis)

Qualitative analysis of safety

Quantitative analysis of safety

Output

Difference in safety level between the different technical layouts (options), expressed in the Infra Managers safety goals for system safety and work safety.

It must be ascertained whether a safety case should be created or if it is already present.

Comparison with S specification as included in the functional Program of Requirements or System requirements and further detailed at the end of the previous phase.

4.7. *LCC analysis*

An LCC analysis is intended to determine the total life cycle costs of a system. If desired, the life cycle costs can be determined per functionality or (sub) system.

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The life cycle costs consist of the following components:

- Initial implementation
- Replacement
- Inspections
- Preventive maintenance
- Corrective maintenance
- Demolition

The period, nominal interest rate and the tool to be used for the implementation of the LCC analysis are determined by the contractor and the project manager.

The LCC analysis is concluded with a comparison with the LCC specification as it is included in the functional Schedule of Requirements and further detailed in the prior LCC analysis.

Question

What are the life cycle costs of the different options of the preferred variant?

Input

Per option (possibly including the existing situation):

- Investment (all one-off costs, such as the initial implementation and replacement)
- Results of the M analysis: costs of preventive and corrective maintenance
- Time window (depending on the life cycle of the systems used), interest percentage, analysis year, first year of LCC
- Results RA analysis: number of disruptions and timetable affecting errors

LCC analysis Variants study

LCC specification drawn up at the end of the previous phase

Method (model / technology / programme)

Net present value calculation

Sensitivity analysis, for example for service schedule or the number of timetable affecting errors

Output

Estimation of life cycle costs per option, with an accuracy of 20%

- Initial implementation
- Replacement
- Inspections
- Preventive maintenance
- Corrective maintenance¹

¹ Costs of Corrective Maintenance as part of the life cycle costs relate not only to the disruptions caused by timetable affecting errors, but also to the errors that do not directly affect the train service.

Comparison with LCC specification as included in the functional Program of Requirements or System requirements and further detailed at the end of the previous phase.

4.8. *Combined RAMS and LCC analysis*

ST

In the Cost for non – availability analysis the results of the RA, M, S and LCC analyses are combined. This analysis is used to determine what RAM quality and safety level (S) can be achieved for what life cycle costs.

This analysis highlights the costs for the client (= traveller or freight shipper) as a consequence of the non availability of the infra due to timetable affecting error or train free period. These costs are compared with the LCC.

In this combined analysis a great deal of attention must be devoted to the interfaces between RAM and Safety. Choices relating to the Safety can have significant consequences for the Availability.

The output of the RAMS / LCC analysis consists of a comparison of the existing with the new situation, expressed in:

Cost for the Infra Manager: LCC (life cycle costs)

Costs of cancelled and delayed trains caused by timetable affecting errors in infra, split into effects for the rail sector and effects for society.

Costs of cancelled and delayed trains caused by train free periods, both in the building phase and the operational phase, split into effects for the rail sector and effects for society.

Costs and benefits for passengers (train and road transport), shippers and authorities as a consequence of the SHE performance

The RAMS / LCC analysis is concluded with a comparison with the RAMS / LCC specification as included in the functional Program of Requirements and further detailed in the prior RAMS / LCC analysis.

Question

What option has the highest level of reliability, availability and safety at the lowest life cycle costs?

Input

Results RA analysis: number of cancelled trains (or delay hours), number of delayed trains (or delay hours)

Results M analysis: maintenance costs, (costs of new construction)

Results S analysis: safety levels achieved

Results LCC analysis: estimation of life cycle costs (= costs Infra Manager) per option, using Net Present Value

Costs of cancelled or delayed passenger trains: function of number of trains per hour, duration of the timetable affecting error or train free period, average number of passengers per train on line, etc.

Costs of delays of freight trains: function of number of trains per hour, duration of the timetable affecting error or train free period

RAMS / LCC analysis previous phase

RAMS / LCC specification drawn up at the end of the previous phase

Method (model / technology / programme)

Net Present Value calculation

Sensitivity analysis, e.g. of the service schedule or the number of timetable affecting errors

Output

Costs of the various options (including the current situation), for passengers and/or freight shippers as a consequence of RAMS quality in relation to the required life cycle costs

- LCC (Investment costs, maintenance costs)
- Costs of cancelled and delayed trains caused by failures in the infra (Value of time passengers, cost for using extra buses, Value of Time freight shippers). Sub-divided into effects for the rail sector and effects for society.
- Costs of cancelled and delayed trains caused by train free periods (Value of time passengers, cost for using extra buses, Value of Time freight shippers). Sub-divided into effects for the rail sector and effects for society.

- Costs and benefits for passengers (train and road transport), freight shippers and authorities as a consequence of the SHE performance.

Comparison with LCC / RAMS specification as included in the functional Program of Requirements or System requirements and further detailed at the end of the previous phase

4.9. Social cost benefit analysis (SCBA)

The RAMS quality of the RAMS / LCC analysis is translated into money with a Social Cost Benefit Analysis. The items that are not included in the LCC or RAMS / LCC are discussed in this guideline under the item “Social Cost Benefit Analysis”. An important factor here is that the Infra Manager values the (non) delivery of certain functionalities and safety in terms of finance.

In fact, the Social Cost – Benefit Analysis is the only type of analysis that can be used to underpin choices in an integrated manner in order to support the decision-making process. A RAMS / LCC alone would only be sufficient for the Infra Manager internal decision-making when the social component is established and may be constantly assumed (e.g. in the form of a requirement) or no longer plays a role.

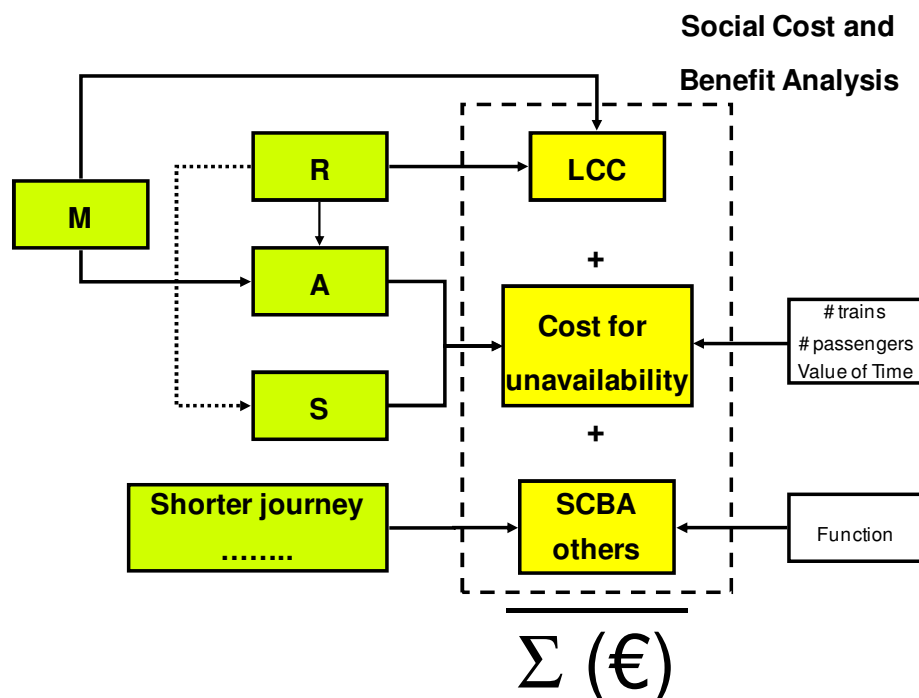


Figure 35: Parts of social costs and benefit analysis

The output of the Social Cost Benefit Analysis consists of a comparison of the existing situation with the new situation, expressed in:

Costs for the Infra manager: LCC (life cycle costs)

Costs of cancelled and delayed trains caused by timetable affecting errors in infra, split into effects for the rail sector (cost for busses, Value of time freight) and effects for society (Value of time passengers).

Costs of cancelled and delayed trains caused by train free periods, both in the building phase and the operational phase, split into effects for the rail sector (cost for busses, Value of time freight) and effects for society (Value of time passengers).

Costs and benefits for the traveller (train and road transport), shippers and authorities as a consequence of the SHE performance.

Costs and benefits for society (travellers and freight transport) caused by changes in:

Transport scope: frequency improvements

Speed: line speed, time gained from transfer

Comfort: adjustment of platform length, train pre-heating, train washing installations, transfer comfort

Efficiency: savings on bus costs, savings on the number of compositions, travelling time and shunting time

Expandability: adjustment of platform length for future trains

Overcapacity

The Social Cost Benefit Analysis is concluded with a comparison with the Social Cost Benefit specification as it is included in the functional Program of Requirements and further detailed in the prior Social Cost Benefit Analysis.

Question

What are the expected costs and benefits related to each option of the preferred variant?

Input

Results RAMS / LCC analysis

Cancellations and delays caused by disruptions in the infra

Standard values for benefits in relation to creation of the production model:

- Journey time improvement / waiting time improvement due to infra adaptation (per option)
- Number of passengers per passenger train
- Number of (passenger / freight) trains per hour or day

Value of Time passenger (figures ProRail):

- Planned: 7 € / hr,
- Unplanned: 2.4 x 7 € / hr

Social Costs – benefit analysis previous phase

Social Costs – benefit specification drawn up at the end of the previous phase

Method (model / technology / programme)

Net Present Value calculation

Output

Estimation of benefits/costs and the absolute sum of the net annual costs incurred per (including current situation)

- LCC (Investment costs, maintenance costs)
- Costs of cancelled and delayed trains caused by failures in the infra (Value of time passengers, cost for using extra buses, Value of Time freight shippers). Sub-divided into effects for the rail sector and effects for society.
- Costs of cancelled and delayed trains caused by train free periods (Value of time passengers, cost for using extra buses, Value of Time freight shippers). Sub-divided into effects for the rail sector and effects for society.
- Costs and benefits for passengers (train and road transportation), freight shippers and authorities as a consequence of a changed SHE performance.
- Costs and benefits for society due to e.g. journey time improvement, waiting time improvement, higher frequency, comfort, efficiency, expandability. Sub-divided into train passengers, freight shippers and e.g. road transportation.

