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RAMS and LCC in Rail Track Maintenance

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PREFACE

The research work presented in this thesis has been carried out at Luleå Railway Research Center (Järnvägstekniskt Centrum, JVTC) and has been sponsored by Swedish National Rail Administration (Banverket).

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Ambika Prasad Patra

December, 2007
Luleå, Sweden

ABSTRACT

Railway infrastructure is a complex system. An important aspect of the rail infrastructure is that the assets have a long useful life. So once installed, it is very difficult to modify the initial design. Thus, the performance of the infrastructure depends on the maintenance and renewal decisions taken during its life cycle. In many countries, restructuring railways and increasing efficiency requirements cause a changing environment for infrastructure management. Responsibilities for parts of the railway system are often handed over to different players. In order to guarantee optimal long-term results for the railway systems, the effects of decision should be systematically evaluated. The infrastructure manager, responsible for design, construction, maintenance, renewal and upgrading the infrastructure, has a clearly defined role and is confronted by increasing performance of the associated partners. Due to increase in operation and maintenance costs, infrastructure managers are compelled to optimise budget, while reliability and availability have to be increased without endangering the traffic safety. A systematic approach is needed by the infrastructure manager for guaranteeing defined levels of performance. As in the current scenario, most of the maintenance and renewal decisions are based on past experience and expert estimations, a need for Life cycle cost (LCC) approach arises. A life cycle costing approach considering Reliability, Availability, Maintainability & Safety (RAMS) analysis will provide a way to optimise the maintenance strategy, considering the short term budget requirements as well as long term costs of ownership.

To achieve overall RAMS and LCC objectives of the system, it is important to follow systematic RAMS/ LCC actions through out the life cycle of the system. One of the important phases of the track system life cycle is the operation and maintenance phase due to its long phase life where RAMS and LCC are to be optimised. The aim of this thesis is to develop an approach for making effective maintenance decisions based on RAMS and LCC analysis. The thesis looks into three aspects of RAMS and LCC analysis, i.e. defining RAMS and LCC in track maintenance context, applicability of RAMS and LCC in maintenance planning of track and uncertainty associated with LCC due to RAMS parameters.

The thesis provides an approach for an effective RAMS and LCC analysis during operation and maintenance phase. The thesis also comprises of the state-of-the-art of RAMS and LCC analysis followed by infrastructure managers and railway manufacturers in Europe. This work has been done as a part of a European project. To realise the benefits of large investments on railway infrastructure, effective maintenance is required. An approach has been developed on how RAMS and LCC facilitates in taking effective maintenance decisions. An integrated maintenance management system along with RAMS management system and LCC management system is must for arriving at the correct decisions. The LCC modelling followed by Banverket (Swedish National Rail Administration) for re-investment and upgrading projects have been described. While taking decisions of maintenance on the track based and RAMS and LCC, uncertainty associated with LCC should be considered. The research presents the uncertainty associated with LCC estimation and defines an approach to calculate uncertainty in LCC estimation due to RAMS parameters. A case was study carried out on iron ore line (Malmbanan) that runs from Luleå to Narvik. The RAMS data were collected from different Banverket's databases. The study helps in calculating uncertainty associated with LCC and thereby act as a decision support tool for effective track maintenance.

Keywords: RAMS, LCC, Railway track, Uncertainty, Maintenance planning

FIGURES

TABLES

DEFINITIONS AND ACRONYMS

0FELIA – *Banverket's fault analysis system*
ANN – *Annual Equivalent or Annuity*
BESSY – *Banverket's inspection system*
BIS – *Banverket's track information system*
CBS – *Cost Break down Structure*
CCA – *Cause Consequence Analysis*
CENELEC – *Comité Européen de Normalisation Electrotechnique (European Committee for Electrotechnical Standardization)*
DoE – *Design of Experiment*
FMEA – *Failure Mode and Effects Analysis*
FMECA – *Failure Mode, Effects and Criticality Analysis*
FRACAS – *Failure Reporting And Corrective Action System*
FTA – *Fault Tree Analysis*
HANNES – *Banverket's speed restriction system*
HAZOP – *Hazardous Operability Analysis*
IEC – *International Electrotechnical Commission*
IHHA – *International Heavy Haul Association*
IID – *Independent and Identically Distributed*
IM – *Infrastructure Manager*
IRR – *Internal Rate of Return*
LCC – *Life Cycle Cost*
LCM – *Life Cycle Management*
LICB – *Lasting Infrastructure Cost Benchmarking*
MDBF – *Mean Distance Between Failure*
MDT – *Mean Down Time*
MDTF – *Mean Distance To Failure*
MGT – *Million Gross Tonnes*
MMT – *Mean Maintenance action Time*
MS – *Maintenance Strategy*
MTBF – *Mean Time Between Failure*
MTBH – *Mean Time Between Hazardous Failure*

MTBSF	*– Mean Time Between Safety System Failure*
MTTF	*– Mean Time To Failure*
RAMS	*– Reliability, Availability, Maintainability and Safety*
RBD	*– Reliability Block Diagram*
RCF	*– Rolling Contact Fatigue*
SAO	*– Small and medium scale enterprises, Academia, and Organizations*
SNCF	*– Société Nationale des Chemins de fer Français (French National Railway Company)*
TFÖR	*– Banverket's train delay system*
TMMS	*– Track Maintenance Management System*
TPV	*– Total Present Value*
UIC	*– Union Internationale des Chemins (International Union of Railways)*
UNIFE	*– Association of European Railway Industries*

SYMBOLS

M	– *Life period of track in MGT (Million Gross Tonnes)*
m	– *Gross tonnage per year in MGT*
N	– *Life period of track (equivalent to M) in years*
r	– *Discount rate*
K	– *Class of curve radii*
CL	– *Average labour cost in SEK (Swedish Kroner)/hr*
L	– *Total length of track section in km*
Li	– *Length of ith curve in km*
Tgi	–*Mean time to grind for ith curve in hr/km*
ngi	– *Number of grinding passes on ith curve*
Ceg	– *Equipment cost for grinding in SEK/hr*
mgi	– *Interval for grinding for ith curve in MGT*
Ttai	– *Mean time to tamp for ith curve in hr/km*
Ceta	– *Equipment cost for tamping in SEK/hr*
mtai	– *Interval for tamping for ith curve in MGT*
Tlu	– *Mean time to refill lubrication material for each lubricator in hr*
Clu	– *Cost of lubrication material for each lubricator per year in SEK*
nli	– *Number of way side lubricators in ith curve*
Tbi	– *Mean time to clean ballast for ith curve in hr/km*
Ceb	– *Equipment cost for ballast cleaning in SEK/h*
mbi	– *Interval for ballast cleaning for ith curve in MGT*
Tt	– *Mean time to inspect track in hr/km*
Cet	– *Equipment cost for track inspection in SEK/hr*
mt	– *Interval for track inspection in MGT*
Cr	– *Cost of rail in SEK/km*
Trri	– *Mean time for rail renewal for ith curve in hr/km*
Cerr	– *Equipment cost for rail renewal in SEK/hr*
mrri	– *Interval for rail renewal for ith curve in MGT*
Cb	– *Cost of ballast in SEK/km*
Tbri	– *Mean time for ballast renewal for ith curve in hr/km*
Cebr	– *Equipment cost for ballast renewal in SEK/hr*

Mbri	*– Interval for ballast renewal for ith curve in MGT*
Cs	*– Cost of sleeper in SEK/km*
Tsri	*– Mean time for sleeper renewal for ith curve in hr/km*
Cesr	*– Equipment cost for sleeper renewal in SEK/hr*
Msri	*– Interval for sleeper renewal for ith curve in MGT*
Cf	*– Cost of fasteners in SEK/km*
Tfri	*– Mean time for fastener renewal for ith curve in hr/km*
Cefr	*– Equipment cost for fastener renewal in SEK/hr*
mfri	*– Interval for fastener renewal for ith curve in MGT*
Trbi	*– Mean time to repair rail break in ith curve in hr*
Cer	*– Equipment cost to repair rail breaks in SEK/hr*
Mrbi	*– Mean time to rail breaks in ith curve in MGT*
frbi	*– Failure rate of rail (breaks) in the ith curve*
H(t)	*– Hazard rate*
Ai	*– Inherent availability*
Aa	*– Achieved availability*
Ao	*– Operational availability*
Ro	*– Operational reliability*
C	*– Capability*

RELATED PUBLICATIONS

Patra, A. P., Espling, U. and Kumar, U. (2007) Life Cycle Cost of Railway Track - An Overview, *Proceedings of 20th International Congress & Exhibition on Condition Monitoring and Diagnostic Engineering Management (COMADEM)*, 2007, June 13-15, Faro, Portugal

Patra, A. P., Söderholm, P. and Kumar, U. (2008) Uncertainty in Life Cycle Cost of Railway Track, *Proceedings of the Annual Reliability and Maintainability Symposium (RAMS)*, 2008, January 28-31, Las Vegas, USA

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Chapter 1

Introduction

A brief introduction to the research problem is illustrated in this chapter. It covers the problem areas of the research study and discusses the research questions and the scope of the thesis.

Railway transportation system is one of the most commonly used mode of transports and its importance and utility is very high for the society. With advancement of the technology, changing environment and increasing customers' demands, railways have to constantly upgrade their various operational activities. A safe and reliable network with sufficient capacity and availability is of prime requirement. In this, the railway infrastructure plays an important role. Railway track forms an essential part of the railway infrastructure, which consists of components like; rail, sleeper, fasteners, switches and crossings, ballast, sub-grade. Each of these components has a different life and degradation rate.

While considering railway track, one needs to look at the various phases of its life cycle like; inception, design, manufacturing, installation, operation and maintenance, and disposal. Once installed, it is very difficult to modify the initial design. Thus, the performance of the infrastructure depends largely on the maintenance and renewal decisions taken during its life cycle. The design phase of the track needs to consider not only the cost, but aspects like; Reliability, Availability, Maintainability, and Safety (RAMS) and Life Cycle Cost (LCC) with respects to technological advancements and changes. After installation, during the operation and maintenance phase LCC besides RAMS is considered for making effective maintenance decisions.

Each of the track components with its varying life and degrading conditions will influence the quality and operability of the track. In order to maintain the quality of infrastructure at an accepted level, two aspects of track quality need to be considered, i.e. measurement of track quality on a continuous basis and means to achieve required track quality when the quality falls below accepted level. Track quality is measured by various parameters, e.g. service reliability, track utilisation and accessibility, track safety, track system and cost-effectiveness. High operation and maintenance costs act as a barrier for achieving financial performance of railway operation.

Track quality is vulnerable to the track system failures. With increase in track requirements in terms of axle load, gross tonnage, speed, etc., the track system experiences more failures on the track with the requirements for more maintenance. At the same time, availability of track to perform necessary maintenance decreases, due to the increased traffic. This requires more budget and other resources. To optimise the maintenance activities in terms of cost-effectiveness and RAMS, a systematic analysis approach is required.

In order to minimise failure for the railway systems, the effects of decision should be systematically evaluated. The infrastructure manager, responsible for design, construction, maintenance, renewal and upgrading the infrastructure, has a clearly defined role and is confronted by increasing performance of the collaborative partners. Due to increase in operation and maintenance costs, infrastructure managers are compelled to optimise budget, while reliability and availability have to be increased without endangering the traffic safety. A systematic approach is needed for communication with the infrastructure manager for guaranteeing defined levels of performance. As in the current scenario most of the maintenance and renewal decisions are based on past experience and expert estimations, a need for a systematic LCC approach arises. A life cycle costing approach in combination with RAMS analysis will provide a way to optimise the maintenance strategy, considering the short term budget requirements as well as long term costs of ownership.

Cost-effective decision making based on LCC usually does not consider the risk aspects. Therefore, while undertaking cost-effective decision making based on LCC for the track system, one needs to consider the uncertainties associated with LCC. The associated uncertainties are the risk factors related to the traffic disruptions/derailment costs and the variable costs due to RAM parameters.

Though some studies have been undertaken in the areas of RAMS and LCC separately (see e.g., Vatn 2002; Swier 2004; Zoeteman, 2006), a scope exists for integrating and undertaking a study for RAMS and LCC for the railway sector for enhancing the cost-effectiveness of railway system.

1.1 Research Problem

Infrastructure managers are facing increasing demands from traffic operators as well as passengers to ensure a safe, reliable and comfortable railway service. To achieve these objectives the quality of the track infrastructure needs to be improved and maintained. Maintenance activities of the track have certain maintenance goals which are linked to the organisational goals and objectives help in achieving the overall objectives of the track.

Karlsson (2005) illustrated Banverket's (Swedish National Rail Administration) vision for maintenance activities by overall goals for securing safety, reliability, comfort and cost-effectiveness.

Usually, the overall maintenance strategy consists of various critical success factors that are necessary to achieve the overall goals for maintenance. The critical success factors include the guidelines of the functions (reliability, safety, and comfort) to be achieved, methods for establishing and measuring the relationship between operational reliability, condition of infrastructure and maintenance work carried out, methods for measuring cost-effectiveness of maintenance operations, etc.

The problem arises of how to achieve track maintenance goals from the track conditions data. Effective measurement of the condition of the track, which includes track degradation and track failures, as well as maintenance actions on the track, is necessary for the achievement of track maintenance goals. Figure 1.1 describes an approach to achieve track maintenance goals by analysing track condition data.

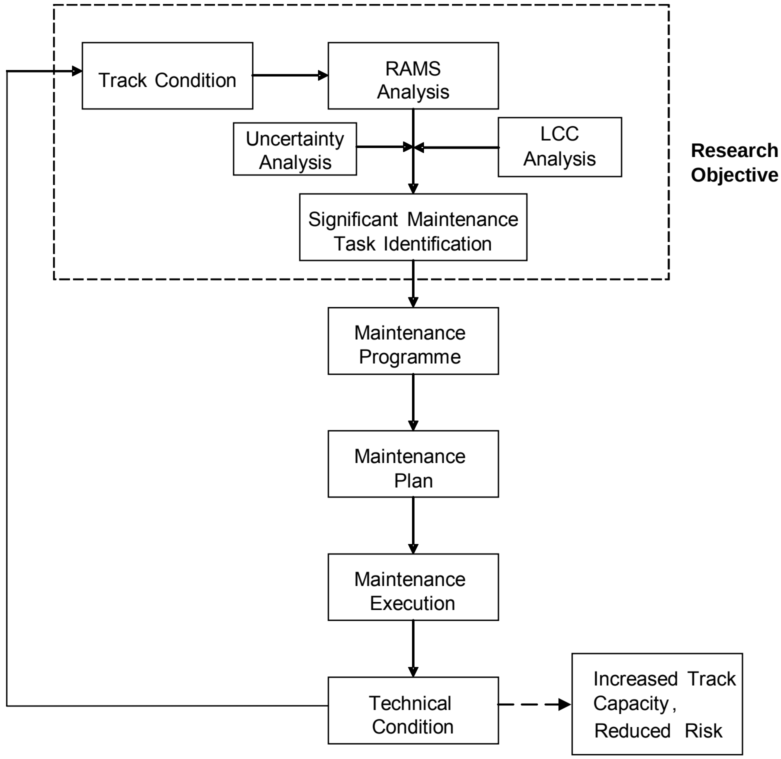

Figure 1.1: Problem description

Track maintenance task identification includes when the infrastructure needs to be maintained, what maintenance actions need to be carried out (preventive or corrective), which maintenance action will meet the track availability objective, what maintenance action will secure the safety of the system, etc. RAMS analysis of the track condition data will help in identifying different maintenance alternatives to be carried out on the track. One of the track maintenance goals is to identify the cost-effective maintenance actions. LCC analysis will help in optimising the cost-effectiveness of maintenance actions derived from RAMS analysis. Cost estimations through LCC help in foreseeing the cost implications of maintenance actions over the service life of the track not just in the short term.

While taking effective maintenance decisions based on LCC analysis, it is important to identify the uncertainties associated with LCC in order to support the decision taking process. The uncertainties associated with LCC can be broadly due to uncertainties in estimating RAMS parameters and uncertainties in economic conditions of cost parameters over a long time horizon. In the railway sector, most of the efforts to implement RAMS and LCC approaches are stand alone, and not integrated with the decision making process. Often RAMS and LCC analyses are also not considered simultaneously in the analyses.

1.2 Purpose of Research

The purpose of the study is to explore and describe the applicability of RAMS and LCC in track maintenance decisions making process considering associated risks and uncertainties.

1.3 Objectives of Research

The objectives of this thesis are to:

1. Study RAMS and LCC methodologies for railway track and identify the factors influencing them.

2. Study applicability of RAMS and LCC tools in track maintenance planning.

3. Develop track maintenance cost models using RAMS and LCC and discuss the variation in cost.

1.4 Research Questions

In order to fulfil the purpose of the study and the objectives of research, the following research questions need to be answered:

1. How are RAMS and LCC defined in railway track maintenance context?

2. How can RAMS and LCC be applied in track maintenance planning?

3. What are the uncertainties associated with LCC analysis for track maintenance planning?

1.5 Scope and Delimitations

The scope of the research is to study RAMS and LCC methodologies for the railway track from operation and maintenance context.

Two main limitations are considered in this thesis. Firstly, the research is focussed on the RAMS and LCC methodologies only in the operation and maintenance phase of the system life cycle instead of all the phases. The reason is the vastness of the research area. Separate research is needed to look into RAMS and LCC principles in other phases of the life cycle such as design, manufacturing, etc which will look in to changes in design characteristics, etc in order to achieve RAMS targets for the track system. The current research looked into the achieving RAMS and LCC targets in the operation and maintenance phase.

Secondly, the uncertainty associated with LCC is considered only because of RAMS parameters. The thesis did not look in to the uncertainty that can be caused due to economical parameters like discount rate, etc. The reason is that because in most LCC calculations, discount rate is considered as constant.

1.6 Structure of the Thesis

The thesis consists of eight chapters. Chapter 1 presents an introduction and background to the research and a problem description of the research. The chapter also outlines the purpose of study, objectives, research questions and delimitations.

Chapter 2 depicts the different phases of research, which includes the research purpose, research approach, data collection, data analysis and evaluation of research reliability and validity.

Chapter 3 describes RAMS fundamentals for railway track. The chapter discusses the different factors that affect track RAMS. RAMS activities for different phases of the system life cycle are described. Finally, a process for RAMS analysis during the operation and maintenance phase of the system life cycle has been illustrated.

Chapter 4 presents the need of LCC for railway infrastructure and the current models in practice. It also discusses the cost model being followed at Banverket (Swedish National Rail Administration) for its new investment and upgrading projects. Finally, a process for life cycle costing estimation is illustrated.

Chapter 5 describes the results of the survey that was conducted on RAMS and LCC practices by infrastructure managers and railway suppliers as a part of a European project.

Chapter 6 describes the use of RAMS and LCC in maintenance decisions for the track. An approach for taking maintenance decisions based on RAMS and LCC analysis has been illustrated.

Chapter 7 illustrates a methodology for estimation of uncertainty linked with LCC, by a combination of Design of Experiment (DoE) and Monte Carlo simulation. The chapter also includes developed maintenance cost models for track and a case study of Banverket (Swedish National Rail Administration).

Chapter 8 contains conclusions and recommendations for future research.

Chapter 2

Research Methodology

In this chapter some research options and methods are described briefly. The chosen research approach and methodologies for achieving the research objectives have been discussed.

2.1 Introduction

Research can be defined in many ways. Most generally defined, research is a process through which questions are asked and answered systematically. As a form of criticism, research can include the questions of whether or not we are asking the right questions (Dane, 1990). In other words, research is a systematic examination of the observed information to find answers to the problems. Research methodology is the link between thinking and evidence (Sumser, 2000). To do research, it is essential to choose a clear methodology. This provides a framework for integration of the different technical, commercial, and managerial aspects of study. The study of research methodologies provides the researcher with the knowledge and skills that are needed to solve the problems and meet the challenges of a fast-paced decision making environment (Cooper and Schindler, 2003).

2.2 Research Purpose

There are many ways to do research, but the purpose of research can be classified into three ways i.e. exploratory (explore a new topic), descriptive (describe a phenomenon) and explanatory (explain why something occurs). The details of these are described in table 2.1.