Comparison with Social cost – benefit specification as included in the functional Program of Requirements or System requirements and further detailed at the end of the previous phase

4.10. Reference to the fixed RAMS parameter or specifications

TS

The purpose of a RAMS / LCC specification is to describe clear goals in relation to the desired RAMS quality, the desired safety level and the maximum permissible life cycle costs.

The point of departure for the creation of the specification is the functional Program of Requirements and the specification from the prior phase.

The following items must be specified in more detail:

RA

- Number of timetable affecting errors, function recovery time per system
- Number of timetable affecting errors, function recovery time and availability per train route
- Number of delayed and cancelled trains due to failures in infrastructure, sub-divided per system
- Effect on the Key Performance Indicators (KPI) for the reliability and availability

M

- Number and duration Train free periods
- Accessibility of the infra
- Maintenance costs, sub-divided per system

S

- Safety level (concrete requirement or, for example, “stand still principle” or “ALARA” (=As Low As Reasonably Achievable)) of the selected technical solution, sub-divided per system

LCC, costs – benefits: Costs Infra Manager, costs rail sector, social costs

The project manager and the contractor must jointly ascertain whether the above list must be supplemented with other items. The desired detail level must also be adjusted per project.

Using catalogue products more or less fixes the RAMS performance to be expected at object level. However, the manner in which the systems are composed and cooperate can affect the RAMS performance at the system and train route level. Two examples of aspects that are

of great importance for performance are the presence of redundancy and the manner in which safety systems projects are set up.

Question

What RAMS requirements can we specify and at what maximum life cycle costs should it be possible to implement the infra change?

Input

Standard values for performance and costs of comparable rail infra solutions

Results RA analysis

Results M analysis

Results S analysis

Results RAMS / LCC analysis

Results Social costs – benefits analysis

RAMS / LCC specification drawn up at the end of the previous phase

Method (model / technology / programme)

Internal comparison with existing infra solutions

Tightening of the RAMS / LCC requirements of the previous phase study on the basis of more detailed info.

Output

Scope: region, cause category (Technology or broader), systems to be studied, period, RAMS analysis tools, specific questions or restrictions...

RA

- Number of timetable affecting errors, function recovery time per system
- Number of timetable affecting errors, function recovery time and Availability per train route
- Number of delayed and cancelled trains due to failures in infrastructure
- KPI's

M

- Number and duration of train free periods
- Accessibility of the infra
- Maintenance costs
- KPI's

S

- Project-specific safety requirements
- Safety level (concrete requirement or e.g. “stand still principle”):
 - Derailment
 - Collision
 - External party on the infra
 - Getting on and off trains
- KPI's

LCC: Costs Infra Manager, Costs rail sector, Costs to society

5. General analytic methods and tools

The following sections shortly describe appropriate analytic methods for the technical analysis and tools for the technical and economical assessment.

5.1. *Analytic methods*

This chapter describes some common analytic methods. These can be used in a life cycle at different phases; research and development, investment, operation and maintenance and disposal. The methods are most often used in the initial decisions before investment. But methods like FTA and ETA can also be used in the operation and maintenance phase to analyze unexpected malfunctions.

TS

RAMS lifecycle, according to EN 50126, is divided into 14 phases. Each phase can be analysed for different options and with different tools. The phases are:

Phase 1. Concept- develops a level of understanding of the system sufficient to enable all subsequent RAMS lifecycle tasks to be satisfactorily performed. Analyses during this phase are used to **identify sources of hazards** which could affect the RAMS performance, eg.PHA.

Phase 2. System definition and application conditions – defines the mission profile of the system, the boundary of the system, establish the application condition influencing, define the scope of the of system **hazard analysis**, establish the RAMS policy for the system and the Safety plan. Required analyses are hazard, safety and risk analysis, e.g. PHA or HAZOP.

Phase 3.Risk analysis, identifies **hazards** associated with the system, **events** leading to the hazards, **determines risk** associated with the hazards and establish a process for on-going risk management. Some analytic methods that could be used are HAZOP, Risk Matrix, Delphi technique or ETA.

Phase 4. System requirements, specifies the overall RAMS requirements for the system and the overall demonstration and acceptance criteria and establish the RAM Programme for controlling RAM tasks. Some analytic methods e.g. FMEA, FMECA, FTA, Markov analysis, HAZOP, PHA, ETA

Phase 5. Apportionment of system requirements, apportion of the overall RAMS requirements to designate sub-systems, components and external facilities. Some analytic methods e.g. FMEA, FMECA, FTA, Markov analysis, HAZOP, PHA, ETA

Phase 6. Design and implementation, creates sub-system and components conforming to RAMS requirements, demonstrates sub-system and components conform to RAMS requirements and establish a plan for future lifecycle tasks involving RAMS.

Phase 7. Manufacturing, implements a manufacturing process which produces RAMS-validated sub-systems and components, establish RAMS-centred process assurance arrangements and RAMS support arrangements

Phase 8. Installation, assembles and installs the system and initiates support arrangements

Phase 9. System validation, validates the total combinations of sub-system, components and external risk, commission the total combination of subsystem, components and external risks. Prepares the safety case for the system and provides data for acquisition and assessment

Phase 10. System acceptance, assesses compliance and accepts the system for entry into service

Phase 11. Operation and maintenance, operates, maintains and supports the system

Phase 12. Performance monitoring, Maintains confidence in the RAMS performance. Analytic models e.g. RCA, FTA, ETA

Phase 13. Modification and retrofit, controls the systems modifications and retrofit tasks to maintain the systems RAMS requirements

Phase 14 Decommissioning and disposal, controls the decommissioning and disposal tasks

5.1.1. Root cause analysis

The root cause analysis is a class of problem solving methods aimed at identifying the root cause of problems or events. The practice of RCA is predicated on the belief that problems are best solved by attempting to correct or eliminate root causes, as opposed to merely addressing the immediately obvious symptoms. By directing corrective measures at root causes, it is hoped that the likelihood of problem recurrence will be minimized. However, it is recognized that complete prevention of recurrence by a single intervention is not always possible. Thus, RCA is often considered to be an iterative process, and is frequently viewed as a tool of continuous improvement (Wikipedia)

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RCA initially is a reactive method of problem detection and solving. This means that the analysis is done after an event has occurred. By gaining expertise in RCA it becomes a pro-active method. This means that RCA is able to forecast the possibility of an event even before it could occur (Wikipedia).

5.1.2. Failure Mode and Effects Analysis (FMEA)

FMEA is an inductive analysis approach by which each potential failure mode in a system is analyzed to determine the results or effects thereof on the system and to classify each potential failure mode according to its severity (MIL-STD-1629A). FMEA is a step-by-step procedure for systematic evaluation of the severity of potential failure modes in a system. FMEA is mainly used for recommending improvement in a system during its design phase.

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5.1.3. Failure Mode, Effects and Criticality Analysis (FMECA)

FMECA is an extension of the FMEA, which focuses on ranking the failure modes according to criticality based on various factors responsible in a particular context. FMECA is a powerful analysis method involving two elements of risk; namely, failure frequency and consequence. FMECA analysis concentrates on identification of the events and frequency resulting in failures and analysing their effects on the components and systems. Table 1 shows an example of a template.

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Table 3: FMECA Template

Failure identification				Failure effects		Failure management		Assessment			
item (component)	Functions	Potential failure modes	Potential causes/mechanisms of failure	Potential consequences of failure	Location	Current detection/diagnostics	Mitigation (design)	P ¹	S ²	D ³	R ⁴
rail	carries load guides vehicle	200 brittle fracture	cold environment	vertical fracture, crack located in rail cap	Head Surface, cap	US, visual	watch over				
rail	carries load guides vehicle	211 detail fracture									
rail	carries load guides vehicle	2201 Corrugations									
rail	carries load guides vehicle	2202 waves									
rail	carries load guides vehicle	2203 gauge corner wear									

Risk Priority Number (RPN)

Risk priority number (RPN) is a methodology for analyzing the risk associated with potential problems identified during a Failure Mode and Effects Analysis (FMEA) (for details refer Reliasoft, 2005).

Assigning RPN requires the analysis team to use past experience and engineering judgment to rate each potential problem according to three rating scales:

Severity, which rates the severity of the potential effect of the failure.

Probability, which rates the likelihood that the failure will occur.

Detection, which rates the likelihood that the problem will not be detected before it reaches the end-user/customer.