Table 2.1: Different kinds of research proposals (Neuman, 2003)

Exploratory	Descriptive	Explanatory
- Become familiar with the basic facts, setting, and concerns. - Create a general mental picture of conditions - Formulate and focus questions for future research - Generate new ideas, conjectures, or hypotheses - Determine the feasibility of conducting research - Develop techniques for measuring and locating failure data	- Provide a detailed, highly accurate picture - Locate new data that contradict past data - Create a set of categories or classify types - Clarify a sequence of steps or stages - Document a casual process of mechanism - Report on the background or context of a situation	- Test a theory's predictions or principle - Elaborate and enrich a theory's explanation - Extend a theory to new issues or topics - Support or refute an explanation or prediction - Link issues or topics with a general principle - Determine which of several explanations is best

The methodologies used in this research are both descriptive and exploratory. The research purpose of this study is to describe the methodologies of RAMS and LCC analysis for the railway track system and describe the methodologies of utilising both RAMS and LCC analysis in making track maintenance planning decisions as well as develop an approach to calculate uncertainty associated with LCC estimation.

2.3 Research Approach

Research may be fundamental or applied in nature depending upon the knowledge about a certain area and the solution intended. Fundamental research aims to widen knowledge of a particular subject so that future research initiatives could be based on it. It is research which is designed to solve problems of a theoretical nature with little direct impact on strategic decisions. Applied research addresses existing problems and opportunities (Cooper and Schindler, 2006).

This thesis is an applied research, the purpose of which is to apply RAMS and LCC methodologies in the railway track context and to develop a process to take track maintenance decisions based on RAMS and LCC analysis. The knowledge gathered from extensive literature study, discussions and consultations with RAMS and LCC experts within Europe was applied to delineate the usefulness of RAMS and LCC analysis in railway track maintenance planning so as to make the planning more effective and risk based.

The research approach can be categorised into induction or deduction (Sullivan, 2001).

- Induction approach uses observations, knowledge base and empirical data to explain and develop theories. The approach involves inferring something about a whole group or class of objects from our knowledge of one or a few members of the group or class.
- Deduction approach can be applied to generate hypotheses based on existing theories, the results of which are derived by logical conclusions.

The research approach can be quantitative or qualitative. In simple terms, quantitative research uses numbers, counts, and measures of things whereas qualitative research adopts questioning and verbal analysis (Sullivan, 2001).

In this research both deduction and induction research approaches have been applied. Deduction approach is applied to develop a process of RAMS and LCC application in railway track maintenance, whereas induction approach is applied to calculate uncertainty in LCC estimation. Both qualitative and quantitative research methodologies have been applied in this research. Quantitative research deals with calculation of uncertainty in LCC analysis and qualitative analysis deals with a survey of RAMS and LCC methodologies in Europe as well as RAMS and LCC process in railway track maintenance.

2.4 Data Collection

Data can be defined as the facts presented to the researchers from the studied environment. Data may be divided into primary and secondary types. Data collected by the researcher for the purpose of study through various experiments or onsite data recording are called primary data. Primary data are sought for their proximity to the truth and control over error. Data collected by other people/organisations and used by the researchers are called secondary data.

They have at least one level of interpretation inserted between the event and its recording (Cooper and Schindler, 2006).

Qualitative data were collected through relevant scientific papers and articles from online databases. The data for the RAMS and LCC survey in Europe were collected from the questionnaires developed (see chapter 5 for details), telephone discussions with infrastructure managers and the reports of the concluding projects at European level. Relevant books were searched from Lucia (Luleå university library's catalogue) and relevant reports, licentiate and PhD theses from various universities were also studied.

Quantitative data were collected from Banverket's (North region) BIS, BESSY and 0felia databases (see details of the databases in Karlsson, 2005) from the iron ore line (Malmbanan) from Kiruna, Sweden to Narvik, Norway from the years 1997 to 2005. Cost related data were collected from personal consultations with experts in Banverket.

2.5 Data Analysis

Researchers generate information by analysing data after their collection. Data analysis is one step, and an important one, in the research process. Data analysis usually involves the reduction of accumulated data to a manageable size, developing summaries, looking for patterns, and applying statistical techniques. Further, the researcher must interpret these findings in the light of the client's research questions or determine if the results are consistent with the hypotheses and theories (Cooper and Schindler, 2006).

In this thesis the analysis of failure and maintenance data for best fitting distributions was carried out. Further Design of Experiment (DoE) and Monte Carlo simulation methodologies were applied to identify the RAMS parameters that are influential on the LCC estimation and their variability. DoE (e.g. Coleman *et al.,* 1993*)* is applied to guide how the RAM parameters should be varied in a systematic way in order to extract as much information as possible and reduce the number of simulations.

2.6 Reliability and Validity

According to Neuman (2003) reliability means dependability or consistency. It suggests that the same things are repeated or reoccur under identical or very similar conditions. Reliability means that the implementation of a study, such as data collection procedures, can be conducted by somebody else with the same result. Validity is concerned with whether or not the item actually elicits the intended information. Validity suggests fruitfulness and refers to the match between a construct, or the way a researcher conceptualises the idea in a conceptual definition, and a measure. It refers to how well an idea about reality fits in with actual reality (Neuman, 2003).

To meet the reliability the data and information used in this thesis are collected either from reputed journals, refereed conference proceedings and reports or from Banverket's databases. The methodologies i.e. DoE and Monte Carlo simulations that are used for data analysis are standard methodologies which have been used effectively for years.

Chapter 3

RAMS Analysis for Railway Track

Reliability, Availability, Maintainability & Safety (RAMS) is defined as characteristic of a system and acts as a performance indicator for system quality and performance. Its application to railway track is quite limited. This chapter looks into the basic principles of RAMS analysis in railway context. Achieving RAMS targets lies in identifying the factors that influence system RAMS. The chapter discusses the different factors that affect track RAMS. RAMS activities for different phases of the system life cycle are described. Finally, a process for RAMS analysis during the operation and maintenance phase of the system life cycle has been illustrated.

3.1 Introduction

Reliability and maintainability management are attracting new interest in today's corporate world. The quest to remain competitive and provide timely and accurate services, is partly responsible for this interest. A company cannot adopt a rapid response strategy if its system is unavailable and unreliable (Madu, 2005). As engineering disciplines, reliability and maintainability are relatively new. Reliability and maintainability are not only an important parts of the engineering design process but also necessary functions in life-cycle costing, cost benefit analysis, operational capability studies, repair and facility resourcing, inventory and spare parts requirement determinations, replacement decisions, and the establishment of preventive maintenance programs.

The first European standard (EN 50126) for the railway system in this context was published in 1999 by CENELEC which defines Reliability, Availability, Maintainability & Safety (RAMS) as a characteristic of a system's long term operation and achieved by the application of established engineering concepts, methods, tools and techniques throughout the lifecycle of the system.

EN 50126 (1999) defines basic RAMS elements as:

Reliability: probability that an item can perform a required function under given conditions for a given time interval.

Availability: ability of a product to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval assuming that the required external resources are provided.

Maintainability: probability that a given active maintenance action, for an item under given conditions of use can be carried out within a stated time interval when the maintenance is performed under stated conditions and using stated procedures and resources.

Safety: the state of technical system freedom from unacceptable risk of harm.

The development of a dependable system calls for the combined utilisation of a set of four techniques Avizienis *et al.* (2001):

- *fault prevention*: how to prevent the occurrence or introduction of faults
- *fault tolerance*: how to deliver correct service in the presence of faults
- *fault removal*: how to reduce the number or severity of faults
- *fault forecasting*: how to estimate the present number, the future incidence, and the likely consequences of faults

The means to achieve a dependable system lie in fault prevention, fault tolerance, fault removal and fault forecasting. Fault prevention is attained by quality control techniques employed during design and manufacturing stages.

Fault tolerance is intended to preserve the delivery of the correct service in the presence of active faults. It is generally implemented by fault detection and subsequent system recovery.

Fault removal is performed both during the development phase, and during the operational life of the system. Fault removal during the development phase of the system life cycle consists of three steps: verification, diagnosis and correction where as during the operational life of the system it consists of corrective and preventive maintenance.

Fault forecasting is done by performing an evaluation of the system behaviour with respect to fault occurrence or activation. Qualitative evaluation aims to identify, classify and rank the failure modes that will lead to system failure. Quantitative evaluation aims to evaluate in terms of probabilities the extent to which some of the attributes of dependability are satisfied.

3.2 RAMS Parameters

A thorough understanding of the technical description of the system is necessary to perform RAMS analysis of the system. In case of track, a track system consists of different components namely, rails, switches, fasteners, sleepers, tie plates, rail anchors, ballast and subgrade (Esveld 2001). Each of the track components gets affected by degradation of other track components, and various internal and external factors. All these aspects need to be considered to estimate RAMS of the track system which makes the calculation more complex. The following sections present some of these factors affecting RAMS. To estimate the RAMS figures at the track system level, one must evaluate the RAMS characteristics at sub-system and component level. In general, reliability and maintainability parameters are estimated both in component level as well as in system level whereas availability and safety parameters are estimated only in the system level. The integration of reliability and maintainability parameters from component level to the system level is done with the help of the Reliability Block Diagram (RBD). The details of this integration are presented in chapter 6.

Reliability Parameters

Reliability targets of the system are defined as per the failure categories explained in Table 3.1. In order to meet the required performance of the track system, the failure modes of the track should be identified and categorised as the failure categories illustrated in the table. A higher reliability target is put for significant failure whereas a not so high target is put for the minor failure category. Thus, the infrastructure managers should know which failure modes of the track should be given more attention in order to achieve reliability at the system level and incur less cost due to failure.

Table 3.1: RAM failure categories (EN 50126, 1999)

Failure Category	Definition
Significant (immobilizing failure)	A failure that - prevents train movement or causes a delay to service greater than specified time and/or generates a cost greater than a specified level
Major (service failure)	A failure that - must be rectified for the system to achieve its specified performance and - does not cause a delay or cost greater than the minimum threshold specified for a significant failure
Minor	A failure that - does not prevent a system achieving its specified performance and - does not meet criteria for significant or major failures

Reliability is defined as the probability that a system (component) will function over some time period (Ebeling, 1997). As reliability is a function of time, the time unit for the track is generally considered in Million Gross Tonnes (MGT). MGT (in Metric Tonne) is expressed as per the cumulative tonnage passed over a track section in one year. This is because train running periods account for more degradation of the track than train free periods but ageing factor can be found in some track components e.g. wooden sleeper.

Among the factors which have an important influence on the equipment reliability are i) period of use and ii) environment of use. Typical reliability parameters that have been used for track are:

Mean Time To Failure (MTTF):	for non-repairable system
Mean Distance To Failure (MDTF):	for non-repairable system
Mean Time Between Failure (MTBF):	for repairable system
Mean Distance Between Failure (MDBF):	for repairable system

Maintainability Parameters

Maintainability is a design related function and must be engineered during the initial design, definition, and development phases of the life cycle. Maintainability engineering is performed for the following reasons:

- To achieve ease of maintenance through design, reducing maintenance time and cost
- To estimate maintenance and system downtime
- To estimate labour, hours, time, and other resources for proper maintenance

Maintainability is most commonly measured by Mean Time To Repair (MTTR). Time elements that are comprised in MTTR are given by access time and repair/replacement time. Maintainability is also represented by Mean Time Between Maintenance (MTBM) or Mean Distance Between Maintenance (MDBM). MTBM/MDBM includes both unscheduled and preventive maintenance.

Availability Parameters

Reliability and maintainability determine the availability of systems and equipment. The system availability can be measured in three ways:

- Inherent availability
- Achieved availability
- Operational availability

Inherent availability: This is the ideal state for analysing availability. Inherent availability is the probability that a system or equipment, when used under stated conditions, is an ideal support environment (i.e. readily available tools, spares, maintenance personnel, etc.), which will operate satisfactorily at any point in time as required (Blanchard and Fabryky, 1998). Inherent availability does not take preventive maintenance into account.

Inherent availability is given by $A_I = \frac{MDBF}{MDBF + MTTR}$ 3.1

Achieved availability: Achieved availability is more realistic in nature as it considers both preventive maintenance as well as corrective maintenance. Achieved availability is the probability that a system or equipment, when used under stated conditions is an ideal support environment (i.e. readily available tools, spares, personnel, etc.), which will operate satisfactorily at any point in time (Blanchard and Fabryky, 1998).

Achieved availability is given by $A_A = \frac{MDBM}{MDBM + MMT}$ 3.2

MMT = Mean Maintenance action Time. It comprises of both corrective and preventive maintenance time.

Operational availability: Operational availability is the probability that a system or equipment, when used under stated conditions in an actual operational environment, will operate satisfactorily when called upon (Blanchard and Fabryky, 1998). Operational availability takes into account that maintenance response is not instantaneous rather it considers logistic issues related to repair.

Operational availability is given by $A_O = \frac{MDBM}{MDBM + MDT}$ 3.3

Increase in preventive maintenance or renewal actions can have an adverse effect on the availability of the system as it reduces MTBM or MDBM. But at the same time it increases the MTBF/ MDBF of the system. So optimisation of the number of preventive maintenance actions is necessary in order to achieve availability of the system.

Mean Down Time (MDT) comprises of Mean Detection Time (troubleshooting time), Mean Decision time (time to take decision in case of a failure), MTTR, Mean Functional Test time (testing for start up time) and Mean Logistic Time.

Safety Parameters

Safety analysis deals with category and severity levels of hazardous events that can occur to the track system. Hazard identification is the first step in the safety analysis. The hazardous events can be categorized as frequent, probable, occasional, remote, improbable and incredible. Similarly the severity level can be divided into four categories i.e. catastrophic, critical, marginal and insignificant.

Safety can be defined as a subset of reliability with consideration of severity of failure modes. Typical safety parameters that have been used for track scenario are:

Mean Time Between Hazardous Failure (MTBHF)
Mean Time Between Safety System Failure (MTBSF)
Hazard rate H(t)

Time units in the above cases are considered in Million Gross Tonnes (MGT).

3.3 RAMS Interrelation

Safety and availability are considered as the output of any RAMS analysis and any conflicts between safety and availability requirements may prevent in achieving a dependable system from being achieved (EN 50126, 1999). Attainment of in-service safety and availability targets can only be achieved by meeting all reliability and maintainability requirements and controlling the ongoing, long-term, maintenance and operational activities and the system environment.

The interrelationship between RAMS components is shown in Fig. 3.1. Failures in a system will always have some effect on the behaviour and performance of the system (details discussed in section 3.2). All failures adversely affect the system reliability whereas some specific failure will have an adverse effect on the safety of the system.

The Figure describes the relationship of RAMS parameters with maintenance support of the system. Maintenance support performance is defined as the ability of a maintenance organization, under given conditions, to provide upon demand the resources required to maintain an item, under a given maintenance policy (IEV 191-02-08, 2007).

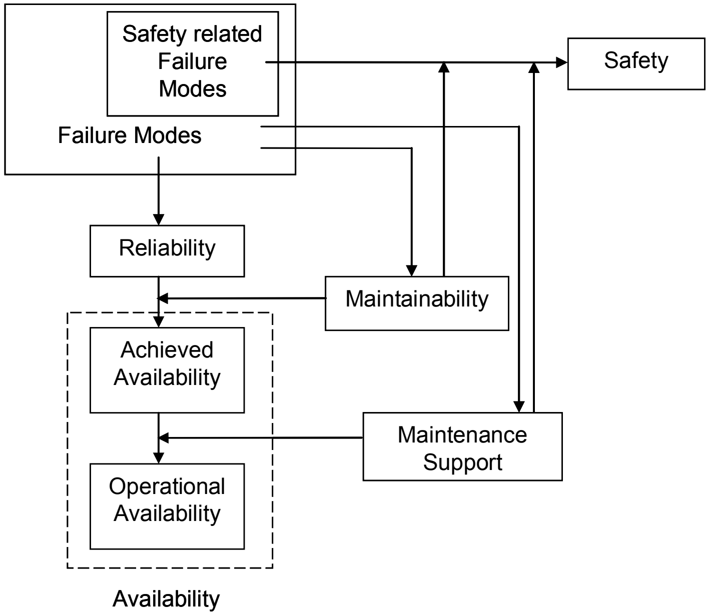

Figure 3.1: Interrelationship of RAMS elements

Maintenance support of a system deals with actual maintenance work by developing maintenance procedures and logistic support, etc. Based on the failure modes, various tools and methods are used to calculate reliability and maintainability of the system, for example, FMEA (Failure Mode and Effects Analysis), FMECA (Failure Mode, Effects and Criticality Analysis), FTA (Fault Tree Analysis), Failure Block Diagram Analysis, CCA (Cause Consequence Analysis), etc (see Markeset and Kumar, 2001). Failure modes directly affect reliability (in terms of probability of occurrence of failure modes), maintainability (in terms of the number of failures occuring in a period of time) and supportability (in terms of probability and criticality of failure modes) of the system.

Safety of the system can be considered as the sub-set of reliability of the system, when the severity of the failure consequences is taken into account. Safety of a system depends on maintainability of the system in terms of ease of performing maintenance of safety related failure modes, time to restore the system into a safe mode, etc and maintenance support of a system in terms of effective maintenance procedures to restore the system into a safe mode. Availability of a system depends on reliability of a system in terms of probability of occurrence of each failure mode, maintainability in terms of time to detect, locate and restore the failure mode and maintenance support in terms of availability of spare parts, maintenance procedures and human factors for carrying out the maintenance actions.

3.4 Factors Affecting RAMS

To achieve a dependable system, factors which could influence the RAMS of the system need to be identified, their effect needs to be assessed and the causes of these effects need to be managed throughout the lifecycle of the system.

RAMS of a railway system is influenced in three ways:

- *System conditions*: sources of failures introduced internally within the system at any phase of system lifecycle.
- *Operating conditions*: sources of failures connected due to system operations.
- *Maintenance conditions*: sources of failures introduced during maintenance actions.

These sources of failure can interact with each others and the relationship is shown in Fig. 3.2. In the figure, it can be seen that reliability is not explicitly shown but, is given through group of internal and external failures in the system. The factors that influence RAMS as shown in the figure are generic and can be applied across all industrial applications with some applications in transport systems. In order to achieve a dependable track system, factors specifically affecting the track RAMS need to be identified (see Table 3.2). Table 3.2 identifies the specific factors that affect the track RAMS.

Factors mentioned above affect the characteristics of RAMS. Similarly, the quality of RAMS data affects the correctness of RAMS estimation. Many types of data are relevant to the estimation and prediction of reliability, availability, and maintainability. Not all are collected in many instances, and the lack of information is sometimes a serious problem in RAMS analysis (Blischke and Murthy, 2003). Markeset and Kumar (2003) illustrated some of the factors influencing the management of RAMS data. The factors looked into user skills and capabilities, locations, etc apart from data type, format and detail level.

Different physical parameters that affect track RAMS have been illustrated in table 3.2. In order to asses the effect of these parameters on the track RAMS, it is important to know the technical characteristics of these parameters. For example in order to estimate the effect of track load on the RAMS characteristics of the track, one must know the bending stress, shear stress and the contact stress imparted by the track load on the track. Similarly, sleeper types and spacing determine the bending stress, stiffness and damping of the track.

We can say that technical parameters are the causes of the physical parameters which directly affect track RAMS. The system condition mostly deals with the design and manufacturing of the track components whereas the operating condition deals with the rolling stock operations. In most of the cases it is difficult to change the system conditions and operating conditions of the track system in the operation and maintenance phase of the track though sometimes operating condition (e.g. change in axle load) can change because of change in railway regulations. However, changes in maintenance conditions are quite possible to enhance RAMS of the track system. An illustration of maintenance conditions affecting track reliability is given below.

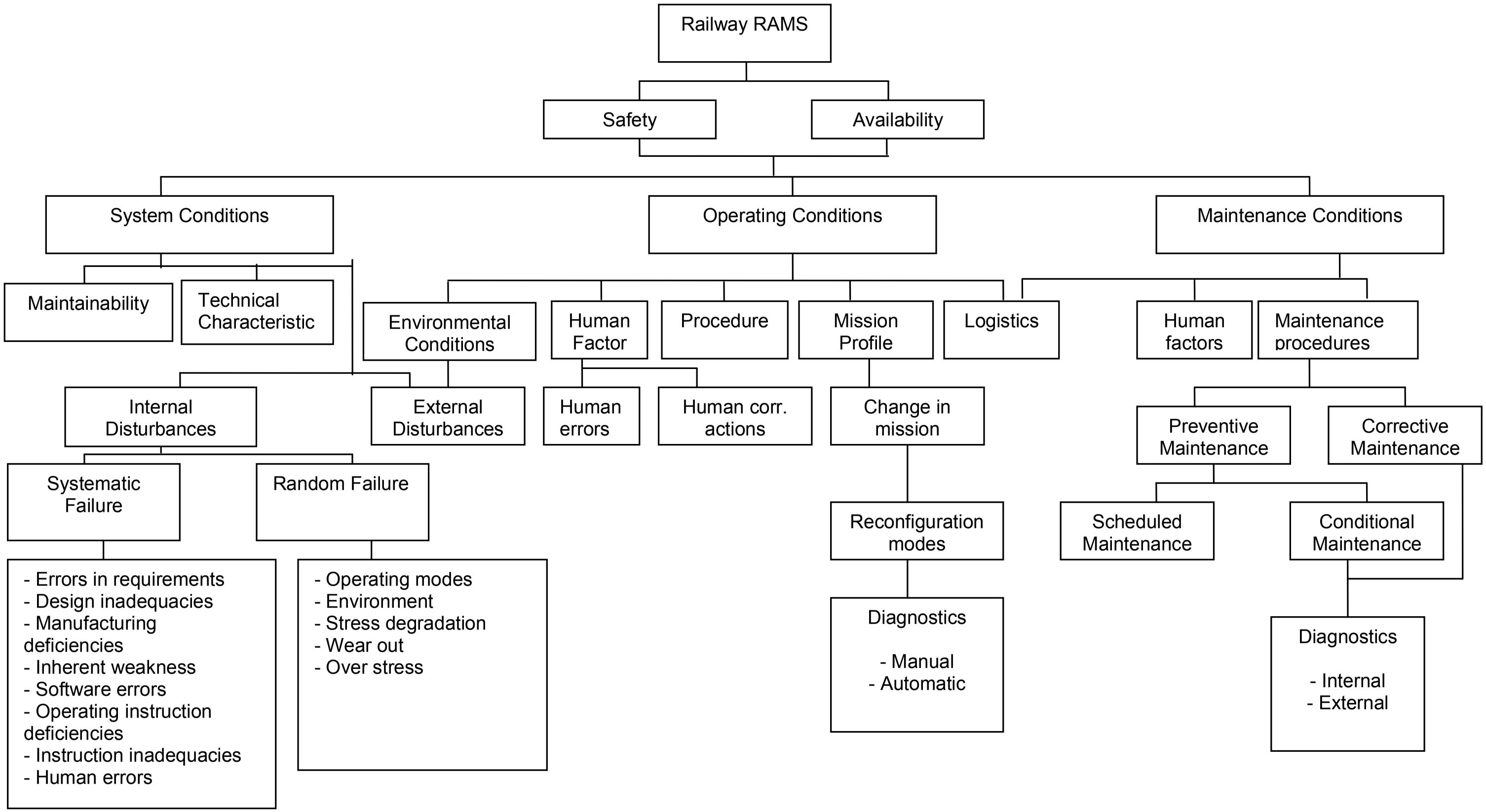

Figure 3.2: Factors influencing railway RAMS (EN 50126, 1999)

Table 3.2: Factors affecting track RAMS

	Physical parameters	Technical parameters
System conditions	Track curvature (transient curve in, transient curve out, radius)	Quasi-static stress
	Track gradients (start, end, value)	Quasi-static stress
	Rail (rail type, jointed or welded)	Yield strength (Young's modulus)
	Ballast (ballast type, ballast size)	Stiffness, Damping
	Sleeper (sleeper type, sleeper spacing)	Stiffness, Damping, Bending stress
	Fastener (fastener type)	Damping
	Subgrade (geological condition)	Stiffness, Damping
Operating conditions	Track operating conditions:	
	Loads (annual MGT, maximum axle load)	Bending stress, Shear stress, Contact stress
	Environment (temperature)	Thermal stress
	Vehicle operating conditions:	
	Speed of trains	Vertical stress, Lateral stress
	Vehicle condition (hollow wheels)	Dynamic stress
Maintenance conditions	Grinding	Wear rate
	Tamping	Change in track stiffness
	Lubrication	Change in friction co-efficient
	Renewal of track components	Interval of renewal
	Corrective replacements of track components	Failure rate of track components

Table 3.3 illustrates the effect of grinding strategy in the Canadian Pacific Railway on the reliability of the rail. It can be seen in the table that as the grinding strategy moves from corrective to preventive grinding the rail life increases considerably. Corrective grinding requires deep and infrequent cuts whereas preventive grinding requires thin but more frequent cuts (Kalousek *et al.*, 1989). Generally for heavy haul railways, the minimum interval for rail grinding is in the range of 10-15 million gross tonnes (Canon *et al.*, 2003).

Wear rate in grinding is the parameter that controls the rail life because as the wear reaches the maintenance/safety limit of the rail, it needs replacement. No grinding is a scenario where the life of rail is determined mostly by RCF. Table 3.3 also gives a comparison of fatigue life in three grinding scenario. Fatigue life of the rail is reached when the number of RCF defects in a specific track section reaches its limits.

Table 3.3: Grinding strategy vs rail life for Canadian Pacific Railway (Magel and Sroba, 2007)

Wear Criteria	**No grinding**	**Corrective grinding**	**Preventive grinding**
Rail wear rate in mm/MGT	0.04	0.06	0.03
Rail life in MGT	469	367	844
Rail fatigue life in MGT	331	496	1322

The difference in rail wear life and rail fatigue life is described in Fig. 3.3. As material removal rate by wear and grinding increases, rail wear life decreases as the approaches the maintenance/ safety limit of the rail.

But, it increases the rail RCF life because grinding and wear take away the RCF generated cracks before they become critical to the rail. Thus, grinding strategy (wear rate) is seen to be an important parameter that affects the reliability of the rail. The figure also illustrates the "magic wear rate" phenomenon. Magic wear rate is the wear rate that preventive grinding strategy should take care of in order to achieve highest reliability for the rail. As shown in the figure, when the wear rate is below magic wear rate rail life is determined by rail RCF life, whereas when wear rate is higher than magic wear rate rail life is determined by rail wear life.

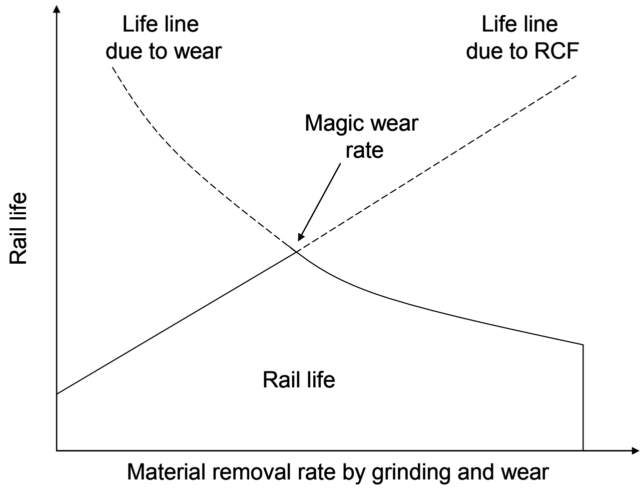

Figure 3.3: RCF, wear and rail life relationship (Magel and Sroba, 2007)

In order to asses the effects of maintenance conditions on the reliability of the track system, it is necessary to consider their combined effect on the system. As described above grinding affects the reliability of the rail. But to perform effective reliability analysis of the rail, the combined effects of other maintenance conditions e.g. lubrication, rail replacements, etc should be taken into account. For example, lubrication reduces the rail wear especially in the track curves (Diamond and Wolf, 2002) and thereby increases the reliability of the rail. But, at the same time lubrication is a factor for RCF defects which is removed by grinding (Rinsberg, 2001). Thus, an estimation of the combined effects of different conditions is necessary in order to measure their influence on the RAMS of the track system.

3.5 RAMS in Operation and Maintenance Phase

The system life cycle is a sequence of phases, each containing tasks, covering the total life of a system from initial concept through to decommissioning and disposal. The life cycle provides a structure for planning, managing, controlling and monitoring all aspects of a system, including RAMS, as the system progresses through the phases, in order to deliver the right product at the right price within the agreed time scales. A system life cycle, appropriate in the context of railway operation, is shown in Fig. 3.4. The top-down branch (left side) is generally called design and development and is a refining process ending with the manufacturing of system components. The bottom-up branch (right side) is related to the assembly, the installation, the receipt and then the operation of the whole system. The "V" representation assumes that the activities of acceptance are intrinsically linked to the design and development activities insofar as what is actually designed has to be finally checked in regard to the requirements. So the validation activities for acceptance at various stages of a system are based on the specification of the system and should be planned in the earlier stages, i.e. starting at the corresponding design and development phases of the life cycle.

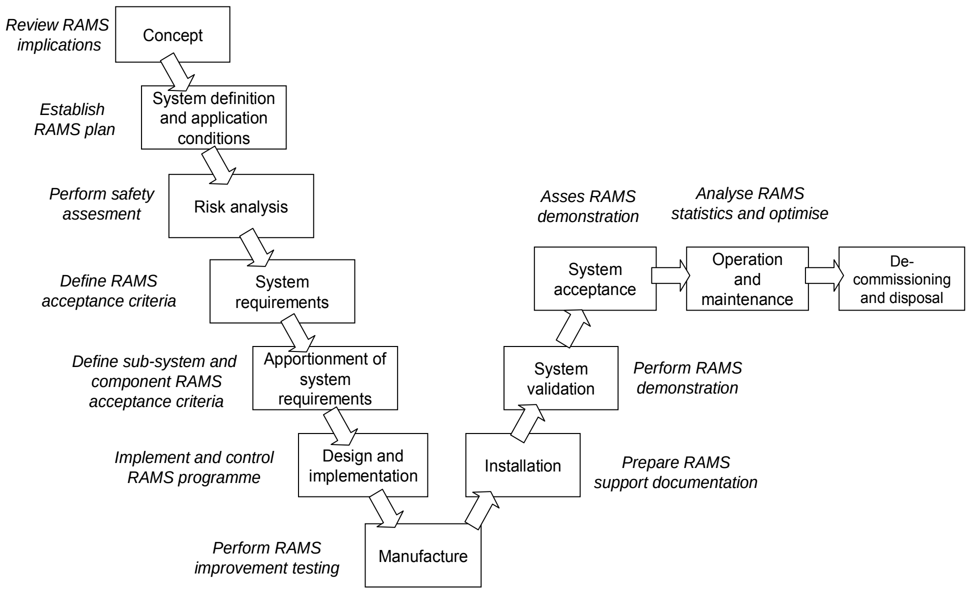

Figure 3.4: The "V" representation of RAMS life cycle (IEC 62278, 2002)

The figure also describes the various RAMS activities being carried out at each phase of the system life cycle (IEC 62278: 2002). To achieve the overall RAMS objectives of the system, it is important to follow systematic RAMS actions throughout the life cycle of the system. As far as RAMS activities are concerned, one of the important phases of the system life cycle is the operation and maintenance phase where RAMS are optimised by analysis of real life failure data.

The objective of this phase is to operate, maintain and support the total combination of components and subsystems such that the compliance with system RAMS requirements is maintained. Fig. 3.5 illustrates the RAMS process for the track system in the operation and maintenance phase of the system life cycle. It is a continuous improvement process throughout the operation and maintenance phase. As illustrated in chapter 3.4, the sources of track failures are due to the system itself, train operation or due to maintenance activities carried out on the track. The failure data are collected by FRACAS (Failure Reporting And Corrective Action System). FRACAS is a closed-loop reporting system for identifying failure modes and their root causes and subsequently determining effective corrective actions for eliminating their re-occurrence. Chapter 6 describes different RAMS databases in detail.

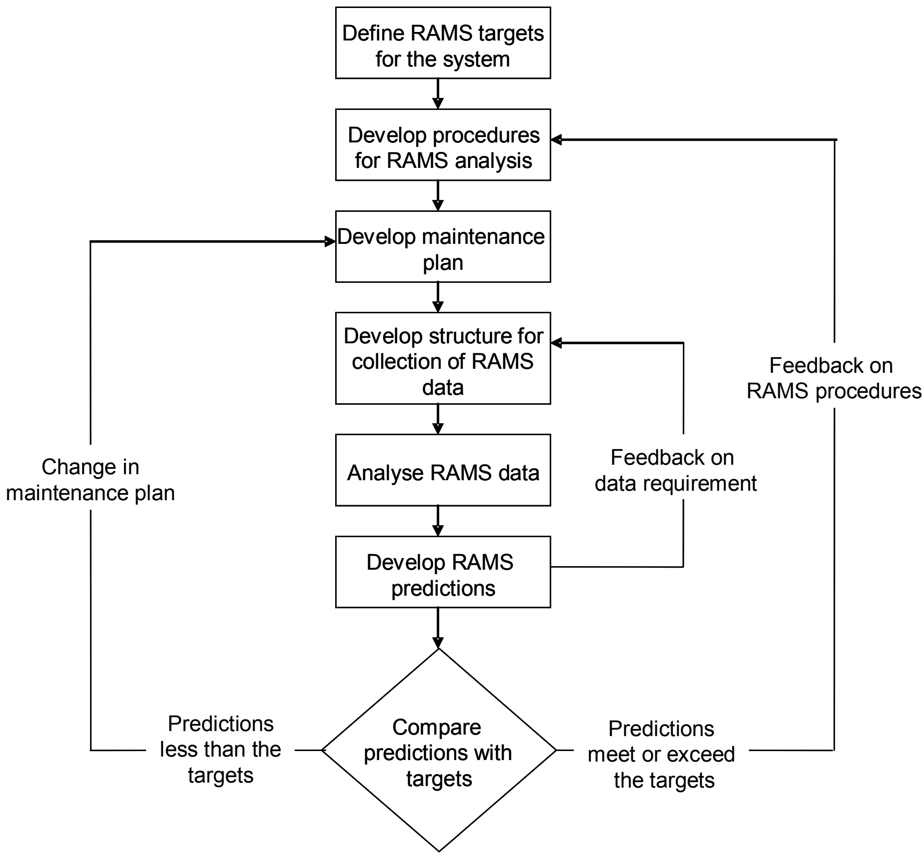

Figure 3.5: RAMS process in the operation and maintenance phase

Failure Mode Effect Critical Analysis (FMECA) is an analysis method involving two elements of risk; namely, failure frequency and consequence. FMECA analysis concentrates on the identification of the events and frequency resulting in failures and analysing their effects on the components and systems. FMECA categorises the failures as non-safety critical failures and safety critical failures. Other tools that are being used for RAMS analysis are Reliability Centred Maintenance (RCM), Markov analysis, etc.

The basic objective of the operation and maintenance phase is to monitor RAMS activities in order to meet the RAMS goals set for the track system. The performance indicators for checking the goals are the RAMS parameters described in chapter 3.3. If the goals are not met at any point of time, then changes in maintenance conditions are made (see chapter 3.4) in order to meet the goals. If the track operating conditions change during the operation and maintenance phase accordingly changes in maintenance conditions are required to meet RAMS goals.

RAMS analysis of the track should not be done with out considering the operational characteristics of the rolling stock. As stated in EN 50126 (1999), operational availability of the track hardly considers the train schedule. To have a realistic measure of the availability of the track, it is necessary to consider demand availability in operational availability. Demand availability is the probability that a system will be in a functioning state on demand (Kumar and Akersten, 2007). In case of track, demand availability defines that a unit length of track is available when the trains pass over it. To achieve the demand availability of the track section following measures must be considered:

- Reduce the corrective maintenance on the track. As failures on track can occur at random, the lower the number of failures the better is the demand availability.
- All the preventive maintenance and renewal actions on the track must be carried out in the train free periods. Maintenance plans on the track need to utilise the train free periods to maximum for all the maintenance actions.

In order to calculate the demand availability of a track section over a period of reliability and maintainability of the track along with the time train time table need to be considered.

Chapter 4

LCC Estimation of Railway Track

Several cost models have been used in the field of railway infrastructure over the years, but the usage of Life Cycle Cost (LCC) in infrastructure is quite limited. These cost models while taking decisions on maintenance and renewal actions rarely consider the whole life cycle perspective of the infrastructure. The important aspect of life cycle cost analysis is to understand the factors that influence the LCC and the parameters that are needed to estimate it. This chapter discusses the railway infrastructure's need for LCC and the current models in practice. It also discusses the cost model being followed at Banverket (Swedish National Rail Administration) for its new investment and upgrading projects. Finally, a process for life cycle cost estimation is illustrated.

4.1 Introduction

Railway infrastructure is a large and complex system with a long useful life. Therefore, once installed, it is very difficult and costly to modify the initial design. Thus the performance of the infrastructure depends on the maintenance and renewal decisions taken during its life cycle. In many countries restructuring of railways and increasing efficiency and effectiveness requirements cause a changing environment for infrastructure management. Responsibilities for parts of the railway system are often handed over to different actors. In order to guarantee optimal long-term results for the railway systems the effects of decision should be systematically evaluated (Zoeteman, 1999).

The infrastructure manager, responsible for the design, construction, maintenance, renewal and upgrading of the infrastructure, has a clearly defined role and is confronted by increasing performance of the actors. Budgets are reduced, as reliability and availability have to be increased without endangering the traffic safety. A systematic approach is needed for communication with the infrastructure manager and government and for guaranteeing defined levels of performance (see Fig. 4.2 for performance) of the infrastructure.

Putallaz (2003) states the three parameters (see Fig. 4.1) that influence the performance of the track infrastructure. The capacity may be expressed in usable train paths during a certain time span. The substance of the infrastructure refers to the average remaining useful life time of its components. Finally, the quality of the infrastructure represents the track's geometry quality and components quality. Managing the infrastructure comes down to setting those three parameters at their most appropriate level, in order to maximize efficiency. Adjustments may be made to capacity through investment policy, infrastructure substance through renewal policy and quality through maintenance policy. These three parameters can not be adjusted independently. An old infrastructure (low substance) requires more maintenance (to increase quality) whereas a bad geometry (low quality) increases the wear on the infrastructure (lower substance). Similarly, more engineering works (maintenance & renewal) require more track possessions (less capacity) whereas more traffic (high capacity) induces more wear to the infrastructure.

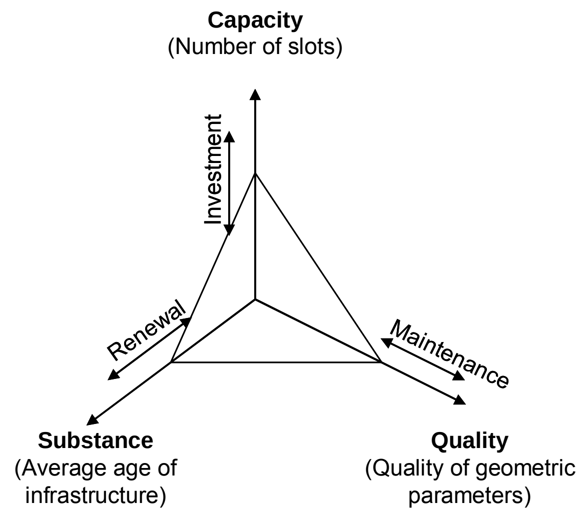

Figure 4.1: Three basic parameters of rail infrastructure influencing performance (Putallaz, 2003)

While adjusting these performance parameters simultaneously the cost aspect of each activity should be considered. As in the current scenario most of the maintenance and renewal decisions are based on the cost models that rarely consider their effects on the whole life of the infrastructure, a need for life cycle cost approach arises. Life cycle cost can be used as a tool to take cost-effective decisions on investment, renewal and maintenance in order to adjust these three parameters to optimise infrastructure performance.

4.2 Life Cycle Cost Theory

Life cycle cost is defined as all costs associated with the system life cycle (Blanchard, 1995) which includes:

- Research and development cost
- Production and construction cost
- Operation and maintenance cost
- System retirement and phase out cost

The total costs can be observed from diverse points of view i.e. from the viewpoint of the system's supplier or of the system's user or owner, or even more broadly from the point of view of society. A basic assumption providing motivation for the LCC approach is that it is usually possible to affect the future costs of a product beforehand, either by planning its use or by improving the product or asset itself (Markeset and Kumar, 2004). Asiedu and Gu (1998) stated that LCC analysis should not only be seen as an approach for determining the cost of the system but as an aid to decision making in design, maintenance, etc. The use of life cycle cost analysis should therefore be restricted to the cost that we can control.

In order to be able to estimate life cycle costs of the rail infrastructure, the factors influencing the performance of the railway infrastructure and their relationship need to be identified. The driving factor causing failures and maintenance is the degradation of the asset. Track degradation depends on many factors, such as initial quality of construction, the quality of the substructure and the loads on the track. Besides asset degradation, there are other factors that also influence the life cycle costs, such as the RAMS targets for the track, the amount of preventive maintenance, market prices of labour, materials and machines, and the operational characteristics of the line (such as axle loads, traffic intensities and the duration of train free periods). The infrastructure manager can manage some of these factors directly (e.g. maintenance strategy) or with the cooperation of transport operators (e.g. quality of rolling stock) and government (e.g. negotiated grant). Exogenous factors, such as the condition of the soil and the interest rate, will also influence life cycle costs (Zoeteman, 2001).