These rating scale ranges from 1 to 5 or from 1 to 10; the higher number the more risk it involves and vice-versa. After the ratings have been assigned, the RPN for each issue is calculated as mentioned below,

$$RPN = Severity \times Probability \times Detection$$

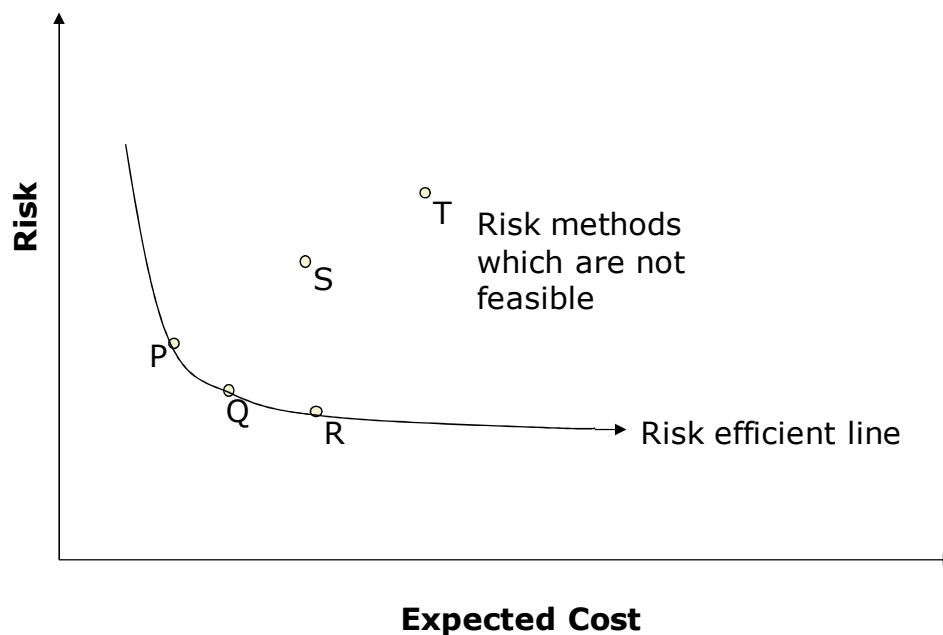
The RPN value for each potential problem can then be used to compare the issues identified within the analysis. Typically, if the RPN falls within a pre-determined range, corrective action may be recommended or required to reduce the risk (i.e. to reduce the likelihood of occurrence, increase the likelihood of prior detection or, if possible, reduce the severity of the failure effect). When using this risk assessment technique, it is important to remember that RPN ratings are relative to a particular analysis (performed with a common set of rating scales and an analysis team that strives to make consistent rating assignments for all issues identified within the analysis). Therefore, an RPN in one analysis cannot be compared to RPNs in other analysis (Reliasoft, 2005). There are several interpretational problems connected with the use of RPN for risk estimation.

Risk Matrix

Many times, in actual practice it becomes difficult to analyze in detail each and every event having a certain potential of risk because of their very large numbers. In such situations, it becomes easier to

rank these events qualitatively and put them in groups denoting different levels of risk. Risk matrix is such a tool for qualitative risk assessment to give an overall ranking for likelihood and consequences. The different blocks of the matrix define different levels of risk. Generally bottom left block is the lowest risk block and top right block is the highest, but it can vary depending on the convention used.

There are many more methods which could be applied efficiently in different context. The different methods could be evaluated based on **Figure 36**. A comparison of risk and expected cost is done. The methods like point P have solutions with less expected cost but on the other hand, become risky. Methods like point R give low risk solutions but they are a bit costly. Yet, those methods which lie on the risk efficient line are far better than methods which lie at point S. Point T represents those methods which are not feasible at all. But a reasonable method should give a solution denoted by point Q, which is a trade-off between risk and cost.



*Figure 36: Risk efficient options
[Adopted from Chapman and Ward, 2004]*

5.1.4. Fault Tree Analysis (FTA)

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The fault tree analysis (FTA) is the most common analysis technique used in reliability and risk analyses. A fault tree is a logic diagram showing the connection between system failures (i.e. unwanted events in the system), subsystems, and components failures. FTA is an example of deductive analysis approach. It is a graphical approach

which starts with a failure and branches out showing possible causes (Andrews and Moss, 2002). Many different fault trees may be required on a subsystem level to evaluate the risk associated with a particular type of hazard in a system. **Figure 37** shows the fault tree of a train accident. The top event of the fault tree is the train accident, which is caused either by a derailment or a collision (undesired events). The middle events, such as technical failure, track failure, etc., are the intermediate events, which connect the bottom events to the top events. The bottom events are the basic events, which consist of different rail defects and the important factors influencing these defects. There are several other conditions under which a train accident can happen, but they are not looked into, as they are beyond the scope of this paper. The rail defects are shown according to their UIC code in Figure 37 (Kumar, S. Gupta, B. and Ghodrati B, 2007).

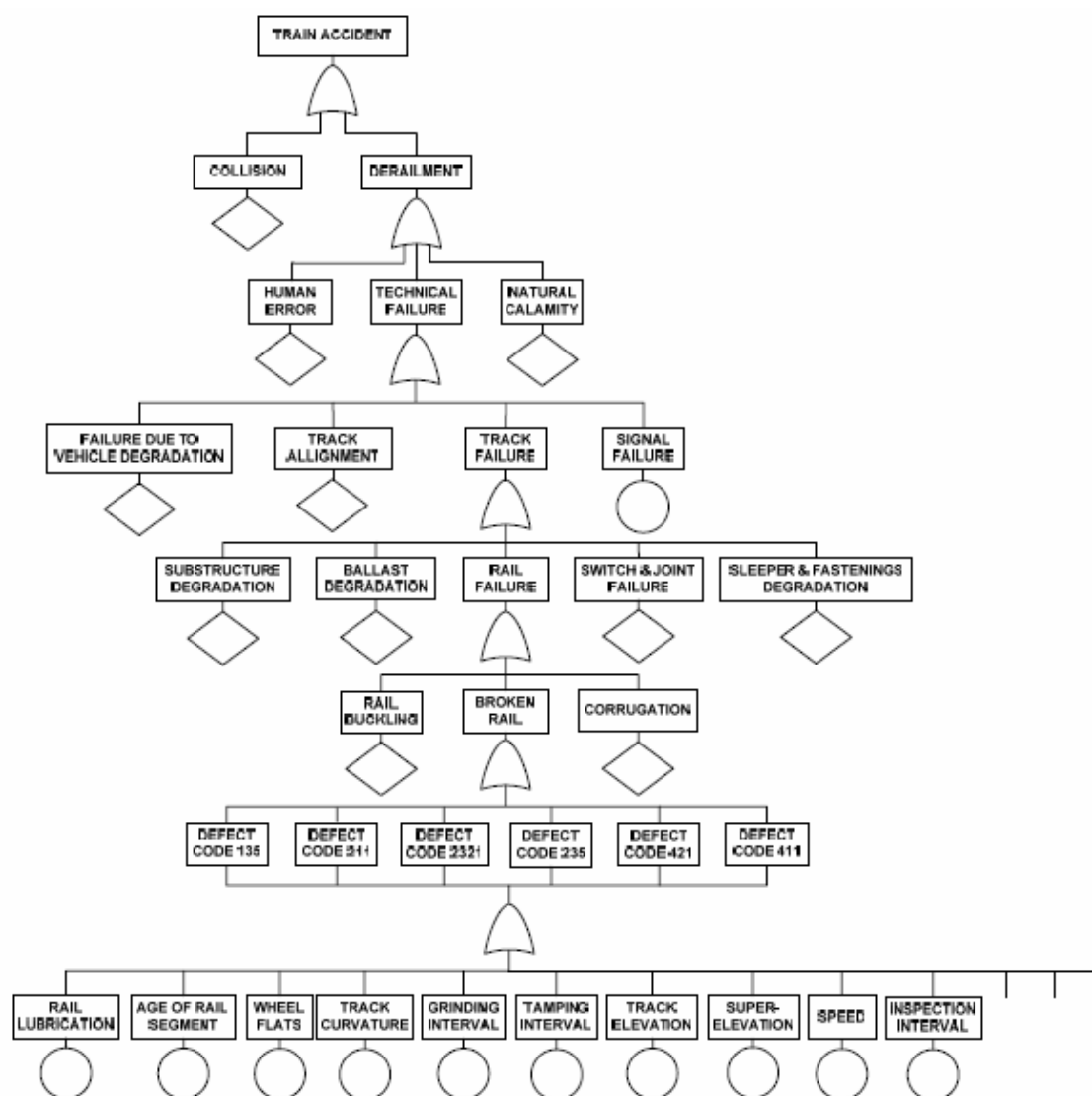


Figure 37: Fault Tree Analysis

5.1.5. Event Tree Analysis (ETA)

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ETA is a hazard identification and frequency analysis technique which employs inductive reasoning to translate different initiating events into possible outcomes (IEC60300-3-9, 1995). ETA is an inductive logic and diagrammatic method for identifying the various possible outcomes of a given initiating event (Huang, *et al*, 2001). An event tree identifies and quantifies possible outcomes following an initiating event. The event tree provides systematic coverage of the time sequence of event propagation. Event trees are frequently used to estimate the probability of events as well as to map the developments from the initiating event to all possible outcomes/consequences. An example from the aviation industry is presented in **Figure 38**.