The performance of the railway infrastructure is defined as the level of safety, riding comfort, noise, vibrations, reliability, availability and the costs of ownership (see Fig. 4.2). Safety and noise standards indirectly influence the life cycle costs, since they determine the tolerances and thresholds for design and maintenance parameters.

Physical design influences the asset degradation together with other conditions, such as traffic intensities and axle loads, the quality of substructure and the effectiveness of performed maintenance. The quality of geometric structure determines the required volume of maintenance and renewal (M&R). The chosen maintenance strategy also influences the amount of M&R. The realised M&R volume causes expenditures and planned possessions. Maintenance strategy also has a direct impact on the life cycle cost. Incident management organisation, realised M&R volume and transport concept determine the train delay minutes caused by the infrastructure and these train delay minutes can be converted into penalties for the infrastructure managers.

Cost models used in the decision support systems or maintenance management systems should be able to provide means to evaluate and compare the costs and benefits of different maintenance strategies and options. In order to carry out an economic analysis, it is necessary to make adjustments to costs to ensure that they are all measured in the same units and represent real resources' costs.

According to Zoeteman (2001),life cycle cost can be presented in three different ways, i) total present value (TPV), ii) internal rate of return (IRR), and iii) annual equivalent or annuity (ANN).

Total Present Value (TPV):

It is the sum of all discounted cash flows. In the LCC method it mostly concerns costs; incomes can be expressed as negative costs. The larger the TPV, the less attractive is the investment compared to other alternative investments or maintenance. Investments made at different times have different economic values. To take these into account, all future costs are discounted to convert them to present values of cost.

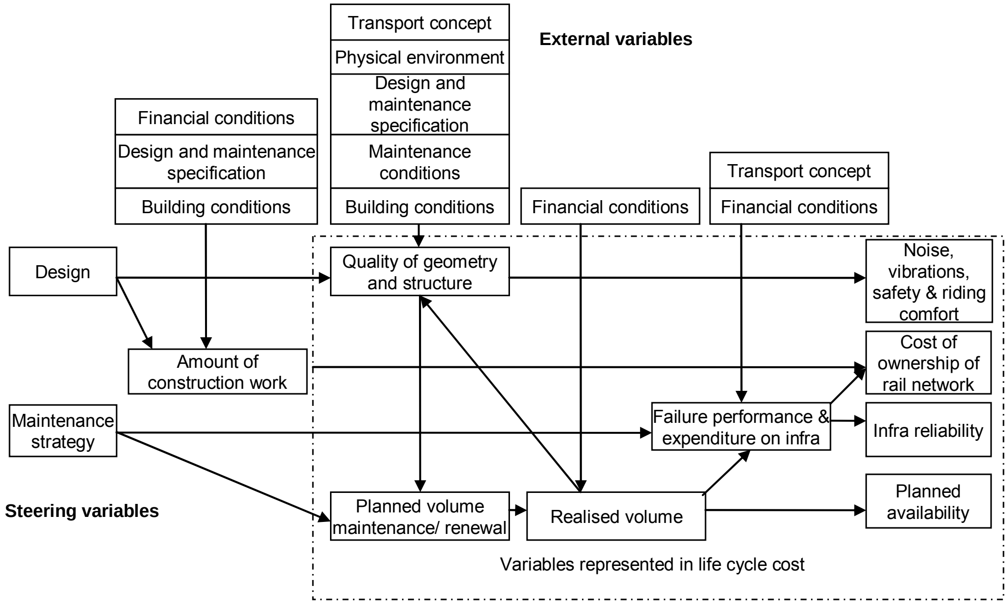

Figure 4.2: Factors influencing the performance of track infrastructure (Zoeteman, 2001)

Total Present Value (TPV) is given by:

$$TPV = \sum_{i=0}^{n} \frac{c_i}{(1+r)^i} \qquad 4.1$$

Ci = sum of all costs incurred in year i
r = discount rate, i = year of analysis

Net present value (NPV) is the difference between the discounted benefits and costs over the analysis period. A positive NPV indicates that the investment is justified at a given discount rate. NPV is given by:

$$NPV = \sum_{i}^{n-1} \frac{b_i - c_i}{(1+r)^i} \qquad 4.2$$

b_i = sum of all benefits incurred in year i

Internal Rate of Return (IRR):

Internal rate of return (IRR) is a method defined as the percentage earned on the amount of capital invested in each year of the life of the project after allowing for the repayment of the sum originally invested. It shows the profitability of an investment compared to alternative investments or maintenance strategies

The IRR is the discounting rate at which the present values of costs and benefits are equal, i.e. NPV = 0 (see Eq. 4.3).

The higher the IRR, the better is the investment. If it is greater than the discounting rate, then the investment is economically justified.

$$NPV = \sum_{i}^{n-1} \frac{b_i - c_i}{(1+r)^i} = 0 \qquad 4.3$$

Annual Equivalent or Annuity (ANN):

ANN is the sum of interest and amortisation, which has to be paid every year to finance the investments and maintenance. With the annuity, projects of different lifespans can be compared. The annual performance fee (ANN) is calculated from the flowing formula. It determines the cost incurred every year to maintain the track.

$$ANN = \frac{(1+i)^n * i}{(1+i)^n - 1} * TPV \qquad 4.4$$

Robustness of LCC:

To check the robustness of LCC models, two methods are used:

- Sensitivity analysis: The disadvantage of sensitivity analysis is that only one variable is tested at a time. Hence possible interactions between factors are not revealed.

- Uncertainty analysis: In this approach the input parameters of the LCC model are considered to be random variables from which samples are drawn. Simulation techniques are used to determine the interaction of input parameters with the outcomes.

Chapter 7 describes the uncertainty analysis of LCC. Uncertainty analysis was carried out by means of Design of Experiment (DoE) and Monte Carlo simulation.

4.2.5 Harmonisation

The life cycle cost of the track infrastructure depends mainly on two aspects of infrastructure i.e. network configuration and complexity; and network utilisation. Complexity is a predominant parameter for investment and cost of maintenance. Some major indicators are:

- Density of switches
- Length of lines on bridges and tunnels
- Lengths of double track lines
- Degree of electrification

In addition configuration parameters like curvature, axle loads and speed level have their impact on life cycle expenditure.

The utilisation of networks has a strong impact on the cost of maintenance and on the components' technical life until replacement. Some major indicators are:

- Average frequencies of trains per year
- Average gross tonnage per year (freight and passenger)

It is difficult to generalise the LCC per kilometre of track because of its variability in terms of complexity and utilisation. A harmonisation model is used to compare the cost data of different track configurations and utilities in the best possible way (Stalder, 2001). Various aspects of the harmonisation model are given by:

- *Single vs. multiple track*: Maintenance and renewal of single-track lines require more work per kilometre than for double or multiple track lines (e.g. for work site logistics, preparatory work). Based on a detailed analysis of French National Railway Company (SNCF) data and surveys of other railways, it is concluded that the cost of maintenance per track kilometre in single track is typically 40% higher than in double track. So this aspect should be taken into account when estimating LCC per track kilometre.

- *Switch densities*: Switches in the main track have a major share in the cost of track maintenance (with high impact on signalling and power supply). With switch densities varying between main tracks, the need for harmonisation is evident.

- *Track utilisation:* Maintenance and renewal as well as lifetimes of track elements depend heavily on the utilisation of networks. Data analysis has proven that maintenance expenditures can best be harmonised according to train frequencies, in particular because of the strong correlation between track access times and maintenance cost. Renewal expenditures are harmonised according to gross tonnage which has a great impact on the wear and tear of the track.

4.3 LCC Modelling

For the maintenance management of the railway asset, cost modelling of railway infrastructure has three major purposes:

- To estimate costs of a maintenance/renewal work
- To assist in the selection of the best maintenance option/strategy in terms of economic return under specified time and financial constraints
- To assist in the scheduling of maintenance works in the most effective way

Various cost models are available which are applicable to infrastructure maintenance and renewal. In 1997, the rule based expert system 'ECOTRACK' was delivered that should enable infrastructure managers to plan maintenance and renewal on the basis of well defined technical and financial rules (Zaalberg, 1998). ECOTRACK defines a five step process for generating a maintenance and renewal work plan. Inputs are track measurements, MR work histories and a rule base. The first three steps are based on an analysis of the track condition with a gradually increasing level of detail. In the initial diagnosis the rough M&R needs are calculated, while the system points the user at desirable, additional data for more detailed diagnosis. In the detailed diagnosis the work plan for each component is refined. Finally, the preliminary work programme is improved in terms of clustering renewal works, which are close in time and space. Finally, the fifth level allows a number of statistical analyses. Relatively more attention has been given in Europe to the development of decision support systems for the life cycle cost. A first LCC example comes from Veit who developed a model to calculate internal rates of return for different maintenance strategies. Applications include an analysis of track maintenance cost impacts from different locomotives and revision of existing M&R practices (Zoeteman, 2006). Zoeteman developed and applied a decision support system named LifeCycleCostPlan in several case studies (Zoeteman, 2001). Inevitably, expert judgement is an important part of the input. LCC models named as QM4C and MOVE were developed not based on degradation models but on historic cost and performance data from the existing railway networks, which have been aggregated for different types of assets (see Levi, 2001; Swier, 2004). Some models such as TMCOST (Andersson, 2002) and LCCRailTrack (Danzer, 2004) include deterioration functions. LCCRailTrack is based on Markov multistate model. The possible states of railway track as well as the chances of transfer from a less worse to a worse deterioration state need to be estimated by users; a disadvantage may be that this Markov model does not further consider the history of the track segments.

Estimation and minimisation of traffic disruption can be considered as a special area of railway research, requiring mathematical algorithms and simulation models. Studies have been undertaken in the last years to develop (Zoeteman, 2006):

- Optimal maintenance execution plans, i.e. scheduling consecutive MR machine runs in order to minimise integrated costs of track works and possessions.
- Optimal clustering and timing of small MR works into regular maintenance slots

The life cycle cost model developed by Vatn (2002) considers the punctuality cost in the model. The basic punctuality information entered is the ordinary speed of the line and any speed restrictions due to degradation. The program then calculates the corresponding increase in travelling time. The model also calculates the economic gain due to the increase in life length brought about by maintenance actions.

It can be noticed that most of the existing models in railways are not taking into account all aspects especially the risk aspects of life cycle costing. Cost modelling on traffic disruption, train punctuality, environmental cost (noise, vibration etc), and customer (end user) dissatisfaction is still in early stages, which can have a major impact on the maintenance and renewal decisions. There is a need to develop cost models for the above mentioned costs so as to introduce them in the LCC analysis of the track.

4.3.1 Cost Modelling at Banverket

Banverket is primarily funded by government grants and its activities are steered by the parliamentary transport policy goals. The overall transport policy goal is to provide a system of transport for citizens and the business sector all over the country that is both economically effective and sustainable in the long term. The five sub-goals of the overall goal are:

1. An accessible transport system
2. A high standard transport quality
3. Safe traffic
4. A good environment
5. Positive regional development

The cost modelling at Banverket considers that goals mentioned above are met and provide a system of transport that is both economically effective and sustainable. Banverket uses the following cost modelling (BV intranet, 2007) steps (see Fig. 4.3). The information was collected from personal consultations (Espling, 2007) with experts in Banverket. The steps of the cost modelling are:

1. Conceptual study: It deals with the details and the consequences of the investment.
2. Pre study: It is based on a long lifespan of up to 60 years. The calculation in this phase is to show the gains for society, and the consequences.
3. Railway Investigation: This phase deals with exploration of new ground, vibration, noise, pollution, etc.
4. Railway plan: It deals with whether any new ground/ land is needed.
5. System documentation: It deals with actual cost planning.
6. Construct documentation: Prepares the documents for construction.
7. Construction
8. Delivery

Banverket's cost modelling is a typical example of LCC analysis performed only for new investment, upgrading and renewal projects. It does not perform a LCC analysis for all the maintenance actions carried out on the track. New investment and upgrading are normally the processes that have a long planning horizon. It has to be put in the three years administration plan and also be published in the network statement.

The calculation in the pre-study is socio-economical, and it shows the gains for society. It is based on a long lifespan of up to 60 years. Upgrading follows the same steps as new investment except the conceptual study phase.

The decision for renewal includes from steps 4 – 8. The decision for renewal is based on judgment of asset condition and analysis of the operational situation. The calculation cost is based on historical data. If the renewal can be done within the budget, it is planned and done, but if more budgets needed, normally steps 4 – 8 are followed, and then this is put into the administration plan for next year. New investment and upgrading are handled by the investment division. Renewal is handled both by the investment division and the operation & maintenance division. The operation & maintenance division takes care of all smaller renewals, e.g. exchange of switches, rail, sleeper etc. In the operation and maintenance phase the cost calculations are based on estimation, historical data, and expertise.

As LCC is being used in every step of the process for taking decision, the need is to develop an effective procedure to calculate LCC so as to take correct decisions on maintenance, renewal and investment.

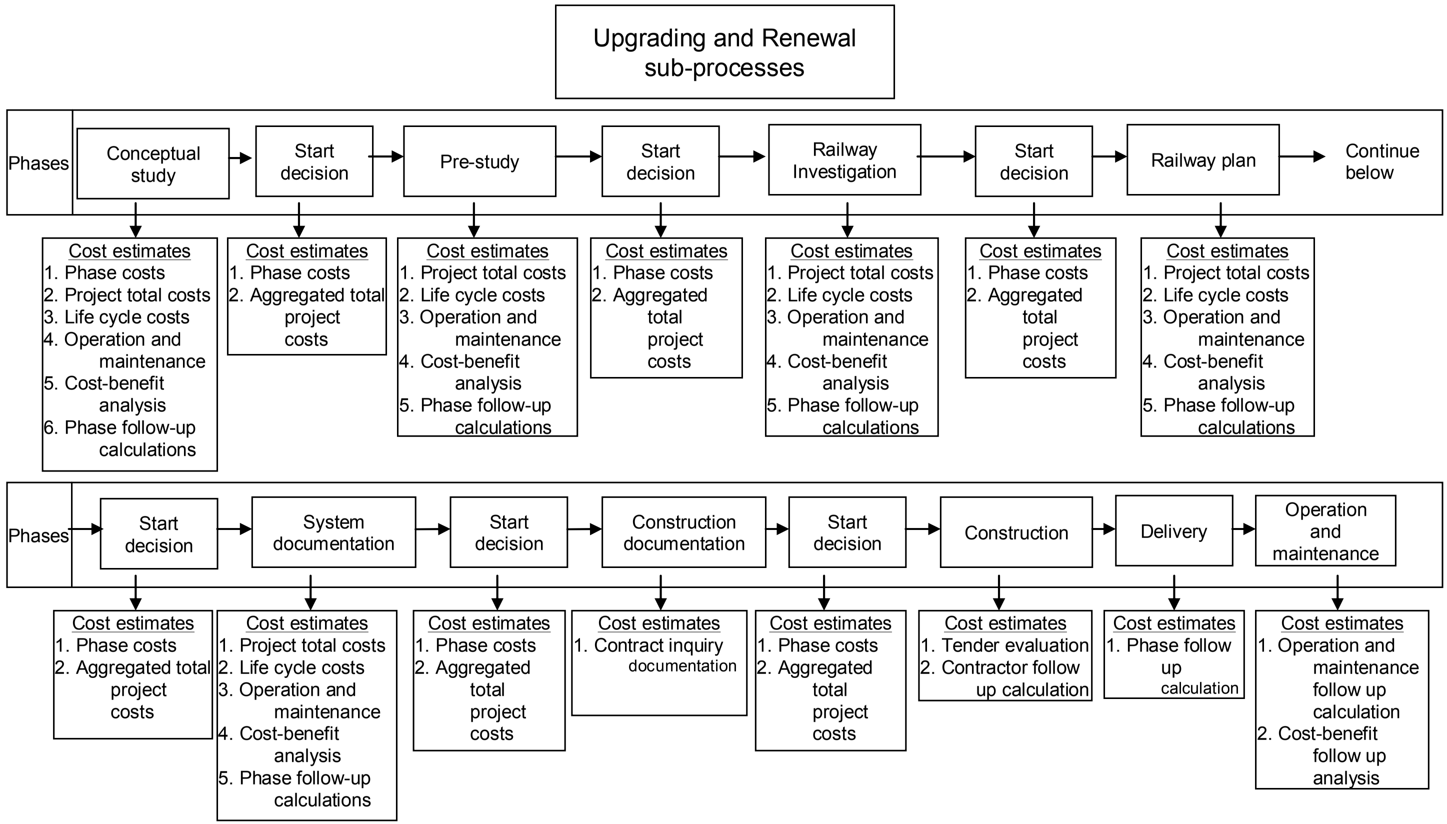

Figure 4.3: Cost modeling for new investment projects at Banverket (BV intranet, 2007)

4.4 LCC Analysis in Operation and Maintenance Phase

Different standards illustrate that the life period for LCC analysis should be comprised of all the life cycle phases of a system life cycle. But from the track perspective as the operation and maintenance phase encompasses the largest share in the lifecycle of the system, it is logical to consider the duration of the operation and maintenance phase as the service life period for LCC analysis.

4.4.1 Service life period

Service life prediction should be done with a lot of care as it determines the point of re-investment for the track. Service life period for LCC analysis is determined by the following measures:

- Technical life period of the system
- Economical life period of the system

While determining service life period for the track system, infrastructure managers should consider the following things:

- The time period should be considered in such a way that most of the track components should have at least one entire life span.
- Too long time periods will account for a great deal of uncertainty in terms of failures and maintenances and thereby increase the overall risk on the asset.
- The decision on life period should be taken by considering the guidelines and standards on the track service life period.

It is difficult to asses the technical life period of the track because it is highly dependent on the external parameters such as traffic volume and tonnage. Also, combinations of lower life components (e.g. switches) and higher life components (e.g. ballast) make it even more difficult to determine the service life period of the system.

The following steps can be considered while taking decisions on the service life estimation of the track (Lounis et al, 1999):

- Measurement of condition or performance profile of the track: The current conditions of the track should be measured and the future condition should be simulated with time as a result of degradation and maintenance
- Measurement of risk profile: Risk associated with degradation and maintenance of the track must be measured in terms of cost and simulated with time to see the risk profile in the life cycle
- Maintenance cost profile: Current maintenance cost of the track must be calculated and then simulated with time in order to have a maintenance cost profile over a period of time.

A decision on the life cycle can be made by putting weighting factors on the measured profile discussed above.

4.4.2 LCC process

In order to develop a robust LCC model, it is imperative to consider all the factors that influence the LCC as well as the risks associated with it. Life cycle costing of the track infrastructure is a continuous process as cost-effective solutions are not reached within budget constraints and without affecting safety and availability of the track. The value of LCC, which is generally modelled in the design phase changes when the system enters into the operation and maintenance phase due to change in stakeholders' requirements and the costs incurred during the operation and maintenance phase become predominant. The operation and maintenance costs become the basis for taking decisions on the maintenance and renewal actions of the track. Fig. 4.4 shows the different steps for estimating the life cycle cost of the track infrastructure in the operation and maintenance phase. The input parameters for each step in the LCC process and the corresponding outputs are described in the figure. The initial step is to understand the technical characteristics of a track section as well as the utilisation of the track in terms of tonnage and frequency of trains. For LCC calculation, a track section can not be generalised because of its complexity and utility varies in different places. So the next step is to define per unit length of track by the harmonisation steps mentioned in section 4.2.5. Track deterioration depends both on various track as well as vehicle characteristics.

Estimation of total track failures will be done by means of track failure data and degradation models of track and vehicle. Track maintenance volume consists of all the corrective and preventive maintenance as well as renewal activities. This is estimated by means of RAMS analysis of the various failure modes (see chapter 6 for details). A reference timetable describes the type of traffic, frequency of trains as well as the train operational hours per day. Track possession time determines the track availability, train speed restriction hours and train delay by means of track failure modes and maintenance cost. Track possession times can be calculated based on the corrective and preventive maintenance actions. Train derailment probabilities are estimated by track failure modes, maintenance volume and track possession time. Finally LCC is calculated by considering all the costs in the life cycle phases as well as the consequential costs. Uncertainty analysis is done to estimate the variable costs in LCC by simulating the several risky RAMS variables in life cycle cost estimates. Finally, total present value can be calculated by means of discounting rate.

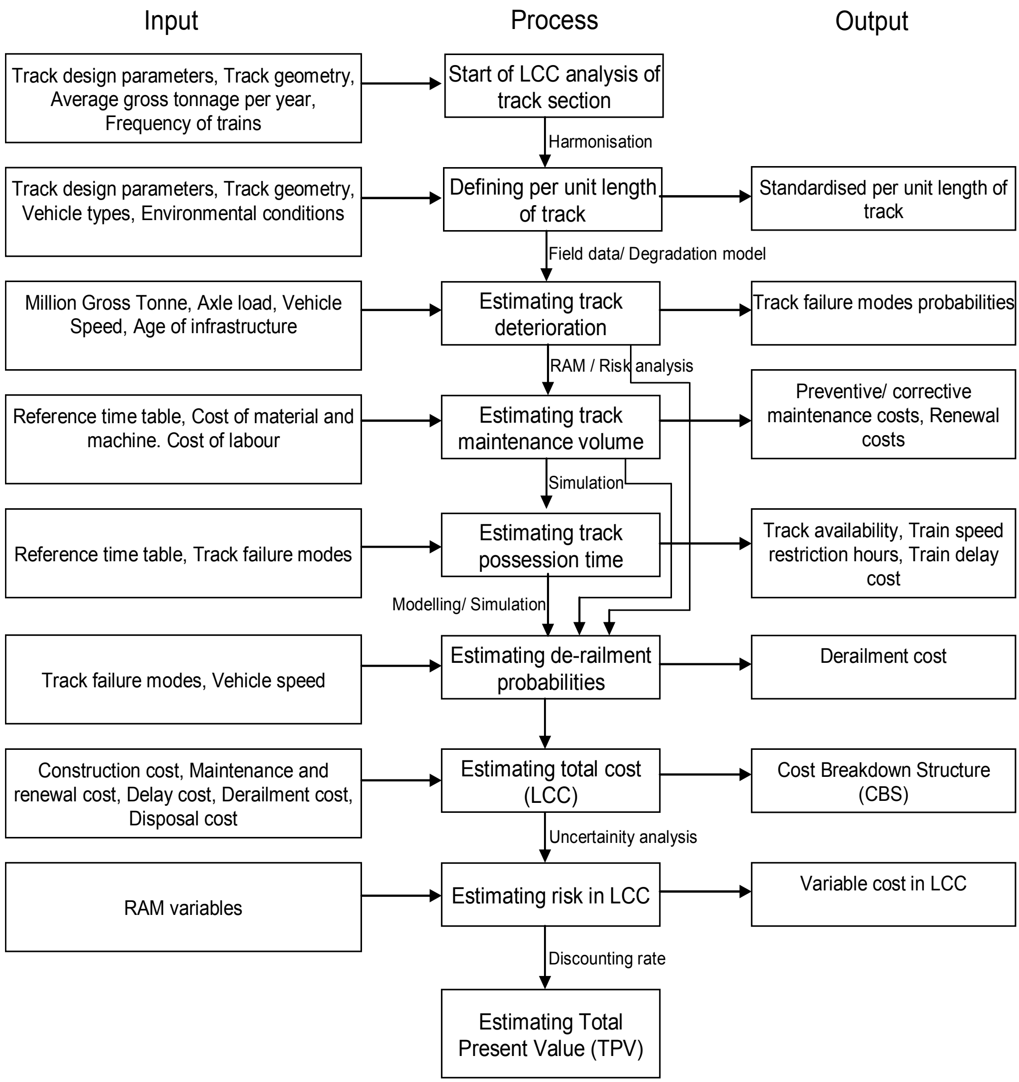

Figure 4.4: Process for life cycle cost analysis in the operation and maintenance phase

Further, cost-benefit analysis can be done by estimating Net Present Value by calculating the residual value of the asset and the cost saved by increasing the residual life of the asset by proper maintenance actions. For effective analysis of life cycle cost of the track infrastructure, it is necessary to understand all the factors that influence the LCC as well as the parameters that are required for the analysis.

Chapter 5

A Survey of RAMS and LCC Work on Rail Tracks in Europe

This chapter describes the results of the survey that was conducted as a part of a European project. The survey dealt with the current practices being followed by the infrastructure managers and the railway supply industries in Europe in the areas of RAMS and LCC. The main objectives of the survey were to find out the rules and standards as well as the models and tools concerning RAMS and LCC being used for railway track system. The functionalities of the models and tools have been illustrated and further improvement areas are also discussed so as to incorporate them in developing effective models in the later stage of the project. Other projects have been looked into for a possible benchmarking of the practices.

5.1 Introduction

Optimisation 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, pre installation technical and economic assessments are necessary to optimise 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 optimisation process.

In the last decade, RAMS and LCC analysis in the railway sector have attracted much more attention than before. Many research demonstrations and commercial applications have been developed from these efforts. This is well justified by a number of projects which had been taken up at the European level in the field of railway, but not specifically on track e.g. Cost, Reliability, Maintenance, and Availability (CRMA, 1998); Maintainability Management in European Rail Transport (REMAIN, 1998); IMPROVEd tools for RAILway capacity and access management (IMPROVERAIL, 2003); Progress in Maintenance and Management of Infrastructure (ProM@in, 2003); Light Rail Thematic Network (LibeRTiN, 2005) and Innovative Modular Vehicle Concepts for an Integrated European Railway System (MODTRAIN, 2007). The objective of CRMA (1998) was to develop LCC methodologies for rolling stock and to identify the parameters required to calculate it whereas REMAIN (1998) focused on condition monitoring and RAMS management for switches. The objective of IMPROVERAIL (2003) was to improve the existing LCC calculating methods by including costs due to vehicle infrastructure interaction and external costs, e.g. delay costs, accident costs, environmental costs, etc. ProM@in (2003) provided a comprehensive overview of RAMS and LCC analysis on railway infrastructure. It provided an overview on LCC based maintenance planning, RAMS based track inspection and RAMS database. LiberTiN (2005) discussed the use of LCC and RAMS principles in contracts. An LCC working group in UNIFE (2001) provided guidelines for LCC for total railway systems. It also developed the "UNILIFE-UNIDATA" LCC model for rolling stock. There are few ongoing projects specific to track infrastructure e.g. Lasting Infrastructure Cost Benchmarking (LICB, 2007) and Urban Track (2007) are dealing with LCC.

There is also some related literature, e.g. Burstrom *et al*. (1994), Stalder (2001), Zoeteman (2001), Esveld (2001), Zoeteman (2006) and Zhao (2006). Details of LCC standards and models are described in chapter 4 whereas RAMS standards are described in chapter 3.

The main focus of these publications (projects and literature) is on developing LCC calculation methodologies as well as the use of LCC in maintenance planning. However, these publications do not discuss the issues of LCC reduction and integrated LCC concepts with RAMS. The application of RAMS has not been yet explored fully for track perspective.

The current project tries to answer the issues mentioned above. The objectives of the project are to reduce LCC (by 30%), while improving the RAMS characteristics of a conventional line with mixed traffic. The results of this project will build on a standardised LCC formulation developed within the project, based on best LCC practices at EU level and independently assessed. To achieve the above mentioned objective the first step was to conduct a survey on the RAMS and LCC practices by the infrastructure managers and suppliers in Europe. Banverket was responsible for conducting this survey. The purposes and results of the survey are given in the following sections. The information gathered in this survey will act as an input to the further work which deals with the development of RAMS and LCC models.

5.2 Purposes

There were two major purposes of this survey. The first one was to find out the incorporated rules and standards which are currently being used by the railway infrastructure managers in Europe while the second one was to find out the models and tools being used for RAMS and LCC analysis for railway track. The objectives are listed below:

- National procedures of railway companies: The procedures deal with the current RAMS and LCC principles and methodologies being practised by the infrastructure managers as well as the railway manufacturers in their respective countries. Procedures dealing with defining, estimating, validating and implementing RAMS and LCC for track as well as its components have been looked into.

- Synergy with ongoing projects and experiences of concluded projects: Few works in the past have been performed on RAMS and LCC at European level (see section 5.1). Possible benchmarking of those practices was considered in the survey.

- Collection and assessment of national and international rules and standards: Some standards have been available on RAMS and LCC in the railway sector (see chapters 3 and 4 for details). One of the purposes of the survey was to collect different national and international standards on RAMS and LCC and to assess whether they are being followed in the railway sector. The assessment also looked into whether the standards are being followed in various life cycle phases of the system.

- Market analysis of models and tools: The survey looked into various models and tools being used in the railway sector as well as in the other sectors. Analysis of possibilities for adoption of methods from other systems was carried out.

5.3 Information Acquisition

Two measures were used for information acquisition, as given below:

- Questionnaires sent to the participants in the project, to get an overview of their knowledge, understanding and use of RAMS and LCC.

Development of the questionnaires took place in three stages as exhibited in Fig. 5.1. In phase 1, investigative questions were formulated from the extensive literature study. Investigative questions are the specific questions on RAMS and LCC that the researcher should formulate to provide sufficient detail and coverage of the survey. Measurement questions are the questions that participants must answer to gather information and resolve the purposes of the survey. For details on investigative question and measurement questions, please see Cooper and Schindler (2006). A pretest in phase 2 was carried out with the experts in Banverket. In phase 3, a pretest was done with the railway experts within the project to make the questionnaire ready for data collection. The questionnaire was sent via electronic mail to the participants. Two questionnaires were developed for this survey. The first one dealt with the rules and standards followed while the second questionnaire looked into the models and tools. The second questionnaire also looked into the details of the answers given in the first questionnaire.

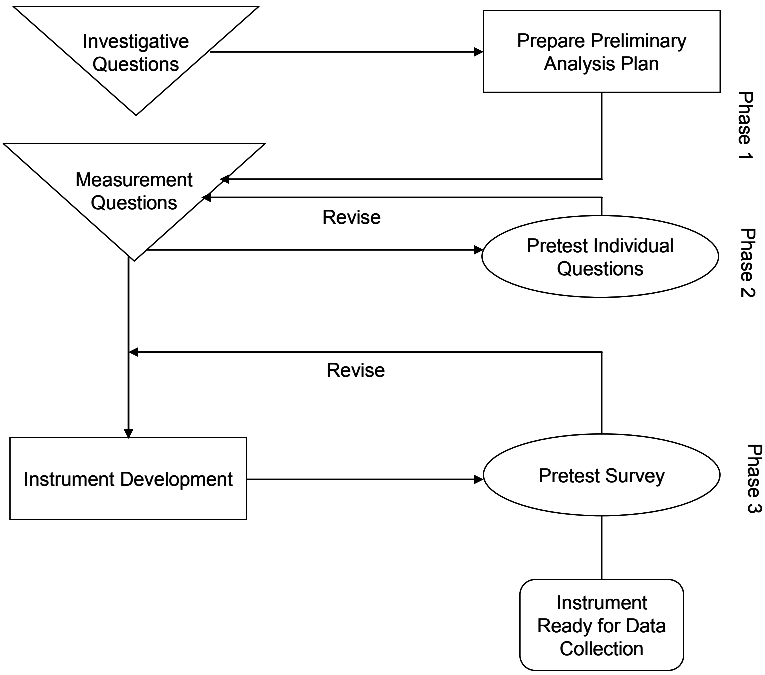

Figure 5.1: Flowchart for design of questionnaire (Cooper and Schindler, 2006)

- Discussion and telephone conversation with infrastructure managers and suppliers.

Personal and telephonic interviews were conducted with some of the participants in order to get more specific and detailed answers on some of the questions in the questionnaire. The reason for conducting these types of interviews was because interviews were fast and effective and gave rise to more follow-up questions.

The primary source of data was from the questionnaires. The questionnaires were sent to 24 participants within the project and eleven responses were received for the first questionnaire and eight for the second one. Hence, the survey does not claim to be exhaustive because there were not many responses from the infrastructure managers and suppliers contacted. The participants were divided into four categories i.e. Infrastructure Managers, Contractors, Manufacturers and SAO (Small and medium scale enterprises, Academia, and Organizations). The categorization was done because the infrastructure managers and suppliers perform different RAMS and LCC activities as per their requirements. The results of the survey have been described in the following sections. Section 5.4 describes the rules and standards whereas section 5.5 depicts models and tools.

5.4 Rules and Standards

The survey looked into two aspects of RAMS and LCC, i.e. general understanding of RAMS and LCC by the participants and detailed understanding of RAMS and LCC principles and usage. Some of the results are given below.

RAMS is still in a very early stage of implementation for railway infrastructure. There are not many standards being followed on RAMS apart from CENELEC standard EN 50126 and other standards like CP-DDE-134, DIN 40041. Databases on RAMS are not many in number. Participants use SAP, SQL, Oracle or self developed dataset in MS Excel and Access to store RAMS data. There is no clear RAMS programme plan existing within the railway infrastructure sector. RAMS analysis is not carried out in all the life cycle phases. It is mostly done in the investment phase and operation and maintenance phase. RAMS experts within the railway industries consider data from track tests, meetings and questionnaires and past faults to carry out RAMS analysis. It can be inferred that a systematic RAMS analysis is needed for the railway infrastructure.

Participants named a few benefits that they have experienced from RAMS and LCC analysis. The major ones are optimising maintenance strategy and taking decision on maintenance/renewal with the regulators and funding bodies. The analysis also helps in pointing out the consequences of non funding for maintenance and renewal. Traffic volume, axle load, type of rail, etc are some of the factors that affect RAMS and LCC values.

Availability in percentage, repair time, numbers of failures, delays on track works by suppliers, etc. are some of the RAMS parameters that are introduced in the contracts by infrastructure managers. However, manufacturers use the information specified to them by the infrastructure managers. Thus, it is necessary on behalf of infrastructure managers to introduce RAMS and LCC parameters in their contracts in order to get highly reliable and cost-effective products from the manufacturers. RAMS and LCC validation after the installation of track is necessary in order to check if the track is meeting the RAMS and LCC targets laid in the design phase. However, there is no clear validation method existing for validating RAMS and LCC calculations. It is being done by taking small samples, simulation, experience etc.

Service life time for the track is calculated both from technical and economical perspectives with more participants following the later. It is mostly done on historical analysis by experts' estimation. Details on service lifetime are discussed in chapter 4. Infrastructure managers use a constant discounting rate for their life cycle period. However, manufacturers and contractors use the discounting rate mentioned by infrastructure managers.

Costs due to downtime, unavailability, traffic disruption, penalties, etc in some cases are calculated by simulation tools such as TRAIL and RailSys. These tools take care of different probabilistic methods. The details of these tools are illustrated in the later part of this chapter. Manufacturers and contractors are not able to calculate these because of lack of information and data from infrastructure managers.

Risk analysis is not considered widely in modeling LCC. However, it is captured through the predictions of future track conditions particularly broken rails that lead to derailments. Environmental costs are not explicitly considered in the LCC calculation except cost for noise barrier or pads.

Data quality and data availability are the major problems faced in order to meet RAMS and LCC targets. Some other problems are linking between inputs and outputs to RAMS and LCC, long lifespan of the system, lack of financial means for renewal/maintenance, etc. One of the reasons can be that there is no clear procedure to get RAMS and LCC data in case of maintenance being outsourced though some railways are using a shared information system with the contractors. Improvement or development of the system (for example higher steel grades, systems with longer inspection and maintenance intervals), regular observations of the track (seeing the trends in the condition) as well as diminishing the number of switches installed etc are the major actions taken by the participants to improve RAMS characteristics and reduce LCC of their systems.

Respondents use historical data of the track to estimate reliability parameters of the track. However, failure distributions of track components are still unknown to them mostly because they do not have enough data for the analysis or they calculate for the whole track system. Broken rails, track buckles, track twist, broken fishplates, switches failures especially frog and tongue failures, etc. are found to be the most frequently occurring failure modes of the track. There is no reliability block diagram existing for the track. The quality of the initial installation, maintenance actions and strategy, loads, wheel-rail-interaction, sub grade, curve radii, etc. are some of the factors that affect reliability the most. Infrastructure managers fix reliability targets for the track on the number of speed restrictions, number of years between service affecting failures per kilometer of track, etc.

Availability targets of the track are fixed based on train delay minutes, number of speed restrictions, etc. Estimation of train delays is simulated based on the number of speed restrictions, allowed time for repair and individual component reliability data. Sub grade, radius and traffic volume are found to be the factors that affect availability most.

There is no clear method to fix maintainability targets for the track. Periodicity of preventive maintenance actions is calculated by engineering judgments, past experience, RCM analysis, deterioration rates derived from regular track recordings and inspection, etc. Sub grade, track radius, traffic volume and deterioration rates derived from regular track recording and inspection are the factors that affect maintainability the most. Please see chapter 3 for details on factors affecting track RAMS.

A safety Risk Model based on fault trees and event trees is used to model a wide range of safety hazards on the railway. In addition a Precursor Indicator Model which is linked to the SRM is established to monitor the trend in precursor events e.g. broken rails and how this trend translates into the risk profile of serious train accidents. However, the use of the above model is quite limited among the participants.

Various design and operational parameters were identified that influence the LCC calculation, such as lifetime of the track, cumulative and annual tonnage, track/technology description type, maintenance and operational difficulties/ hindrance, etc. Track renewal cost was found to be the major cost driver in the survey. Track possession time optimisation, contracting strategy (reducing number of renewal contractors) are some of the actions that are taken to reduce the track renewal cost. Other cost drivers were found to be high initial quality of track, rehabilitation of sub-standard formation, extension of lifespan of the track, etc. LCC costs are mostly on an aggregated level, not broken down to labour costs or maintenance vehicle costs.

5.5 Models and Tools

The survey identified a number of models and tools being used by infrastructure managers for RAMS and LCC analysis of the track. A model is defined as a representative of a system that is constructed to study some aspect of that system or the system as a whole. Models differ in theories in that a theory's role is explanation whereas a model's role is representation (Cooper and Schindler, 2006). References for some the models/tools mentioned in the following section have not been given due to confidentiality of the documents and the names of the infrastructure managers and railway suppliers who use these tools are kept un-disclosed.

5.5.1 LCC Models/Tools

T-SPA: T-SPA is known as Track Strategic Planning Application. It was developed by Serco, UK (see T-SPA, 2007 for details). T-SPA is a decision support tool designed to provide an analysis of a broad range of renewal and maintenance options, linking in particular the volumes and cost of the work to the condition and ultimately the performance of the railway infrastructure. The primary objective of T-SPA is to support the development of robust long term plans, the quality of which is critical to the future funding of the infrastructure maintenance and renewal. The requirements on a decision support tool to support robust long-term plans for the rail network are demanding, including a need to:

- Enable the user to specify a comprehensive range of scenarios constructed around future train service patterns, varying maintenance regimes and renewal options.

- Incorporate relationships that provide quantification of for example: when assets have reached the end of their service life; how the condition of the assets changes during their time in service; and how the degradation impacts on the performance of the network.

- Draw from detailed and, in some cases, disparate data sources - including asset age and type, historical and forecast traffic, and current asset condition - to enable the model relationships to predict with an appropriate degree of accuracy.

- Allow analyses to be performed at different levels of detail ranging from single routes or sections of routes through to the whole railway infrastructure comprising almost 20,000 track miles (32,187 track kilometres).

- Perform calculations sufficiently quickly to provide a practical what-if capability, implying computational times in the order of a few minutes for a route to a few hours maximum for the whole network.

D-LCC: D-LCC was developed by Advanced Logistics Developments (A.L.D) group, Israel. For details please see D-LCC (2007). D-LCC provides bottom-up cost estimating, supports the detailed examination of costs and parameters affecting LCC and performs Net Present Cost analysis incorporating the time scale (life cycle phases). It allows the user to apply pre-defined LCC models as well as to create new cost breakdown structures (CBS) and models. An existing CBS can be easily tailored to meet all the needs of any particular project. The product tree cost calculation option allows for incorporating the product. D- LCC supports detailed examination of the dynamics of future cash flows over multiple time periods.

D-LCC has the following functionalities:

- Evaluation and comparison of alternative design approaches
- Comparison of alternative strategies
- Identification of cost-effective improvements
- Project's budget and economic viability assessment
- Long term financial planning

LCM: Life Cycle Management (LCM) helps in finding out the cost-effectiveness of maintenance action out from different alternatives. LCM calculations include the following steps:

- Define the project, time frame, boundaries, delimitations, etc.
- Define different maintenance alternatives. Information on different alternatives is gathered by expert groups doing the brain storming.
- Description of the project. It includes the length of the project.
- Different maintenance activities, costs, failure rates, etc are entered into the tool. The tool does not provide a scope of calculating failure rate from the failure data. It is calculated manually and entered into the tool.
- The tool provides total costs for different alternatives broken down to different cost categories and finds out the most cost-effective alternative.
- The tool also represents the costs graphically. A sensitivity analysis can be carried out.
- Lastly, description of why the alternative is chosen is entered into the tool.