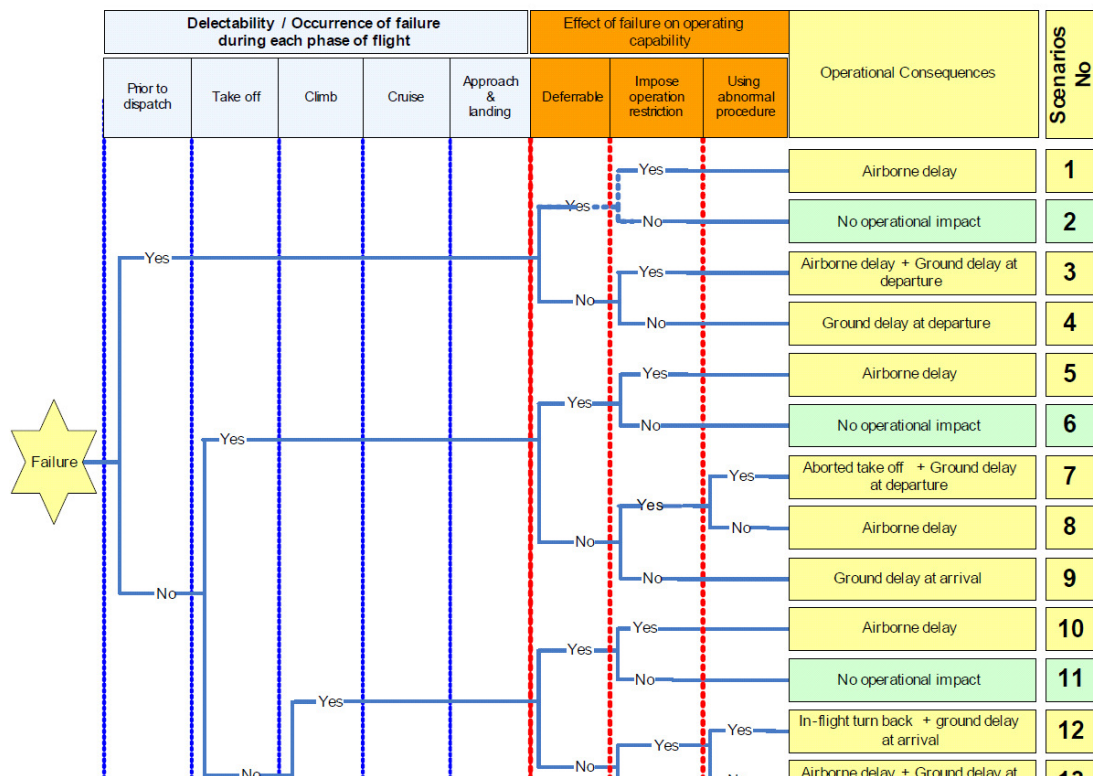


Figure 38: Event tree for assessing the possible operational consequence scenarios caused by aircraft system failure

5.1.6. Hazard and Operability Study (HAZOP)

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HAZOP is a fundamental hazard identification technique, which systematically evaluates each part of the system to see how deviations

from the design intent can occur and whether they can cause problems (IEC60300-3-9, 1995). The technique aims to stimulate the imagination of designers and operators in a systematic manner so that they can identify the cause of potential hazards in a design (Andrews and Moss, 2002).

5.1.7. Preliminary Hazard Analysis (PHA)

It is a technique that can be used early in the design stage to identify hazards and assess their criticality (IEC60300-3-9, 1995). It is used as a first step to understand risk present and the need for risk control. This method was initially applied to nuclear industry and is the basis of large number of formal risk assessment today (Modarres, 1993).

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5.1.8. Delphi Technique

Delphi technique is a means of combining expert opinions that may support frequency analysis, consequence modeling and/or risk estimation (IEC60300-3-9, 1995). It is a widely used method for expert judgments. A set of questionnaires are prepared by a panel of experts and individual opinion on these questions are looked into as feedback to the expert panel. This refines the views of experts ending up to a general consensus (Akersten and Espling, 2005).

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5.2. *Tools for technical assessment*

The technical analysis and assessment of a system, subsystem or component with methods like Markov-Analysis, FMEA, FMECA or FTA can be supported by tools like²

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IQ-FMEA Pro APIS (www.apis.de/en),
 Relex FMECA (www.relex.com),
 the software tools from ReliaSoft (www.reliasoft.com) or
 from isograph (www.isograph-software.com)

These tools provide standardized procedures, documentations with many different views and guide the user through the assessment process. The use of such tools is recommended in either case.

² The list of tools shows only a small extract of possible tools

5.3. Tools for economical assessment

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The LCC-tool has a central position in the LCCA and has to ensure the development of powerful LCC models and good data handling. So-phisticated LCC models are necessary to analyse the questions from different views and to compare several alternatives. Like shown in **Figure 39**, the LCC model ensures the link between technical parameters like life time, maintenance intervals and the economical parameter like investment, cost per maintenance issue or cost for non-availability.

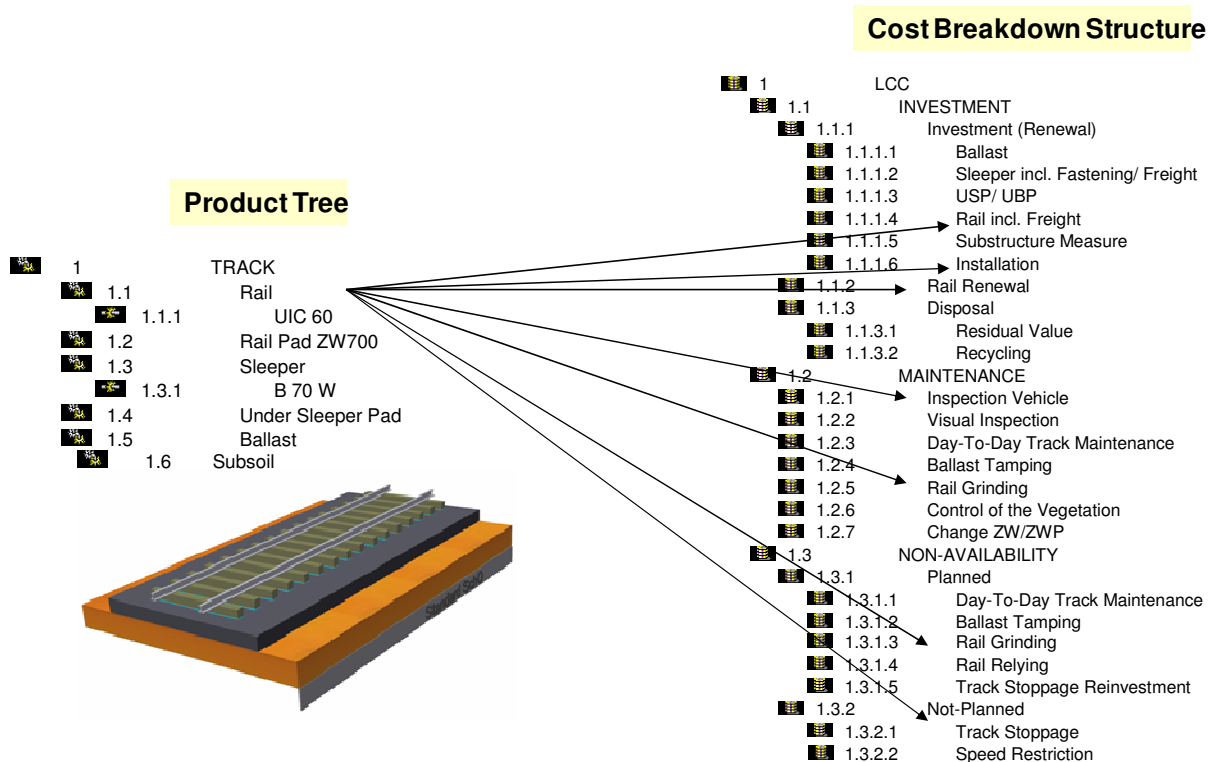


Figure 39: LCC – Model – the link between technical and economic aspects

Within the project InnoTrack a comprehensive benchmark of existing LCC-tools were carried out. The list of criteria consists of up to more than 100 issues related to different topics like user interface, modeling capabilities or reporting. The benchmark shows very clearly that a commercial tool, which fits all the needs of infrastructure manager, does not exist (see InnoTrack deliverable D6.2.2).

During the project the commercial tool D-LCC (www.albservice.com) was improved to handle Monte-Carlo simulation or the import and export of variables. The LCC models developed with D-LCC allow the

control of the calculation from the product breakdown structure and therefore the fast analysis of different alternatives.

Also other companies like Relex, Isograph or Systecon provides commercial LCC-tools. For more details see InnoTrack deliverable D6.2.2.

It is very important to define a framework for the development of the LCC models, which fixes boundaries like the structure and IDs of the cost items, useful sub functions and the documentation of the models. The definition of standard cases enables the test of the models and ensures the validity of the calculation.

Like the analytical methods, the tools for technical assessment, the LCC-tools need skilled users for the development of the LCC-models.

6. Compilation of results

A RAMS / LCC study must be defined as lean as possible. Only the items that help the project manager are needed. Sometimes RAMS / LCC can help to choose between variants and sometimes a prediction for future performance is needed. Therefore the content of an analysis is always specific for a project.

Knowing that a good defined RAMS / LCC analysis fulfills the needs of the project manager it becomes clear that the project manager is eager to know the conclusions of the report.

There are many reasons to have a proper discussion about the RAMS / LCC report between the project manager, the writer of the report and RAMS experts:

- Does the analysis meet the goals of the project manager?
- Does everyone understand the RAMS / LCC analyses and are the conclusions clear?
- Good reliable performance, cost and safety data is hard to get. It is good to get commitment for the used sources.
- Sometimes an analysis is a trigger to do more research or to try to find more information. This can lead to additional work.
- It is not always possible to find answers to all the questions stated in the initial request for RAMS / LCC analyses.

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- The RAMS / LCC analyses can lead to a change in design. This design must also be investigated on RAMS / LCC.
- The RAMS / LCC analyses can lead to a change in the specifications.
- Sometimes no RAMS / LCC specifications are available. A RAMS / LCC analyses can then be used to calculate the performance, LCC and safety of the designed system or the new infrastructure. The resulting performance, LCC and safety can be used as basis for the specification for the next phase.

Experience learns that often the report has to be changed after the discussion. This is not caused by lack of knowledge or experience of the writer. The main reason to change the report is that the review of the (concept) report is the first time a whole team has a discussion about RAMS / LCC for that specific project. This again emphasizes the need to have this discussion before the start of the RAMS / LCC analyses. That leads to a better analysis with a shorter lead time and more commitments in the organization for the conclusions.