5.5.2 RAMS Models/Tools

TRAIL: TRAIL is a discrete event simulation model used to estimate availability based on individual component reliability data. Some of the important features of TRAIL are given below:

- TRAIL's level of granularity is user definable and can be down to the level of individual track circuits or other assets. This allows the reliability of each track circuit to be incorporated into the overall model by incorporating the MTBF, MTTR and performance degradation effects, thereby modeling the entire failure profile.

- When a failure is generated, train services that enter the faulty section between the failure time and the end of the repair are subjected to the effects characterized by the failure modes. The delays are applied to each train delayed and the sum of the delay is attributed to the faulty section for the final statistics.

- TRAIL has the ability to model a number of failure rate distributions using standard functions such as Weibull. This allows failure rates to be entered as a function of time or usage.

- The final aspect of availability is analysis of down time or performance loss. TRAIL analyses the performance loss in two elements. The first element is the performance loss that occurs between the start of the failure and the commencement of the repair. The second element is total performance loss of an asset that occurs during the repair.

- The ideal way in which TRAIL could move to an optimal solution would be to stipulate a target performance, e.g. to achieve less than 100,000 minutes, and list either asset categories or individual assets that make the largest contribution to delay and what changes in reliability would be required. The result would likely be some form of Pareto relationship ordered by assets requiring the greatest amount of upgrade.

RailSys: RailSys is a simulation tool developed by Rail Management Consultants GmbH (RMCon) in close cooperation with the Institute of Transport, Railway Construction and Operation, University of Hanover (see RailSys, 2007 for details). It calculates delay time of the traffic for both planned and unplanned situations. The simulation with RailSys results in calculating delay time per train, which is multiplied by delay cost per minute. Finally, the costs for non-availability are calculated on the possession time according to the track standard.

Some features of RailSys are given below:

- Microscopic mapping of the infrastructure
- Modular design of the simulation area
- Simulation of new technologies of train protection on systems
- Conflict recognition by means of occupation time steps
- Timetable construction and planning for new or existing lines, nodes and networks

- Elaboration of complete operation programmes in consideration of marginal conditions
- Dimensioning and assessment of the infrastructure
- Simulation of non-disrupted and disrupted operation to judge the timetable stability/quality

Optimizer+: Optimizer+ is a simulation tool which determines the relationship between maintenance costs and performance - in terms of availability, reliability and safety. It was developed by MaintControl BV, The Netherlands, in conjunction with Baas & Roost Maintenance, and several founders (see Optimizer+, 2007 for details). The following steps are taken to achieve the objectives:

- Collecting information on objects and building library database – Information like failure mode, failure cause, failure condition, MTTF, MTTR etc are gathered for each component and introduced to the library database

- Building systems – Systems can be modelled in Optimizer+ using the building blocks. For each system, a risk analysis is carried out, in which the specific failure behaviour is described at the component level. Within the model, all possible risks with regard to the company goals are mapped out. The goal of the model is to make the risks posed to the company goals by component failure more transparent, so that maintenance can be modified accordingly.

- Formulating risk analysis – For several building blocks, carrying out a thorough risk analysis makes it possible to formulate a concrete relationship between failure behaviour, its effect on company goals and the frequency with which this effect repeats itself. This determines the risk (probability multiplied by effect). The company goals with regard to costs, availability and safety form the point of departure for the risk analysis.

- Anchoring maintenance plans – On the basis of the results of the risk analysis, the existing maintenance plan is modified for several building blocks. With the help of Optimizer+, preventive maintenance actions are determined for the critical components as well as the frequency with which they are to be carried out.

- Simulation and optimisation – With the help of the simulation module within Optimizer+, the quantitative relationship is determined between failure behaviour on the one hand and availability, reliability and maintenance costs on the other. Based on the risk analysis, several simulation models are created and calculated.

In this context, another tool of interest is TrainPlan (see Nilsson, 2006). The system TrainPlan is a tool for planning timetables and available resources and is used for long time timetable construction. The system contains information about each train, such as, train number, description of the train, departure time, arrival time, etc. However, this tool does not calculate reliability or availability of the system explicitly.

In the later stage of the project, there will be benchmarking of these existing tools in order to develop effective tools for RAMS and LCC analysis.

5.6 Synergy

The working group of the project found Lasting Infrastructure Cost Benchmarking (LICB) an ideal project for synergy. LICB (see Stalder, 2001; LICB, 2007) is an international benchmarking project established by the Infrastructure Commission of the International Union of Railways (UIC). Fig. 5.2 illustrates the different types of harmonisation steps being considered. The details of harmonisation are described in chapter 4.

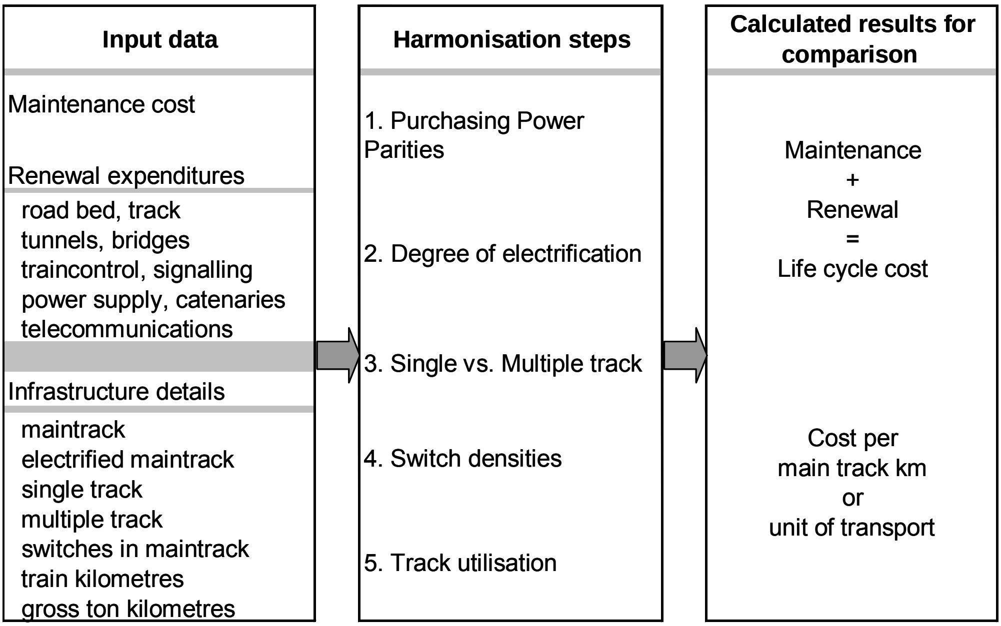

Figure 5.2: Aspects of harmonisation (Stalder, 2001)

LICB considered maintenance and renewal cost as the Life Cycle Cost of the asset and the possible reasons for the difference in LCC between IMs identified were:

- Line type coupled with complexity and utilisation (train frequencies/tonnage) of the asset.
- Technical life time of the infrastructure components. Protecting asset life through well-conceived maintenance strategies and by expanding lifetimes through a more advanced condition based decision making may save money.
- Re-investment planning.
- Track quality.
- RAMS requirement of the track.

The methodologies realised in LICB projects were studied and the possible synergies with the current project have been found, as given below:

- Definitions such as main track, side track, freight lines, branch lines, etc can be used. In order to have realistic comparisons of LCC costs between infrastructure managers, it is necessary to have common definitions of network characteristics.

- Different possible reasons for cost differences have been described by LICB. LICB found cost drivers in terms of construction in urban territory, design speed, traffic interface and labour cost. The relationships of LCC with these cost drivers can be established further.

- Average lifetimes of infrastructure components were found in LICB in terms of years. They can be changed to MGT for effective calculation. This will in turn help in defining the service life time of the infrastructure. Estimation of service lifetime is important for the LCC calculation. Details can be found in chapter 4.

- LICB illustrated the relationships of LCC with RAMS, quality and age of the infrastructure. As RAMS, quality and age are the variables that influence the LCC calculation, the relationships will help in doing sensitivity analysis on LCC.

- Amount of exchanged rails/sleepers/ballast that is exchanged per year can be used as indices for following up with the target LCC.

5.7 Areas of Improvement

The survey looked into potential areas of improvement so as to incorporate them in further work in the project while developing effective RAMS and LCC models. Some of the improvement areas are described below.

- Environmental costs need to be considered while modeling LCC. As we are moving towards a pollution free railway service, it is necessary to estimate the cost due to noise pollution to incorporate it in the LCC calculation.

- Risk analysis has to be considered in LCC calculation. Risk can be defined as the additional cost associated with LCC due to unforeseen failures in the future. Necessary actions must be taken well in advance in order to identify the risks associated with LCC and the methodologies to estimate those risks. Details are described in chapter 7.

- Infrastructure managers have to clearly define RAMS and LCC specifications in the contracts with manufacturers and contractors. In order to carry out RAMS and LCC analysis from early phases of the system life cycle, manufacturers and contractors should be aware of the RAMS and LCC specifications and targets they need to meet.

- Infrastructure managers should define achievable RAMS targets and lay out a procedure to attain those targets.

- Unforeseen costs like reduction of passengers, loss of good will due to train delays should be modelled. To make the LCC estimation more effective, it is necessary to calculate all the indirect costs associated with it. Costs due to reduction of passengers or loss of good will are of significant value but difficult to measure.

Chapter 6

RAMS and LCC in Track Maintenance Planning

This chapter describes the utilisation of RAMS and LCC methodologies in track maintenance planning. It provides a process on how RAMS helps in making maintenance decisions and LCC optimises those decisions. A track maintenance management structure in combination with RAMS management and LCC management has been described. Finally, track quality of service has been illustrated.

6.1 Track Maintenance Planning

Maintenance is defined as the combination of all technical and administrative actions, including supervisory actions, intended to retain an item in, or restore it to, a state where it can perform a required function (IEV 191-01-07, 2007). Maintenance has long been considered as a reactive, fire fighting approach. However, as dependability targets of the assets have become increasingly important, several proactive maintenance approaches and methods are being developed. All the decisions related to the rail track maintenance are taken in order to keep a balance between economic and safety aspects. The goal is to find the effective maintenance procedure to optimise the track possession period and train speed restriction regime and ultimately increase the track availability.

Different components of the railway asset are structurally and economically interdependent. Scale effects are involved in their maintenance and renewal, while their degradation is often structurally related. As operations have to be continued on the rail network and budgets are often restricted, all kinds of constraints have to be considered in the planning of infrastructure maintenance. The concepts of the maintenance planning process are developed in the following steps (Zoeteman, 2006):

- Generation of maintenance strategies for individual assets (e.g. corrective or preventive, time based or condition based, strategies are distinguished based on criticality of the individual asset for the entire production system)
- Definition of clustering rules, which optimise the frequencies of activities on the basis of scale or scope effects
- Definition of rules for assigning time windows to maintain packages on the basis of opportunities that occur in the middle or short term.

The initial analytical work for track maintenance was done in the early 1980s. Fazio and Prybella (1980) pointed out a number of prerequisites for planning track maintenance. The existence of track quality measures and track deterioration models are highlighted as key areas for a structured planning process to be established.

Zarembski (1998) described three tools for railway organisations to improve the efficiency of maintenance operations (see Fig. 6.1); automated inspection systems, databases and maintenance planning systems. The lack of integration between these tools has prevented railway organisations from taking full advantage of their potential.

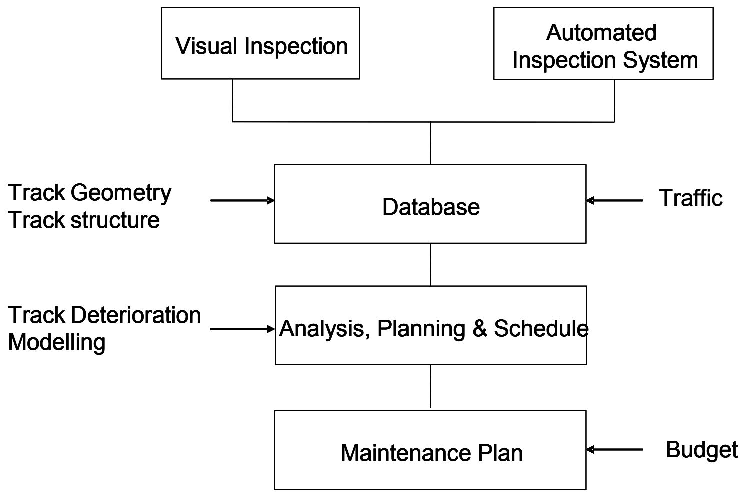

Figure 6.1: Maintenance planning overview (Zarembski, 1998)

These different data sources need to be linked in a general database for planning purposes. By adding models on track deterioration relationships, the state of the infrastructure can be assessed over time. Planning of specific maintenance activities will be affected by conditions of the track. This requires a detailed knowledge of each component of the track and its relationship with other components of the track as well as the degradation pattern of each component.

Thus, the objectives of track maintenance planning can be defined as follows:

- What are the current conditions of the track? (Track quality indices)
- What will be needed in the short term as well as the long term as far as maintenance is concerned? (Forecasting of maintenance actions)
- What should be done first? (Prioritization of maintenance activities)

In order to fulfil the above mentioned objectives, RAMS and LCC analysis will play a major role in track maintenance planning. The details are presented in the following sections of the chapter.

6.2 RAMS Analysis for Track Maintenance

RAMS analysis is a process which utilises the failure information from a system in order to develop probability distributions that the system will be able to perform its intended functions. RAMS analysis for the track is based on the following elements:

- RAMS database of the track
- Failure modes of the track
- Methods and tools for RAMS analysis

6.2.1 RAMS Database

Utilisation of failure and maintenance data is an important factor in RAMS analysis and management of the system. There are several dimensions with respect to collection of RAMS data. One should ascertain that the data being collected should support all types of RAMS analysis required for the system. Another important aspect is that data should support the life cycle perspective of the system and more importantly, the maintenance phase in this case. Fig. 6.2 illustrates the use of RAMS database as a feedback to RAMS analysis as well as to the operation and maintenance phase of the system life cycle.

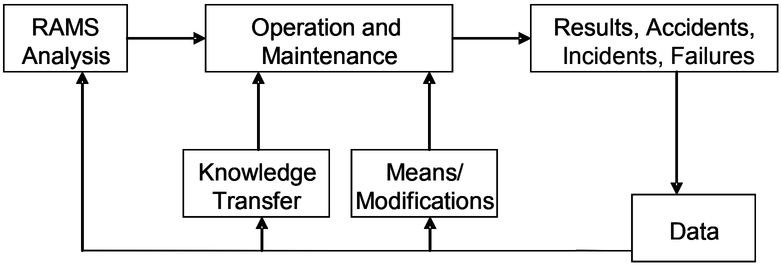

Figure 6.2: A process loop showing use of RAMS database in RAMS analysis (Prom@in, 2003)

Prom@in (2003) states that RAMS database is a conceptual term representing several physical databases for the track system. The most important of these are:

- A component reliability database
- An incident and accident database

Component Reliability Database

The basic elements of this database are a plant register, where each type of physical equipment (e.g. a switch) is represented as one record. Next is the event register, where failures and maintenance works are represented as records. Combination of these registers enables the estimation of hazard functions, renewal functions, repair times and other parameters required in a quantitative RAMS analysis.

Incident and Accident Database

In this database, one record corresponds to an incident or an accident. The objective of such a reporting system is not to estimate reliability parameters but rather use the data to identify problems and root causes. UIC is now working towards implementing such an accident database on a European level.

For an effective analysis of RAMS, traffic and track geometry databases should be considered along with failure and maintenance databases as mentioned above. Thus, track must be divided into homogenous analysis segments with respect to track curvature, grade, super elevation, traffic density, etc. The following data are also a part of RAMS database along with the failure data (Esveld, 2001).

I) *Layout and operating data*

- Curves (start and end km, transition curves, radius, etc.)
- Loads (annual load (MGT), maximum axle load (tons), date from which the data is valid, etc.)
- Speeds (speed of freight and passenger trains, date from which speed is valid, etc.)
- Gradients (start, end, value)

II) *Infrastructure*

- Subgrade (geological conditions, various monitored parameters, etc.)
- Ballast (ballast type, date of installation, ballast thickness, etc.)
- Sleepers (sleeper type, sleeper spacing, new/old sleepers when laid, type of fastenings, date of installation)
- Rails (rail type, joined or welded track, weld type, date of installation, new/old rails when laid, date of installation, cumulative tonnage on rails when installed)

III) *Work history*

- Renewals, grinding and tamping work history (start km, end km, type)
- Speed restriction history (start and end date of temporary speed restriction, value of reduced speed)
- Spot maintenance history (type, date)

Banverket uses BIS (Track information system), BESSY (Inspection system), 0FELIA (Fault analysis system) and TFÖR (Train delay system) for maintenance planning. Recent developments are HANNES (Speed restriction system) and a Track geometry data system. These existing systems are more or less stand alone modules using BIS as a reference system (Andersson, 2002). Thus, the need is to integrate different databases for efficient analysis of RAMS and maintenance planning.

6.2.2 Failure Modes of Track

In order to identify relevant maintenance actions on the track, it is crucial to have a good understanding of failure modes and their causes on the track. FMECA acts as a tool to reveal these failure mechanisms. To support this task four failure progressions are defined as (Jovanovic, 2006):

1. The component is subject to gradual degradation, which might be observed by suitable equipment.
2. The component is subject to gradual degradation, which can not be observed.
3. The component is subject to a sudden degradation, which can be observed by suitable equipment.
4. The component is subject to shock degradation, immediately leading to failure.

The classification is particularly useful when reliability parameters are assessed, as these parameters have different interpretations for four categories of failure progressions. Track failure modes and their corresponding limits can be categorised as below (Esveld, 2001). The limits can be put per unit length of the track.

- Track geometry condition (Standard deviation in longitudinal level, standard deviation in cross level, standard deviation in gauge).
- Ballast condition (percentage of weedy ballast, percentage of surface soiling).
- Fastening condition (percentage of loose fastenings).
- Sleeper condition (percentage of bad sleepers, percentage of medium sleepers, percentage of good sleepers).
- Rail defects (number of RCF defects, number of rail breaks, number of weld defects, amplitude of corrugation).
- Rail wear (vertical wear of the rail head, lateral wear of the rail head).

Measuring the infrastructure condition is prerequisite for track maintenance planning. Banverket has a number of condition indices to describe the condition of their infrastructure facilities (Andersson, 2002). The main condition indices are known as K-value and Q-value. These are calculated from detailed inspection car measurements of the track. The inspection car measures relative rail position (lateral and vertical), rail profile and rail gauge. The Q-value is a weighted index of the standard deviation of two inspection car measures calculated as deviation from geometric comfort limits set for specific track class. The Q-value is calculated per kilometre track as:

$$Q = 150 - 100\left[\frac{\sigma_H}{\sigma_{H\lim}} + 2.\frac{\sigma_S}{\sigma_{S\lim}}\right]/3 \qquad 6.1$$

where σ_H and σ_S are the average standard deviation of height and interaction on the section measured. The standard deviation for interaction is calculated as a combined effect from cant and side position of the rail. σ_{Hlim} and σ_{Slim} are the comfort limits for a given track class. Track class classifications are based on the speed of the train

The K-value is calculated for a longer section of the track and is expressed as:

$$K = \frac{\sum l}{L}.100\% \qquad 6.2$$

where $\sum l$ is the sum of track length where all σ values are below the comfort limits for a given track class and L is the total length of the track considered. K-value is not suitable for shorter track sections.

Failure modes mentioned above must be categorised as per the failure category given in Table 3.1 so as to proceed with RAMS analysis and define RAMS figures for different failure categories.

6.2.3 Methods and Tools

Various tools and methods are used for RAMS analysis. Many of these tools and methods, for example, FMEA (Failure Mode and Effects Analysis), FMECA (Failure Mode, Effects and Criticality Analysis), FTA (Fault Tree Analysis), Failure Block Diagram Analysis, CCA (Cause Consequence Analysis), HAZOP (Hazardous Operability Analysis), used in RAMS analysis originate from the military, power plant, aircraft and space industries (see Markeset and Kumar, 2001).

Canon *et al.* (2003) describes failure modelling of the track in following ways:

Statistical models based on historic data:

This type of model is based on statistical analysis and presentation of observed behaviour. These models include the failure modes of the track as data and these data are normally related to some measure of rail loading (e.g. months/years of operation) or global measure of wheel loading (i.e. gross tonnage). Data are then fitted to a statistical model. The process of selecting these statistical models is illustrated in Fig. 6.4. These types of models are particularly appropriate when specific track conditions, behaviour etc. are unknown or not sufficiently known.