7. Operational Phase and Implementation

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RAMS and LCC should be implemented across the infrastructure manager's business and is applicable to anyone involved in planning and operation or the specification and procurement of new equipment, track upgrades or other improvement projects. RAMS data is also of great importance to maintenance teams allowing maintenance to be planned effectively, budgeted and resourced.

However, RAMS and LCC tend to be implemented initially in the assessment of new innovation or new products or during planning stage of an upgrade project where life cycle cost is considered and also the impact on availability and capacity. RAMS parameters also enter supply and service contracts and used as key performance indicators. To ensure implementation LCC and RAMS consideration should be a specified step in all capital projects or major procurement decisions. It is important that infrastructure managers have a particular person, department or contractor who will build and maintain the reliability data and also act as a champion and point of contact for RAMS within the organization and ensure that the correct

personnel are using and are have sufficient training to implement RAMS and LCC, or they act as the body that carries the analysis and this will depend largely on the structure of the organization and it's existing processes.

However, the effective use of RAMS and LCC can ensure that projects deliver the cost effective solutions that meet the requirements of performance and availability and can be used with suppliers to drive reliability and reduced life cycle costs.

7.1. Feedback from operational site back to planning/construction

The relationship between project engineer and reliability engineer is an important one and clear communication between them is required throughout project planning. It must be ensured that the reliability engineer understands the project and can apply the data or calculations correctly. Also after the completion of the project reviewing the actual system reliability is essential to add to the reliability data and to understand if there are any significant differences between this and the calculations in the planning stages.

However, it can be difficult to collect data for maintenance cost and condition due to long technical life time, different accounting systems for maintenance, modification and renewal costs and different maintenances contracts e.g. lump sum performance contracts.

The fact that the railway system is operated and maintained by several different companies/organisations makes it problematic to share or get hold of decision support data, in order to plan and maintain the system with a holistic approach rather than just achieving sub-optimisation. An important task is therefore to develop methods and information systems to improve the feedback of failure rates and other RAMS and cost data between the manufacturers and Infrastructure Managers. To achieve minimal LCC and to improve the quality (RAMS) of a system/product/component requires a close cooperation between operator and supplier.

Feedback of collected RAMS data to the supplier, enables the supplier to identify problems and improve their product, it also allows them to assess their performance against a target RAMS specification. If the supplier is selling products/assets with LCC commitments they should also get feedback of the maintenance process and also factors

TA

that might affect the product lifetime, i.e. how stipulated maintenance strategy is conducted and traffic over that component. The communication with suppliers regarding RAMS and LCC can ensure that the infrastructure manager maintains best value for money and does not procure very costly equipment which is more reliable than it needs to be, but also ensure that critical equipment is fit for purpose.

In conclusion the use of RAMS and LCC in a decision making process needs be clearly defined for each organization and will be dependent upon the structure and existing processes within that company. However, the effective use of RAMS and LCC can ensure that projects deliver the cost effective solutions that meet the requirements of performance and availability.

See annex I for examples regarding the

decision about level crossing or underpass and
use of new rail steel and optimised grinding strategy

When the InnoTrack project started the general understanding about RAMS and LCC was in its infancy stage among most of the participants. Therefore INNOTRACK aimed to support the use of LCC thinking and RAMS technology within the railway sector. Tools and models are mostly self-developed. Some tools in use for RAMS analysis are TRAIL (used by NR), RailSys (used by BV), Optimizer+ and for LCC; LCM, D-LCC, T-SPA. RAMS standards are not universally used and participants do not consider RAMS issues in all phases of system life cycle. Only IMs define reliability target for their systems. One reason may be that there is not sufficient feedback from the IMs to the manufacturers. Manufacturers and contractors depend on the information provided by IMs to carry out their RAMS and LCC analysis

Today sharing of maintenance data is not common, which can make it risky for the contractors to commit themselves to long duration contracts, guaranteeing a performance deliverable. Therefore a platform for exchanging maintenance data such as failure rate, failure type and maintenance action could be beneficial, but it must also be balanced with the commercial issues of sharing such data.

During the operation phase, manufacturers can benefit from obtaining information about their product's technical health as well as conformance and deviations from the expected performance targets. Such feedback to the industry of relevant data could be used to implement technical improvements, e. g. more reliable vehicles. This

requires a transparent communication and exchange of data between operator/maintenance and manufacturers. The practice of reliability management does not need more information, but it needs better, reliable and resilient data.

Manufacturers and contractors depend on information from the IMs to carry out their RAMS and LCC analysis.

A Feedback from the operator enables that the manufacturer and supplier implement the changes and optimise their products and afterwards to deliver the best technical-operating solution, which in turn, ensure a life cycle reduced solution.

7.2. *Validation of RAMS and LCC calculations*

The validation of the technical data is also important task in order to confirm the system performance. There is a different level of validation, either full validation (e. g. in depth technical validation) or review validation (i. e. confirming the validation already carried out). For example, the technical data of the following items could be validated:

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- life time of the component

- installation (time, procedure)

- maintenance interval

- maintenance activities

In some cases this data is available from maintenance records and databases and by analysing this data as described in section 4.5, the key RAMS parameters can be calculated. However in many situations this data can be difficult to obtain or in the case of new innovations it is simply not available.

Where there is no clear validation method for RAMS and LCC calculations, for example where little or no actual reliability data is available, then RAMS and LCC data from small samples, simulation or experiences can be used. A well defined procedure (how, who, when) would be very helpful for validation as an important part of RAMS and LCC analysis.

The RAMS performance and the used RAMS data should be validated, especially in the case of a new system/product/component, because in general the technical and economical data of innovation are unknown. This procedure ensures also that the RAMS key values and RAMS data are updated.

In general, the validation of technical data regarding the system performance assures the completeness and plausibility of RAMS and LCC input data.

7.3. *Monitoring of the analysis*

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The achievement of aims and benefit resulted from the RAMS and LCC analysis need to be monitored in some way.

Findings, results and gathered data have to be serviceable for future applications, especially in reference to high efficiency and a consistent procedure as possible. Continuous improvement of the database decreases the time and effort for LCC and RAMS assessments. Furthermore the identification and use of standard values is recommended.

Periodic reporting of key figures must be ensured for different kind of organisations e.g. client/contractor organisation, even if maintenance is outsourced. Arrangements for this must be developed as well as methods and tools for exchange of key data between parties involved in the railway system, i.e. infrastructure managers, traffic companies, supplier, contractor, etc. Also methods to measure and monitor changes that affect the operation of the assets of which the supplier or the contractor have no influence over needs to be developed.

The development can be accelerated by the parties learning from best practice, e.g. by enhanced cooperation between the partners involved in infrastructure asset management and by starting the use of method and tools already in use. Low resolution models in use are DeCoTrack, TETrAs and VTISM. Some equipment for monitoring traffic characteristics are Argos, DafuR and Stratoforce and there are also some templates and handbooks in use (see InnoTrack deliverable D6.4.2).

It is therefore vital to be able to measure and monitor the operation and maintenance process. Key values for RAMS and LCC needs to be developed and transformed to a railway user environment.

Periodic reporting of key figures must be ensured even if maintenance is outsourcing. Arrangements for this must be developed. Similarly methods and tools developed for the exchange of key data between parties involved in the railway system, i.e. infrastructure managers, traffic companies, supplier, contractor, etc. Methods to measure and monitor changes that affect the operation of the assets, but supplier or the contractor cannot influence, is another development area.

It is vital to be able to measure and monitor the asset management process for the railway infrastructure. LCC and RAMS technology are two acknowledged methods for assisting the optimisation process. Key values for RAMS and LCC needs to be developed and transformed to a railway user environment and be adapted for operation and maintenance.

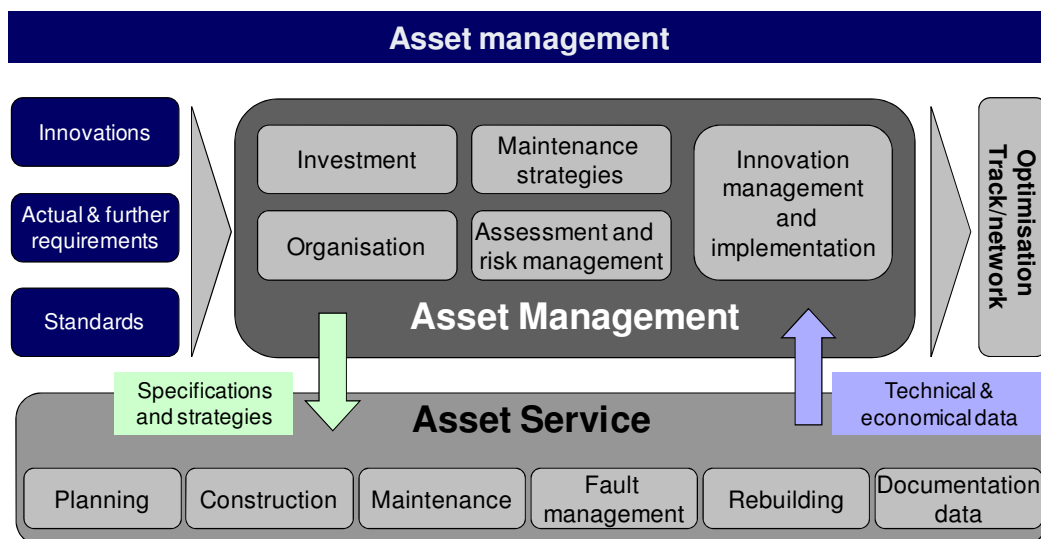


Figure 40: The optimisation process of assets needs RAMS and LCC relevant data

It is necessary that the suppliers selling products/assets with LCC commitments will get feedback from the maintenance process i.e. how stipulated maintenance strategy is conducted. The supplier also has to receive data for failure statistics and inspection notes as well as the changes in traffic, i. e. how the assets are operated.

Annex I Examples

Level crossing or underpass?

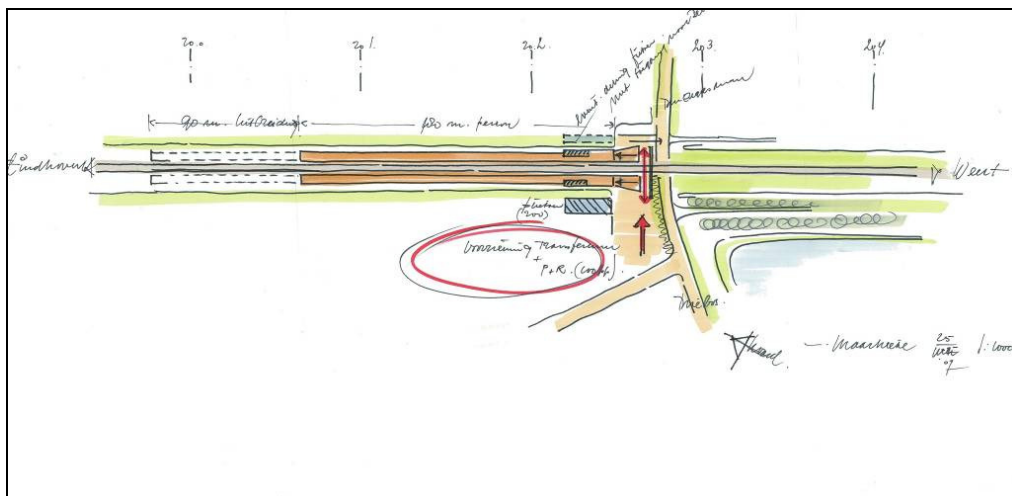
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This example shows that also with “small projects” one can use RAMS and LCC to make a choice between variants. Infra manager ProRail asked an engineering company to make an analysis to be able to choose between 2 variants.

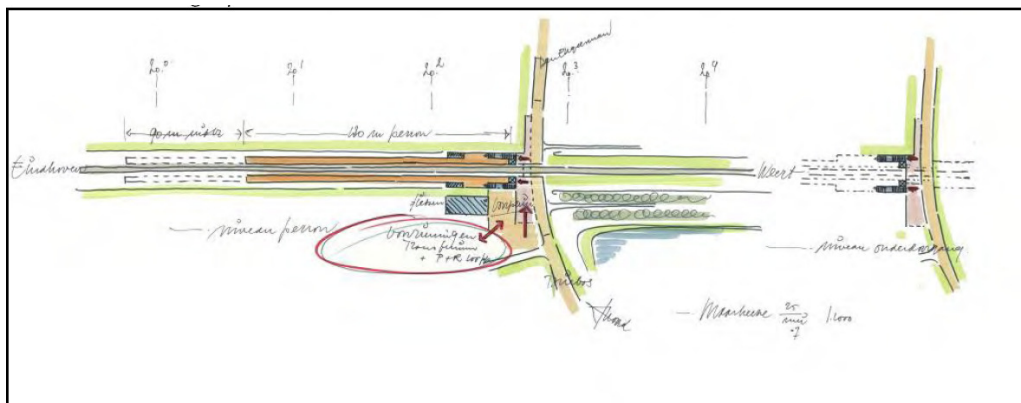
In Maarheeze (The Netherlands) a new station is designed. It consists of 2 perrons outside the 2 tracks. The end of the perron is located 25 meters from the current level crossing. The busses, taxi, P & R and the area for bikes are all situated at the south of the station. North of the station is a new and expanding industrial area.

Although we know that the estimation of the cost for maintenance is wrong we show the highlights and results of this study.

Variant 1: Level crossing



Variant 2: Underpass



Question: Which variant is the optimum when we look at the RAMS, LCC and social cost – benefits?

Performance data

ProRail has lots of performance data available for level crossings. But you can't compare them all. A level crossing outside town has a different performance then one in an urban environment. And a level crossing near a station has more people walking over it and trains stopping near. This leads to specific problems. We searched for performance figures for comparable level crossings, over the last 5 years. 6 level crossings were found, see next 2 tables.

Timetable affecting errors

Performance level crossing: timetable affecting errors	function repair time [hour]	Number of errors	Average function repair time [hour]	Average number of errors
Error caused by technique	7,550	6	1,258	0,200
Error caused by third parties	30,050	20	1,503	0,667
Error caused by wheather	7,267	2	3,633	0,067

Non-timetable affecting errors

Performance level crossing: non-timetable affecting errors	function repair time [hour]	Number of errors	Average function repair time [hour]	Average number of errors
Non-timetable affecting errors	731,150	125	5,849	4,167

For underpasses in comparable situations (12 found) no timetable affecting errors are registered in the last 3 years. For non-timetable affecting errors no reliable data was found.

Based on every hour four passenger trains and one freight train per direction this leads to delay and cancellation of trains. Knowing it is not correct we simplified the model by assuming for this study that a timetable affecting error only leads to cancellation of trains.

Performance data	All Level crossings average Netherlands	Comparable Level crossing	Comparable Tunnel
Number of hours not available (due to errors)	0.535	1.496	0
Number of cancelled passenger trains	4.280	11.964	0
Number of delayed freight trains	0.535	1.496	0

Safety:

Like performance also safety on a level crossing near a station has its own specific key figures. We searched for safety figures for comparable level crossings, see next table:

Safety data	Deaths / year	Seriously injured / year	Slightly injured / year
Level crossing	0,044	0,022	0,00
Underpass	0	0	0

Cost data:

For the two variants the cost data is shown in the next table:

Cost data	Level crossing	Tunnel	Comment
Total Investment (including station and perron)	6.455.000	1.458.100	
Investment (excluding station and perron)	1.854.000	9.974.000	
Social costs for train free period during realization phase			Figures can vary per Infra Manager

Cost data	Level crossing	Tunnel	Comment
1 period of 29 hours in weekend	98.000		
1 period of 52 hours in weekend		201.000	
Preventive maintenance cost per year	40.000		
Periodic replacements level crossing			
Roaddeck (40 year)	354.300		
Replace track (20 year)	75.000		
Half barrier (25 year, 6 pcs)	60.000		
Barrier motor (15 year, 6 pcs)	15.000		
Maintain track (15 year)	10.000		
Maintenance tunnel			
Small maintenance (1 year)		5.500	
Large inspection (10 year)		1.500	
Painting (15 year)		8.500	
Large construction repairs (40 year)		100.000	
Social cost for road transport		57.000	
Cost for safety:			
Deaths	1.500.000		Figures can vary per Infra Manager
Seriously injured	200.000		
Slightly injured	30.000		
Economic value of delayed freight train per hour	1.000	1.000	
Cost for repair in case of errors	1.000	1.000	
Cost for cancelled train on track Eindhoven – Weert:			
Week days: based on 263 passengers per train	15.233		Figures can vary per Infra Manager
Weekend days: based on 124 passengers per train			

Based on the performance, safety and cost data it is possible to make a complete RAMS / LCC analyses using the methodology shown in this guideline.

LCC:

Next table shows the LCC costs using Net Present Value (interest + inflation = 4 %),:

LCC	Level crossing	Tunnel
Net Present Value 30 year	3.853.417	9.890.259
Net Present Value 50 year	4.372.113	9.934.517
Net Present Value 100 year	4.717.799	9.956.606

Including all the social cost – benefits the total costs during the lifetime using Net Present Value (interest + inflation = 4 %) are:

LCC + social cost – benefits	Level crossing	Tunnel
Net Present Value 30 year	7.812.598	9.890.259
Net Present Value 50 year	9.238.223	9.934.517
Net Present Value 100 year	10.238.176	9.956.606

So based on all these data the decision for a variant can be made. But be aware that RAMS / LCC is not the only parameter the project managers uses to choose for a variant!

Hinderscenario's

Standaard hinderscenario: Prorail

Naam hinderscenario: Prorail

Toelichting: This figure give an overview of the cost of unavailability due to planned or unplanned activities. It consist of social cost, cost for using busses and income loss of the train operators.

Wissen

☒ Toepassen maatschappelijke kosten vertraging
☒ Toepassen verbussingskosten
☒ Inkomstenderving reizigers vervoerders
☒ Nachtnet aanwezig

Aantal reizigerstreinen per werkdag: 138 treinen per dag
 Gemiddeld aantal reizigers per trein op een werkdag: 263 reizigers
 Aantal reizigerstreinen per weekenddag: 114 treinen per dag
 Gemiddeld aantal reizigers per trein op een weekenddag: 124 reizigers
 Aantal goederentreinen per dag: 10 treinen per dag
 Aantal overige treinen per dag: 0 treinen per dag
 Duur vertraging reizigers per geplande verstoring van een uur: 40 minuten

Resultaat

Gemiddelde kosten waarde tijdsvertraging op een werkdag	€	3.952	per uur
Gemiddelde kosten verbussen reizigers op een werkdag	€	2.329	per uur
Gemiddelde kosten inkomstenderving op een werkdag	€	928	per uur
Totaal gemiddelde kostenderving personenvervoer op een werkdag	€	7.209	per uur
Gemiddelde kosten waarde tijdsvertraging op een weekenddag	€	1.539	per uur
Gemiddelde kosten verbussen reizigers op een weekenddag	€	907	per uur
Gemiddelde kosten inkomstenderving op een weekenddag	€	453	per uur
Totaal gemiddelde kostenderving personenvervoer op een weekenddag	€	2.899	per uur
Kosten waarde tijdsvertraging goederenvervoer	€	521	per uur
Kosten waarde tijdsvertraging overig vervoer	€	---	per uur
Kosten van een uur ongeplande verstoring	€	15.233	per uur

Toepassen OK Annuleren Help

Figure 41: Calculating cost for unavailability

Standard steel grade vs. heat treated rails?