Probabilistic simulation models

Such analysis requires at least two probability density functions; one describing the loads applied and the other describing the strength and resistance of the loaded body. The overlap of the two functions is the unreliability distribution, which can be defined as the probability of failure and a safety index. Reliability analysis can be taken further by extending the content of loading and the strength distributions. The additional content of loading can be due to dynamic loading and quasi-static loading on the track apart from the static load. However, in many cases it is difficult to combine these additional variables mathematically. Thus, Monte Carlo simulation is often used to combine variables.

Proper RAMS analysis can help in effective maintenance planning of the track infrastructure and meeting maintenance objectives. The usefulness of RAMS analysis for track maintenance planning is given below:

- *Reliability analysis*: Predict "when" to take maintenance actions depending on the failure modes of the track.
- *Maintainability analysis*: Determine "what" maintenance actions need to be taken on the event of failures occurring on the track and "how" much time is taken to carry out those maintenance actions.
- *Availability analysis*: Predict the frequency and duration of track possession periods due to maintenance actions carried out on the track.
- *Safety analysis*: Estimate the risk of carrying out different maintenance actions on the track in terms of severity and cost.

The maintenance decision process is a continuous process to make the maintenance decisions effective while meeting the RAMS targets laid for the track system. Reliability and maintainability analysis affect the initial maintenance decisions. Availability and safety parameters are calculated from reliability and maintainability analysis as well as the maintenance decisions. Availability and safety analysis give feedback to reliability and maintainability analysis and maintenance decisions.

Reliability analysis of the track deals with the failure data from the RAMS databases. Data is tested for trend and Independent and Identically Distributed (IID) characteristics before proceeding with a specific reliability model. Fig. 6.3 illustrates the steps for failure data analysis before choosing the best fitting model.

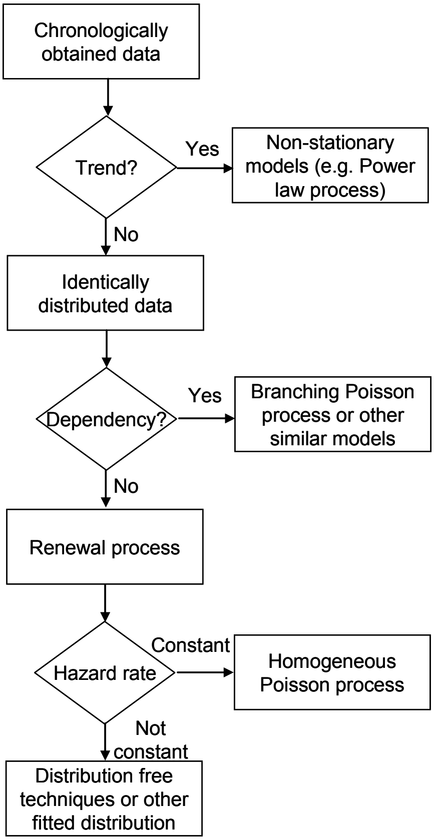

Figure 6.3: Possible exploratory steps in field failure data analysis before fitting distribution models (Asher and Feingold, 1984)

Table 6.1 illustrates the application of reliability analysis on track maintenance planning of the track. Various sources of information have been examined in order to develop the table. These include a literature survey, various railway related conferences attended and discussions and consultations with rail maintenance experts.

Table 6.1: Reliability analysis in track maintenance planning

Track component	Type of maintenance	Maintenance decisions	Reliability analysis	RAMS database
Rail	Grinding	• When to grind?	• Grinding interval is determined by developing a trend of RCF defects data of rail. The point of grinding is determined when the trend reaches the number of defects fixed for the rail.	• Type and number of RCF defects. • Past grinding dates.
Track	Tamping	• When to tamp?	• Tamping interval is determined by developing a trend of the standard deviations measured from the desired dimensions of track geometry. The point of tamping is when the trend reaches the standard deviations fixed for the track.	• Track stiffness. • Track geometrical quality indices. • Past tamping dates.
Rail	Inspection	• What is the frequency of inspection?	• Inspection interval is determined by analysing the rail car inspection data and developing a trend of number of rail defects formed in a specific interval of time.	• Rail car inspection data. • Visual inspection data. • Hand held equipment data.
Ballast	Cleaning	• When to clean ballast?	• Ballast cleaning life estimation. Forecasting of ballast cleaning life is done by developing a probability distribution of past ballast cleaning data and ballast condition factor. Ballast condition factor is determined by the percentage of void in the ballast.	• Past ballast cleaning dates. • Condition of ballast.
Rail	Renewal	• When to renew rail in a given track section? • What is the percentage of the	• Rail service life estimation for different curve radii. Rail service life is determined from rail fatigue life and rail wear life whichever comes earlier. Forecasting of rail fatigue life is done by limiting number of RCF	• Historical rail installation dates and age of rail when installed. • Type and number of RCF defects.

		rail need to be renewed in a given track section?	defects per kilometre of track per MGT where as rail wear life is estimated by keeping a threshold value for rail wear. Residual rail life is calculated by using the current condition of rail.	• Rail wear profile.
Sleeper	Renewal	• When to renew sleepers in a given track section? • How many sleepers need to be renewed in a given period of time in a given track section?	• Sleeper service life estimation for different curve radii. Forecasting of sleeper service life is done by developing a probability distribution of past sleeper renewal data. Remaining useful life of sleeper is calculated by using the current conditions of sleepers.	• Historical sleepers installed dates and conditions when installed. • Sleepers condition distribution (e.g. good, medium and bad) in a given track segment. The segmentation is based on the failure modes on the sleepers. Used life of good, medium and bad sleepers is in terms of percentage of average sleeper life.
Ballast	Renewal	• When to renew ballast?	• Ballast service life estimation for different curve radii Forecasting of ballast life is done by developing a probability distribution of past ballast renewal data.	• Historical ballast installation dates • Condition of ballast
Rail	Replacement	• When to replace the rail?	• Rail break life estimation. Rail break life forecasting is done by developing a probability distribution of past rail breaks data. It can be also estimated by identifying the rail defects which have got the potential for rail breaks and developing a trend of those defects forming the rail breaks.	• Historical rail break data. • Rail defects data. • Wear limit.

While performing reliability analysis of the system, it is important to consider as-good-as new and as-bad-as old phenomena while repairing/replacing any track components. Minimal repair on the track in terms of grinding, tamping, ballast cleaning etc. keeps the track components as well as the track in as-bad-as old conditions. Renewals of track components bring the components to as-good-as new condition but the track remains in as-bad-as old conditions. The track comes to as-good-as new condition, when the whole track renewal takes place.

In the following table, those maintenance decisions that require reliability analysis have been illustrated and corresponding RAMS database for reliability analyses have been found. Steps illustrated in Fig. 6.3 can be implemented for reliability analysis in Table 6.1.

6.3 LCC in Maintenance Optimisation

As rail infrastructure and particularly track, is an expensive asset with a long lifespan, the cost-effectiveness of long term design and maintenance decisions should be guaranteed. LCC, an engineering economics technique, can be utilised to focus on maintenance strategies to minimise life cycle cost, while meeting the dependability requirements. Fig. 6.4 depicts LCC calculations based on the business and technical requirements of the track, which is based on a specific operational scenario. Maintenance policy and budget constraints play a major role in selecting the alternative maintenance strategies. They act as a crucial input while deciding upon a particular maintenance strategy. Fig. 6.4 shows how RAM affects LCC calculation at various stages. The maintenance strategy (MS) with lowest LCC is considered as the cost-effective solution to be implemented in the infrastructure operations. The maintenance strategy can be a single maintenance action (e.g. grinding) or a cluster of maintenance actions. For an effective decision on maintenance strategy, it is important to consider a cluster of maintenance actions for LCC calculations as maintenance actions affect each other.

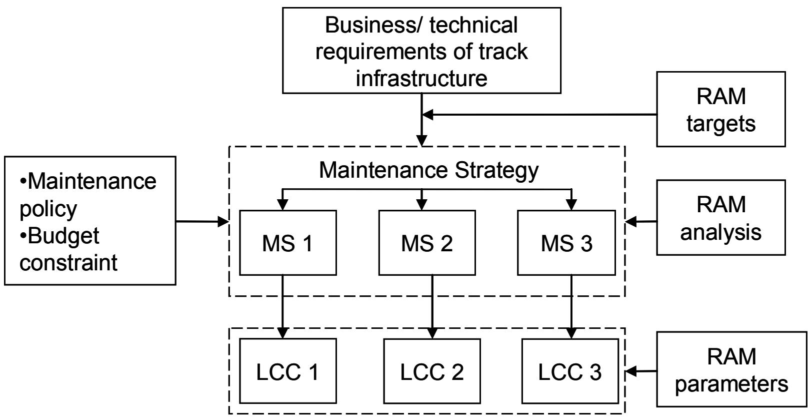

Figure 6.4: Maintenance decisions based on LCC

While considering the lowest LCC as the cost-effective solution, it is important to consider the RAMS figures associated with that particular maintenance strategy. Thus, without considering the lowest LCC as the best solution, a trade-off between RAMS targets and LCC value is necessary in order to achieve an effective maintenance strategy. The details of this trade-off is given in the following sub-section

6.3.1 System-effectiveness

The idea of system-effectiveness emerges so as to make the LCC analysis cost-effective. System-effectiveness deals with RAMS characteristics of the system. Blanchard *et al*. (1998) define system-effectiveness as the probability that a system may successfully meet an overall operational demand within a given time and when operated under specified conditions. In short, system-effectiveness is the ability of a system to do a job for which it was intended. It can be defined as a function of the system's operational availability, operational reliability and capability.

Operational availability (A_o) of the track system is defined as the probability that the track system is operationally available during the train traffic.

Operational reliability (R_o) is the probability that during the train traffic operation, the track system will not suffer from any failures.

Capability (C) is the ability that the track system will meet its required objectives.

System-effectiveness can be defined as:
System-effectiveness = Operational availability *Operational reliability *Capability

$$= A_o * R_o * C \qquad 6.4$$

The higher the system-effectiveness, the better is the track system to achieve its objectives.

6.3.2 Cost-effectiveness

Cost-effectiveness analysis yields quantitative results to aid the decision maker, with risk analysis, and provides a useful decision tool.

Fig. 6.5 shows the calculation of cost-effectiveness from the LCC values of different alternatives. Thus while taking a decision on maintenance alternatives; it is necessary to calculate the cost-effectiveness of different maintenance alternatives. The higher the cost-effectiveness, the better is the maintenance alternative.

Maintenance alternatives	Life Cycle Cost (LCC)	System effectiveness	Cost-effectiveness (SE/LCC)
M1	LCC1	SE1	SE1/LCC1
M2	LCC2	SE2	SE2/LCC2
M3	LCC3	SE3	SE3/LCC3

Figure 6.5: Cost-effectiveness of maintenance alternatives

6.4 Maintenance Management

The asset strategy is the maintenance approach and plan developed for each item of system. It determines what planned and programmed maintenance work should be carried out and considers what potential problems may require an unplanned, reactive response (Wilson, 1999). The approach to be taken in developing the maintenance activities and from these the asset strategies needs to be understood before the maintenance management strategy is completed. This is because until it is known how much maintenance activity will be required, by whom and with what spares etc, then the approach to their organisation cannot be finalised.

Infrastructure managers try to ensure the successful management of costs, quality and the relation between two. It is essential because the train operators as well as the passengers impose ever increasing quality requirements on the rail infrastructure. Thus, the infrastructure managers require the best infrastructure quality at the lowest cost. The way to achieve this objective is through proper maintenance management.

Esveld (2001) illustrated the type of data required for Track Maintenance Management System (TMMS), as given below:

- Measurements
- Planning
- Infrastructure
- Inspections
- Work carried out
- Costs

However, difficulties in the accurate anticipation of maintenance prevent extremely precise maintenance planning and management. Besides, the amount of funding allocated for maintenance work is often regarded as a compromise, being too much according to top management, and too little according to the operating and maintenance staff. Thus, selection of the optimal maintenance strategy can be challenging. A systematic approach for the determination of deterioration of track components is necessary to fully gauge the status of the track system and components. This will require proper track condition assessments, the establishment of a standard condition rating system, and the development and regular updating of prediction models for various track components.

Esveld (2001) illustrated the idea of rational rail management for the infrastructure. Rational rail management is aimed at the objective assessment of the qualitative and quantitative assessment of the rail infrastructure, after which, based on system objectives, and rules and standards, decisions may be taken regarding the maintenance and renewal of rail infrastructure. Rational rail management is dealt in the following objectives:

- To be less dependent on the individual know-how of co-workers
- To create optimal working conditions regarding business economy
- To bear responsibility and to report to the management

Thus, an effective track maintenance management system requires RAMS management and life cycle cost management to be thoroughly integrated into the asset management of the system. Fig. 6.6 describes the relationship between maintenance management, asset performance and asset maintenance.

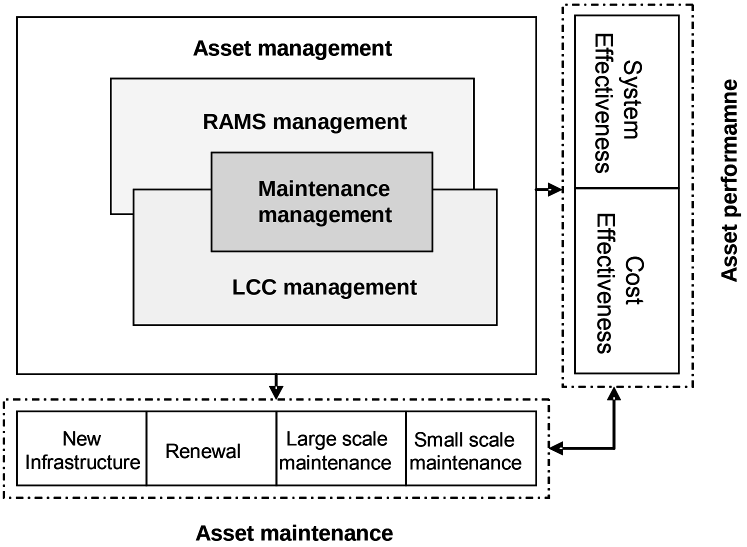

Figure 6.6: Factors influencing maintenance management (Adapted from Swier and Luiten, 2003)

Asset management of the track deals with two important aspects of the asset i.e. asset performance and asset maintenance. System-effectiveness and cost-effectiveness act as indicators for asset performance. Asset maintenance deals with activities ranging from small scale maintenance actions to the building of new infrastructure. As described in the previous sections, RAMS and LCC analysis act as tools to estimate system and cost-effectiveness of the asset as well as to take effective decisions on maintenance of the asset. There is a close relation between asset maintenance and asset performance as effective asset maintenance increases the asset performance whereas asset performance acts as a decision tool for asset maintenance.

6.5 Railway Quality of Service

Rail traffic is the most important public traffic medium in Europe as the density of the railway network is very high compared to the other parts of the globe. To be in competition with other modes of transportation, railway traffic must be quick, comfortable, cheap and primarily safe. There have been contractual agreements concerning the aimed level of reliability and punctuality in the performance regime within the railway sector.

The business needs of a track infrastructure can be defined as lower ownership costs, interoperability, enhanced safety, improved punctuality, increased capacity and reduced journey times. But when it comes to quality of service, it is a measure of level of satisfaction of the train users which in turn depends on safety, punctuality and riding quality of the train service. Railway quality of service is not a stand alone phenomenon. It invariably depends on the different components of the railway system. Railway quality of service evaluation is particularly difficult due to system complexity. This is because of the number of components and the complex relation existing between failures and possible delays (see Fig. 6.7). The present context describes the effect of track infrastructure on the railway quality of service and the means to achieve it.

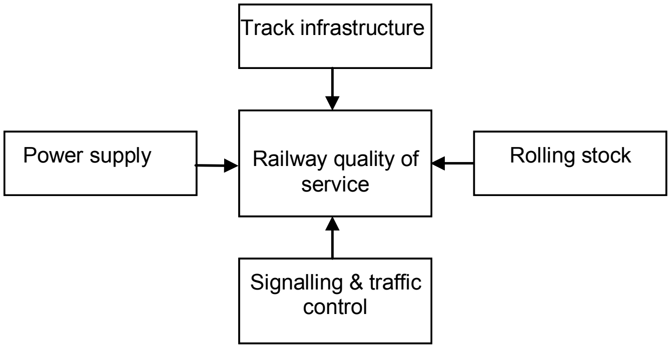

Figure 6.7: Railway quality of service

The goal of a railway system is to achieve a defined level of rail traffic in a given time, safely. RAMS describes the confidence with which the system can guarantee the achievement of this goal and has a clear influence on the railway quality of service. Quality of service is also influenced by other attributes such as frequency of service, regularity of service, fare structure, etc. The relationship is shown in Fig. 6.8.

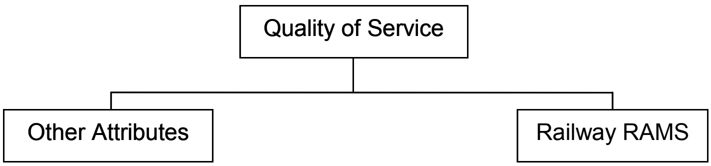

Figure 6.8: Quality of service and railway RAMS (EN 50126, 1999)

6.5.1 Hierarchy of Track RAMS

In order to achieve track quality of service, the first step is to identify the parameters that attribute to it. Fig. 6.9 illustrates the RAMS parameters in different hierarchy levels. RAMS hierarchy levels have been divided into three levels i.e. infrastructure level, system level and component level. RAMS parameters indicate the business characteristics of the track infrastructure at infrastructure level, technical characteristics at the system level and failure characteristics at the component level. Train delay, service reliability, number of train cancellations or train speed restrictions are some of the parameters that define RAMS at the top level of the hierarchy which directly reflect the track quality of service. Service reliability is defined as the ability to provide a timetabled service, usually to a contractually determined level within the performance regime, e.g. 12 out of 13 trains (92.31% reliability) should arrive within five minutes of the scheduled arrival time.

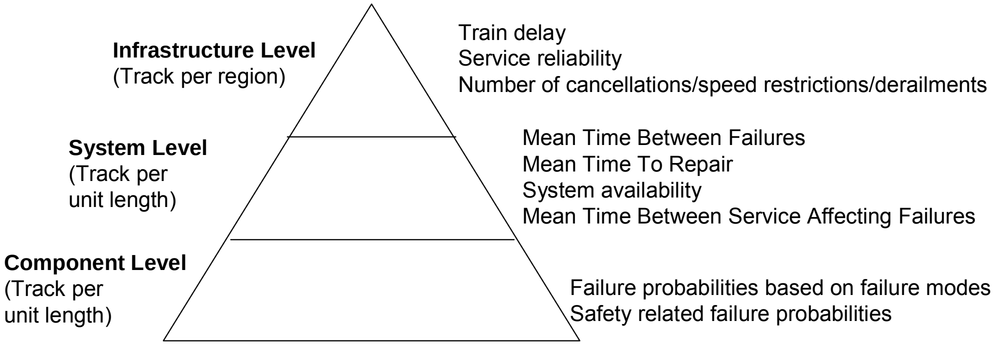

Figure 6.9: RAMS hierarchy within track infrastructure

The component level in the RAMS hierarchy deals with the failure probabilities of the different track components e.g. rail, ballast, switch and crossing, etc. FMECA (Failure Modes Effect Criticality Analysis) is the tool used for estimation of the parameters. In the system level, the parameters are estimated by tools such as RBD (Reliability Block Diagram), Markov analysis, etc. Infrastructure level parameters are estimated by considering the parameters at the system level coupled with train schedules and track possession periods.

RAMS analysis and effective track maintenance procedures act as tools to meet and enhance track quality of service.

Chapter 7

Uncertainty in Track LCC Estimation

Life Cycle Cost (LCC) is used as a cost-effective decision support for maintenance of railway track infrastructure. However, a fair degree of uncertainty associated with the estimation of LCC is due to the statistical characteristics of Reliability, Availability and Maintainability (RAM) parameters. This chapter illustrates a methodology for estimation of uncertainty linked with LCC, by a combination of Design of Experiment (DoE) and Monte Carlo simulation. The chapter also includes developed maintenance cost models for track and a case study of Banverket (Swedish National Rail Administration).