The second example shows that the use of RAMS and LCC are very useful to optimize the technical and economical performance of the track and to analyze and assess the maintenance strategy.

The objective of this analysis was to identify the technical and operational boundaries for the economical use of heat treated rail. The analysis includes different steel grades, rail types and maintenance parameter like metal removal, under grinding of RCF, type of grinding machine (see Figure 42). To analyse the influence of the wear limits a new rail type called UIC70^{plus} was taken into account. This rail type has a higher rail head and provides therefore higher wear limits and a longer life time. The new design of the rail web potentially reduces the radiation of noise.

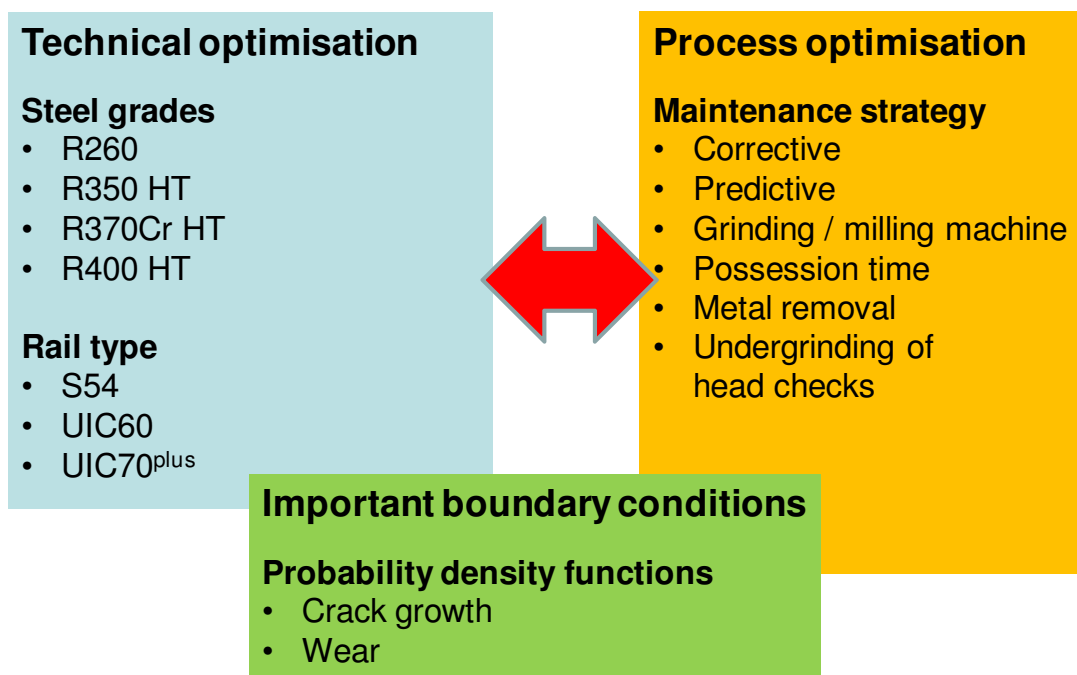
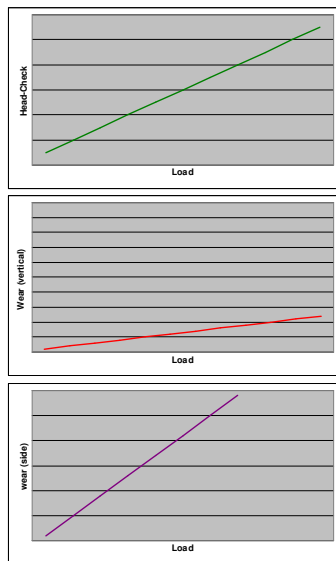


Figure 42: Parameters for LCC optimisation

The analysis is based on real growth rates of rolling contact fatigue (RCF) and wear of the rail profile. It also takes into account an estimated probability density function for the crack growth. **Figure 43** shows all parameters and the crack growth and wear rates, which are used in the LCCA. The documentation of important boundary conditions and input parameter is shown in **Figure 46 to Figure 49**.

Wear and RCF values based on field tests



- Grinding specs
- Service life time

Technical parameters

- limit values
- wear
- undergrinding of HC

LCC Model

Boundary conditions

- Track category
- Rail type
- Steel grade
- Radius class
- Actual Load [MGT/a]

Process parameters

- Type of grinding machine
- Maintenance strategy
- Metal removal
- Possession time

Figure 43: LCCA: the LCC model handles technical and economical parameters

Figure 44 shows as one result of the LCCA the NPV for the reference steel grade R260 to the steel grade R350HT as a function of the annual load of the track. Only for low annual tonnage the standard steel grade delivers lower LCC.

NPV of R260 vs. R350HT dep. on Load

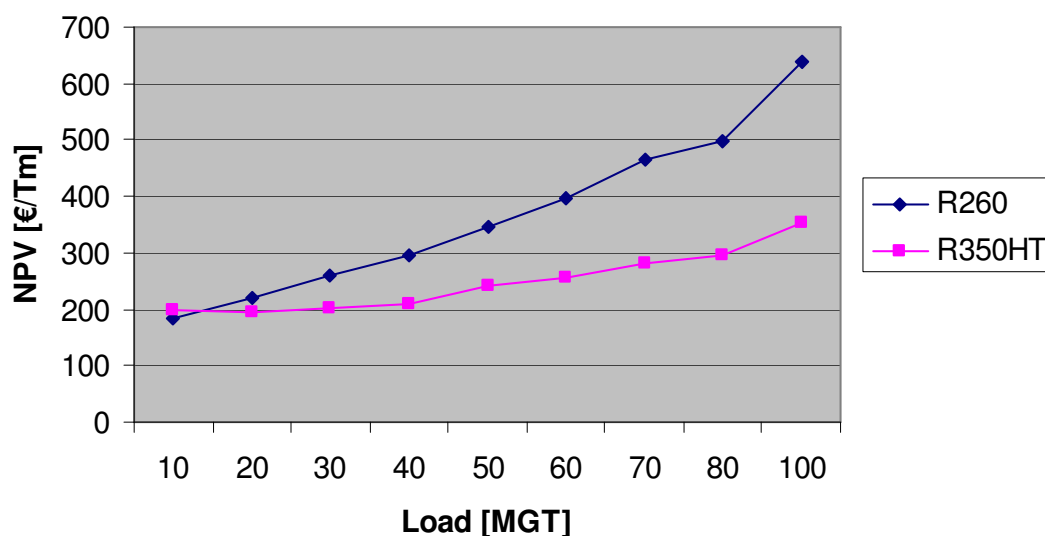


Figure 44: LCCA: NPV for reference and alternative as function of the load

Because of the fact, that the first appearance of a crack or the deepest crack is more relevant for maintenance than mean values the probability of crack growth is very important for the predicted LCC.

The results of this analysis are shown in Figure 45. As expected, the probability has a great influence on the LCC and therefore on the optimization of the technical performance of the rail and the maintenance strategy.

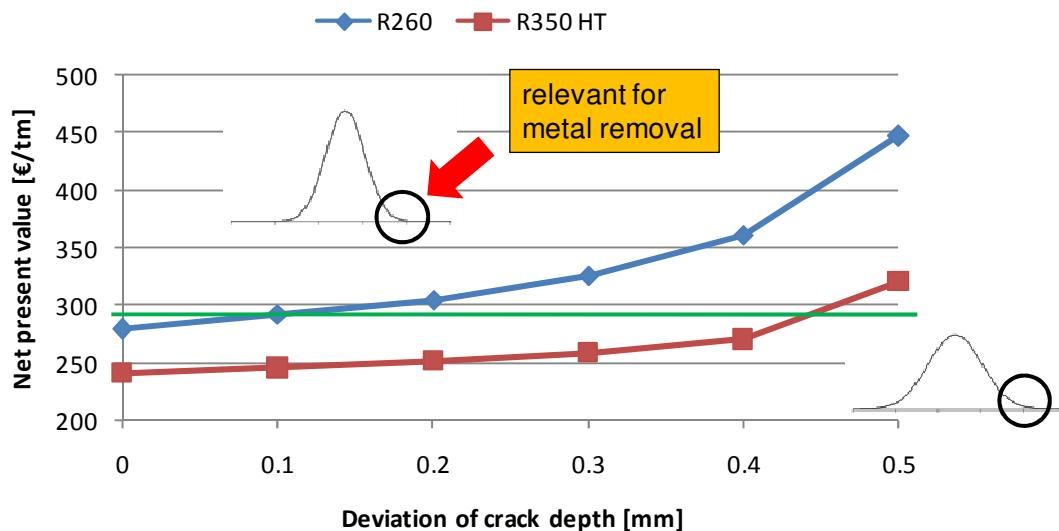


Figure 45: LCCA: NPV as a function of the probability density function

This result demonstrates clearly, that often the analysis with mean values does not deliver the right results and may lead to the wrong decision. A RAM(S) analysis provides all necessary information and supports the prediction. The conjunction of RAMS and LCC analysis therefore is the best basis for strategic decisions or decisions with high impact on system modifications.

In/Out-frame – Standard rail grade vs. hard rail grade

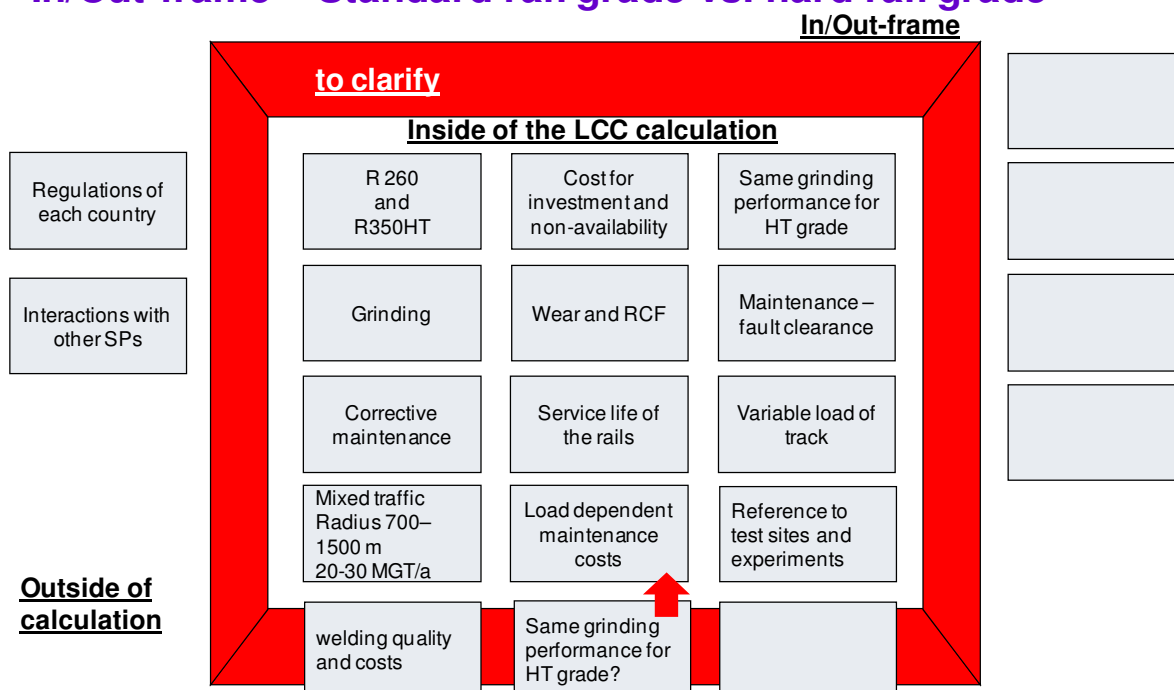


Figure 46: LCCA: IN/Out Frame

Used cost elements

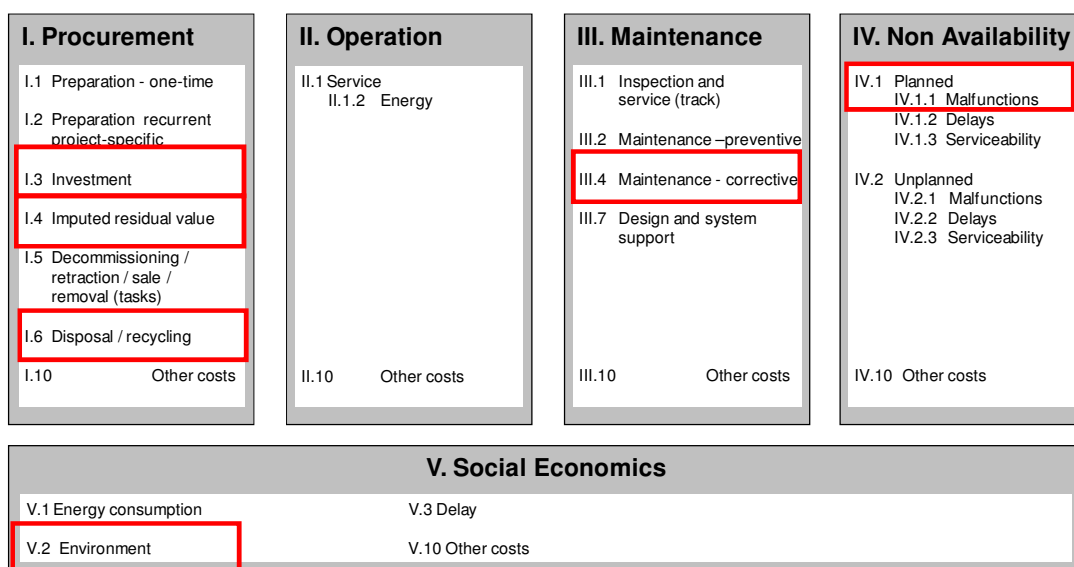


Figure 47: LCCA: used cost blocks

LCC - standard rail grade vs. hard rail grade

Parameter	Reference case R260 (standard rail grade)	Innovation R350 HT (hard rail grade)
Service life (R 700-1500 m)	20 years for 30 MGT/a	40 years for 30 MGT/a
Wear rates	w ₁ : 0,3 mm/100 MGT, w ₃ : 0,7 mm/100 MGT	w ₁ : 0,2 mm/100 MGT, w ₃ : 0,4 mm/100 MGT
RCF rate / Head-Check	0,75 mm/100 MGT	0,30 mm/100 MGT
Grinding interval for 0,8 mm metal removal	~2 [a] 30 MGT/a	~6 [a] 30 MGT/a
Rail renewal	Load dependent, at least 1 during 40 years	Load dependent
Remark: RCF measurements at DB		
<div> <div>■ Discount rate:</div> <div>8 %</div> </div> <div> <div>■ Inflation rate:</div> <div>2 %</div> </div> <div> <div>■ Effective rate :</div> <div>5.8 %</div> </div>		

Figure 48: LCCA: extract of important technical parameters

LCC - standard rail grade vs. hard rail grade

Cost block	Data structure	Reference case R260 (standard rail grade)	Innovation R350 HT (hard rail grade)
Investment	Euro Cycle Source Quality	xxx €/Tm ^{*)} load dependent, nom. 20 year Procurement Experts / Analysis	xxx €/Tm load dependent, nom. 40 year Procurement Experts / Analysis
Operation	Euro Cycle Source Quality	N/a	N/a
Maintenance Rail renewal	Euro Cycle Source Quality	xxx €/Tm load dependent, nom. 20 year IM Experts / Analysis	1xxx €/Tm load dependent, nom. 40 year IM Estimation / Experts / Analysis
Maintenance Rail grinding	Euro Cycle Source Quality	x-xx €/m per shift load-, radius dependent, 1 year RIM Experts / Analysis	x-xx €/m per shift load-, radius dependent, 3 year IM Experts / Analysis
Non-Availability	Euro Cycle Source Quality	Track Category dependent load dependent IM Analysis	Track Category dependent load dependent IM Analysis

^{*)} Tm = Track meter

Figure 49: LCCA: extract of important economical parameter

Annex II Questions per project phase per RAMS / LCC analysis

Questions	1 Investigation	2A Variants study	2B Preferred alternative	3 Implementation
RA	What change in reliability and availability of the train routes can (as a consequence of infrastructural changes) be expected if the function change is implemented?	What change in RA performance is expected for the different variants, in relation to the existing situation?	What change in RA performance is expected for the different options of the preferred variant in relation to the current situation?	What change in RA performance is expected for the chosen technical solution in relation to the existing situation?
M	What change in maintenance work (hours, money) is expected when the change is implemented in relation to the current situation?	What change in maintenance work (hours, money) is expected from the different variants in relation to the current situation?	What change in maintenance work (hours, money) is expected for the different options of the preferred variant in relation to the existing situation?	What change in maintenance work (hours, money) is expected after implementation in relation to the existing situation?
S	What change in the safety of the railway system can be expected if the intended function change is implemented?	What change in the safety of the rail system is expected from the different variants in relation to the existing situation?	What change in the safety of the railway system is expected for the different options of the preferred variant in relation to the existing situation?	What change in the safety of the railway system is expected for the selected technical solution in relation to the existing situation?
LCC	What change in life cycle costs is associated with the implementation of the function change?	What life cycle costs are associated with the different variants?	What life cycle costs are associated with the different options?	What life cycle costs are expected after implementation?
RAMS / LCC	What reliability, availability and safety can be achieved at what life cycle costs?	What level of reliability, availability and safety can be achieved per variant at what life cycle costs?	What option has the highest level of reliability, availability and safety at the lowest life cycle costs?	What technical solution provides the highest level of reliability, availability and safety at the lowest life cycle costs?

Social cost – benefit analysis	What expected costs and benefits relate to the function change?	What expected costs and benefits relate to every variant?	What expected costs and benefits relate to every option?	What costs and benefits are expected after the implementation?
RAMS / LCC specification	What RAMS requirements can we specify, and at what maximum life costs should it be possible to implement the function change?	What RAMS requirements can we specify and at what maximum life cycle costs should it be possible to implement the infra change?	What RAMS requirements can we specify and at what maximum life cycle costs should it be possible to achieve the infra change?	What RAMS performance is expected in the operational phase and what are the maximum life cycle costs for the selected technical solution?

Annex III References

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Public deliverables of InnoTrack

- D6.1.1 Incorporated rules and standards, 2007
- D6.1.2 Models and Tools, 2007
- D6.2.1 Unique Boundary Conditions, 2007
- D6.2.2 Benchmark of LCC Tools .2008
- D6.2.4 Database and Requirements, 2008
- D6.3.1 RAMS Boundary Conditions 2008
- D6.3.2 Requirements for RAMS analysis of railway infrastructure, 2008
- D6.3.3 Necessary developments of RAMS technologies, 2009
- D6.4.1 Key values for LCC and RAMS 2009
- D6.4.2 Models and monitoring methods for LCC and RAMS relevant parameters, 2009

Websites

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Mil Standards - Department of defense www.uscg.mil

APIS - www.apis.de/en

Relex - www.relex.com

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isograph www.isograph-software.com

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