7.1 Introduction

Capital costs have traditionally been used in the railway sector as the primary comparison criteria to select the best among many available systems. In general the capital costs mostly encompass the costs associated with design, manufacturing, installation, marketing, etc. It can be argued that decisions based on capital cost alone are easy to make but not so precise. Therefore, a more systematic approach using Life Cycle Cost (LCC) should be used as a basis to select the best alternative among many systems available. LCC takes into account all costs associated with the life time of the system, such as operating costs, maintenance costs, energy costs and taxes apart from capital costs. For many complex assets, the cost of maintenance plays an important role in the LCC analysis, especially for assets like track infrastructure, where the operation and maintenance phase comprises a major share of the system's life cycle.

However, though most infrastructure managers today consider all the costs incurred by the system from conceptual design to disposal in their LCC calculations, there are still some issues associated with the correctness of these calculations. Some important issues are related to uncertainties in the LCC calculations. Fig. 7.1 illustrates two different levels of uncertainties associated with LCC of track infrastructure. Level I uncertainty is costs due to penalties imposed by traffic operators on the infrastructure manager due to such factors as train delay, traffic disruption, or derailment. These anomalies can be caused by planned or unplanned maintenance actions, but also by lack of necessary maintenance. Hence, the resulting costs are related to decisions about maintenance actions and can be estimated by probabilistic assessment of train delay, derailment, or traffic disruptions considering the technical and operational characteristics of the track, as well as the maintenance actions. Level I uncertainty can also be viewed as belonging to the external risk of the LCC analysis, where the costs should be included to make the LCC analysis more effective. However, there is also the Level II uncertainty, which is the internal risk associated with LCC. The Level II uncertainty pertains to the variable contribution to total LCC originating from the uncertainty in Reliability, Availability, and Maintainability (RAM) parameters. However, the RAM parameters also indirectly impact the Level I uncertainty. As conventional LCC analysis only considers point estimates of RAM parameters, it leads to an incorrect estimate of the LCC. To get a more correct estimate of the LCC, it is essential to also consider the interval estimate of the RAM parameters.

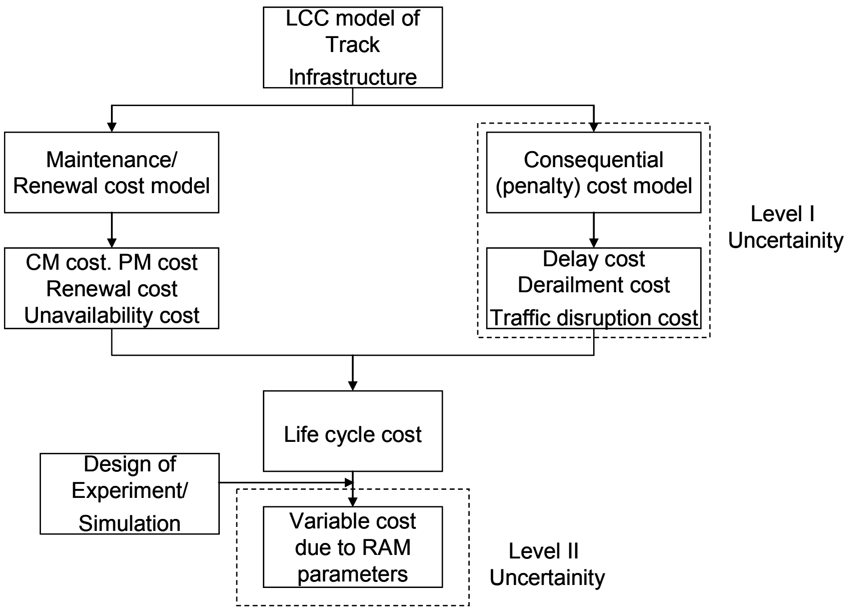

Figure 7.1: Uncertainties involved with LCC modelling

7.2 Railway Track Maintenance at Banverket

The maintenance process at Banverket is divided into corrective and preventive maintenance, where the later is based on condition or time. The current strategy at Banverket is to minimise corrective maintenance and to change time-based maintenance to condition-based (Karlsson, 2005). Table 7.1 shows the different track maintenance strategies and actions at Banverket.

Table 7.1: Track maintenance at Banverket

Maintenance Strategy	Maintenance Action	Maintenance Trigger
Preventive Maintenance	Rail grinding	Time
	Tamping	Condition
	Rail lubrication	Time
	Ballast cleaning	Condition
	Track inspection	Time
Renewal (Preventive Maintenance)	Rail renewal	Condition
	Ballast renewal	Condition
	Sleeper renewal	Condition
	Fasteners renewal	Condition
Corrective Maintenance	Rail replacement	Failure

7.3 Maintenance Cost Modelling

LCC, which is generally modelled in the design phase, changes when the system enters into the operation and maintenance phase due to changes in stakeholder requirements, which makes the costs incurred during the operation and maintenance phase predominant. Maintenance costs of track infrastructure consist of preventive maintenance cost, renewal cost, and corrective maintenance cost as described in Table 7.1. Maintenance costs associated with track have been estimated separately for different curve radii as different curve radii experience different failure probabilities and magnitudes. In this paper maintenance cost models have been developed with respect to the type of maintenance intervention summarised in Table 7.1.

Nomenclature

M	Life period of track in MGT (Million Gross Tonnes)
m	Gross tonnage per year in MGT
N	Life period of track (equivalent to M) in years
r	Discount rate
K	Class of curve radii
CL	Average labour cost in SEK (Swedish Kroner)/hr
L	Total length of track section in km
Li	Length of *i*th curve in km
Tgi	Mean time to grind for *i*th curve in hr/km
ngi	Number of grinding passes on *i*th curve
Ceg	Equipment cost for grinding in SEK/hr
mgi	Interval for grinding for *i*th curve in MGT
Ttai	Mean time to tamp for *i*th curve in hr/km
Ceta	Equipment cost for tamping in SEK/hr
mtai	Interval for tamping for *i*th curve in MGT
Tlu	Mean time to refill lubrication material for each lubricator in hr
Clu	Cost of lubrication material for each lubricator per year in SEK
nli	Number of wayside lubricators in *i*th curve
Tbi	Mean time to clean ballast for *i*th curve in hr/km
Ceb	Equipment cost for ballast cleaning in SEK/h
mbi	Interval for ballast cleaning for *i*th curve in MGT
Tt	Mean time to inspect track in hr/km
Cet	Equipment cost for track inspection in SEK/hr
mt	Interval for track inspection in MGT
Cr	Cost of rail in SEK/km
Trri	Mean time for rail renewal for *i*th curve in hr/km
Cerr	Equipment cost for rail renewal in SEK/hr
mrri	Interval for rail renewal for *i*th curve in MGT
Cb	Cost of ballast in SEK/km
Tbri	Mean time for ballast renewal for *i*th curve in hr/km
Cebr	Equipment cost for ballast renewal in SEK/hr
mbri	Interval for ballast renewal for *i*th curve in MGT
Cs	Cost of sleeper in SEK/km
Tsri	Mean time for sleeper renewal for *i*th curve in hr/km
Cesr	Equipment cost for sleeper renewal in SEK/hr
msri	Interval for sleeper renewal for *i*th curve in MGT

Cf Cost of fasteners in SEK/km
Tfri Mean time for fastener renewal for *i*th curve in hr/km
Cefr Equipment cost for fastener renewal in SEK/hr
mfri Interval for fastener renewal for *i*th curve in MGT
Trbi Mean time to repair rail break in *i*th curve in hr
Cer Equipment cost to repair rail breaks in SEK/hr
Mrbi Mean time to rail breaks in *i*th curve in MGT
frbi Failure rate of rail (breaks) in the *i*th curve

7.3.1 Mathematical Formulation

Maintenance costs are the most complex cost component of an asset during its life since maintenance is a long continuous process throughout the asset life. While the cost of any specified maintenance work on an asset can be comfortably estimated using engineering costing methodologies, estimating maintenance costs throughout the asset life is a much more sophisticated process. This is because the types of maintenance are dependent on many factors, of which the most important are asset deterioration rates, maintenance policy, and budget constraint. Maintenance schedules therefore need to be predicted/planned to enable the maintenance costs to be estimated. Maintenance costs of track must include:

- Materials, equipment, and labour
- Condition monitoring and inspection
- Track possession time

In this chapter the maintenance costs have been determined as per the maintenance policy followed at Banverket. The track has been divided into different sets of curve radii (K), i.e. 0-300m (K=1), 300-450m (K=2), 450-600m (K=3) and so on. Curves with radius more than 2000m have been considered as tangent track. The segmentations of the track have been done as per of availability of the track failure data.

A few things must be considered while performing the segmentations of a track section. The segmentation of the track must be done for a specific track section and should not be generalised. The segmentation of the track must done as per i) the number of each individual curve existing in a track section and ii) the number of track failures occurring in each type of curve over a period of time. For example, if there are few curves of curve radii between 700m to 1000m, it is safe to take 700-1000 m as one segment whereas if there are a lot of curves existing of curve radii between 500 to 600 m the 500-600 m must be defined as a track segment. The same logic can be applied for number of failures in different curve radii. If numbers of curves as well as numbers of failures are high in a particular segment, it can still be divided into further segments. The segmentation of track section should not be symmetrical over the whole track section.

Rail grinding cost

Grinding is the maintenance action done on the rail to control Rolling Contact Fatigue (RCF) defects. Cost due to rail grinding primarily depends on the periodicity of grinding and the number of grinding passes and is given by:

$$\sum_{i=1}^{K}\sum_{j=1}^{N-1}\frac{((Tgi*CL*Li*ngi)+(Ceg*Tgi*Li*ngi))*(\frac{m}{mgi})}{(1+r)^{j}} \qquad 7.1$$

Track tamping cost

Tamping is the maintenance action done on the track to correct the alignment of the track. Cost due to track tamping depends on the interval of tamping and is given by:

$$\sum_{i=1}^{K}\sum_{j=1}^{N-1}\frac{((Ttai*CL*Li)+(Ceta*Ttai*Li))*(\frac{m}{mtai})}{(1+r)^{j}} \qquad 7.2$$

Rail lubrication cost

Lubrication is done on the rail to control rail wear. Cost due to lubrication depends on the number of lubricators in the curves and the cost to maintain each lubricator in terms of filling, which is given by:

$$\sum_{i=1}^{K}\sum_{j=1}^{N-1}\frac{(Tclu*CL*nli)}{(1+r)^{j}} \qquad 7.3$$

Ballast cleaning cost

Ballast cleaning is the maintenance action done to eliminate trapped water inside the ballast in order to restore the track quality and stiffness. Cost due to ballast cleaning primarily depends on the periodicity of ballast cleaning and is given by:

$$\sum_{i=1}^{K}\sum_{j=1}^{N-1}\frac{((Tbi*CL*Li)+(Ceb*Tbi*Li))*(\frac{m}{mbi})}{(1+r)^{j}} \qquad 7.4$$

Track inspection cost

Track inspection is done to detect the flaws on the track that can lead to failures. The cost due to track inspection primarily depends on the interval of track inspection and is given by:

$$\sum_{j=1}^{N-1}\frac{((Tt*CL*L)+(Cet*Tt*L))*(\frac{m}{mt})}{(1+r)^{j}} \qquad 7.5$$

Rail renewal cost

Rail renewal is done when the rail deterioration reaches maintenance or safety limits. The cost due to rail renewal is given by:

$$\sum_{i=1}^{K}\sum_{j=1}^{N-1}\frac{((Cr*Li)+(Trri*CL*Li)+(Cerr*Trri*Li))*(\frac{m}{mrri})}{(1+r)^{j}} \qquad 7.6$$

Ballast renewal cost

Ballast renewal is done when ballast deterioration reaches maintenance or safety limits. The cost due to ballast renewal is given by:

$$\sum_{i=1}^{K}\sum_{j=1}^{N-1}\frac{((Cb*Li)+(Tbri*CL*Li)+(Cebr*Tbri*Li))*(\frac{m}{mbri})}{(1+r)^{j}} \quad 7.7$$

Sleeper renewal cost

Sleeper renewal is done when the sleeper deterioration reaches maintenance or safety limits. The cost due to sleeper renewal is given by:

$$\sum_{i=1}^{K}\sum_{j=1}^{N-1}\frac{((Cs*Li)+(Tsri*CL*Li)+(Cesr*Tsri*Li))*(\frac{m}{msri})}{(1+r)^{j}} \quad 7.8$$

Fastener renewal cost

Fastener renewal is done when the fastener deterioration reaches maintenance or safety limits. The cost due to fastener renewal is given by:

$$\sum_{i=1}^{K}\sum_{j=1}^{N-1}\frac{((Cf*Li)+(Tfri*CL*Li)+(Cefr*Tfri*Li))*(\frac{m}{mfri})}{(1+r)^{j}} \quad 7.9$$

Rail replacement cost

Rail replacement is done when rail breaks occur on the track. Cost due to rail break primarily depends on the probability of rail breaks and is given by:

$$\sum_{i=1}^{K}\sum_{j=1}^{N-1}\frac{((Cr*Lr)+(Tri*CL)+(Cer*Tri))*(\frac{m}{mri})}{(1+r)^{j}} \quad 7.10$$

Track downtime cost

Downtime on the track occurs due to track possession due to maintenance actions on the track. Train-free periods are usually used for planning maintenance actions, i.e. the hours between two consecutive trains. However, as the train-free periods are not long enough in most cases, this leads to train cancellations, train speed restrictions etc., which imply penalties imposed on the infrastructure manager by the traffic operators. Preventive maintenance and renewal actions are usually planned well ahead so as not to affect the traffic. However, corrective maintenance on the track generally affects the train operation. In our case we have considered rail breaks for corrective maintenance.

MTTR for rail break is given by $\frac{\sum_i \text{frbi} * Trbi}{\sum_i \text{frbi}}$ 7.11

In this case, track possession time is calculated as the difference between MTTR and train-free period. Hence, the track downtime cost can be calculated by multiplying the track possession period with the penalty cost. Table 7.2 describes the R&M parameters associated with track maintenance.

Table 7.2: R&M parameters associated with track maintenance

Maintenance actions	R&M parameters	
Rail grinding	T_{gi}	m_{gi}
Tamping	T_{tai}	m_{tai}
Rail lubrication	T_{lu}	
Ballast cleaning	T_{bi}	m_{bi}
Track inspection	T_t	
Rail renewal	T_{rri}	m_{rri}
Ballast renewal	T_{bri}	m_{bri}
Sleeper renewal	T_{sri}	m_{sri}
Fasteners renewal	T_{fri}	m_{fri}
Rail replacement	T_{rbi}	m_{ri}
Downtime cost	T_{rbi}	f_{rbi}

7.4 Uncertainty in LCC

The statistical characteristics of RAM parameters contribute to uncertainty in LCC. The reason for this is that the times and conditions for these types of events are so complex that they can not be predicted with a fair degree of accuracy. Therefore, it was decided to explore a method that combines the use of Design of Experiment (DoE) methodologies with Monte Carlo simulation to estimate the uncertainty involved with LCC. The area of Design of Experiments (DoE) was developed in the 20th century to increase the effectiveness and efficiency of experimentation. However, for experiments to be effective and lead to correct conclusions there are a number of requirements that should be fulfilled (Coleman *et al.*, 1993). For example, the response must be measurable and be correlated to the purpose of the experiment. Furthermore, even though not an absolute necessity, the power of statistical operations will be greater if the response is continuous and preferably also normally distributed. The responses of this study are the point estimate for LCC of the track and its related uncertainty, which both are continuous, but not necessarily normally distributed. The following are valid for the present study:

1) The factors that are tested in the experiment are RAM-parameters, which all are continuous and numeric. They are also measurable, controllable and deemed important for the selected responses;

2) The factors that are not under investigation can easily be held constant, since the study is analytical and not empirical. These factors are the cost factors not directly related to RAM. Hence, no randomization is considered necessary.

Since the study is analytical there are no major economical constraints. Hence, the design is mostly dependent upon the number of RAM parameters that are to be investigated. In order to fulfil the purpose of this study, a two-level factorial design is considered valuable. However, in order to reduce the number of runs, a fractional factorial design is considered sufficient. The analysis is supported by the software tool STATGRAPHICS, which provides suitable tables and graphs for presentation.

The probability distribution of LCC can be found by the use of Monte Carlo simulation. A Monte Carlo simulation is effectively a random number generator that creates values for each RAM parameter. Values are chosen within specified ranges of each parameter and with a frequency proportional to the shape of probability distribution associated with each RAM parameter.

7.4.1 Case Study

The case study was on the iron ore line (Malmbanan) that runs from Luleå in Sweden to Narvik in Norway. The line allows 30 tonne axle load with mixed traffic. Data (see Appendix 1) was collected from Banverket's failure and maintenance databases (i.e. BIS, Bessy, and 0felia) that range from 1997 to 2006 with some data being collected from (Kumar, 2006). The study was performed on the rail replacement cost on both high and low rails separately. The idea of separating high rail and low rail for cost estimation lies in the fact that they both have different failure deterioration due to quasi-static forces in the track curvatures. The following assumptions were made after consultations with Banverket's track experts in the case study.

- Average gross tonnage per year is assumed to be 25 MGT
- Life of track for LCC estimation is 600 MGT (24 years)
- Discount rate is taken as 4 percent
- Cost of BV50 rail (including neutralisation) is 1,395 SEK/m
- Average labour cost is 525 SEK/hr. This includes the track worker cost, track welder cost and inspection personnel cost
- Welding equipment cost is 60 SEK/hr
- Average length of rail replacement/rail break is 8 m

LCC analysis was done on curves of radius 450 to 600 meters, with cost figures given in Swedish kronor (SEK). Independent and identical distributed (IID) test was performed on the failure and repair data and the results show that the data are IID. Appendix 2 shows the tests for IID.

Table 3 shows the probability distribution of MTTF and MTTR for both high and low rails. The analysis was supported by the software tool Weibull++. MTTF was estimated by considering both failure events (time period to occurrence of rail break) and suspended events (no rail break has occurred) for the particular curvature of the track. Reliability analysis must include suspended events in calculation in order to arrive at the correct value. MTTR considered here comprises of the logistic time, welding time and inspection time necessary to repair the rail breaks. A two-sided 90% confidence level was considered for determining the upper limit, mean and lower limits of MTTF and MTTR.

Table 7.4 shows the LCC estimation by considering DoE principles. The high and low rails were analysed separately, but followed the same design. The applied design was a screening, full factorial, two-level design with the two experimental factors MTTF and MTTR, i.e. a 2^2-design that requires four runs. These four runs were performed 10 times (i.e. 10 blocks with four runs in each), resulting in a total of 40 runs for high and low rails respectively. The high and low levels for MTTF and MTTR were selected as the upper and lower limits of their distributions. The experiment contained two responses, i.e. the point estimate and the Log (s^2) of LCC. The rationale for analysing Log (s^2) is described in Bisgaard and Fuller (1995). The input data was generated by Monte Carlo simulations. These data were entered into Equation 7.10 and varied according to the experimental design summarised in Table 7.4.

Table 7.3: MTTF and MTTR probability distributions for high and low rails

		High Rail	Low Rail
MTTF (MGT)	Probability distribution	Log Normal (μ=5.9933, σ=0.2523)	Weibull- 2 parameter (η=369.7161, β=3.5315)
	Upper Limit	482.7046	403.5625
	Mean	413.6783	332.8091
	Lower Limit	354.5227	274.4603
MTTR (Hours)	Probability distribution	Weibull- 2 parameter (η=4.6972, β=1.8871)	Normal (μ=3.4458, σ=1.0296)
	Upper Limit	5.5300	3.9347
	Mean	4.1690	3.4458
	Lower Limit	3.1431	2.9569

Table 7.4: LCC estimation with DoE principles

Type	MTTF	MTTR	LCC (Average)	Log (s^2)
High Rail	-1	-1	-1050.378	3.4198
	1	-1	-940.5847	3.4784
	-1	1	-1086.606	3.4572
	1	1	-973.0265	3.5139
Low Rail	-1	-1	-1252.146	3.0577
	1	-1	-1113.337	3.0128
	-1	1	-1288.255	3.0824
	1	1	-1130.418	3.0230

Table 7.4 indicates that Log (s^2) of LCC is quite stable for both high and low rails. However, changes in the levels of MTTF and MTTR do affect the variability in LCC. Since there is no interaction effect present (see Fig. 7.2 for example), the factors can be considered individually. An interaction between two factors means that the effects of either one cannot be judged independently. If there is an interaction between two factors, the effect of one factor on the response will depend on the setting of the other. In order to reduce the variability in LCC, one should look into the lowest value of Log (s^2). The effects of variability in MTTF and MTTR on the LCC of high and low rails are shown in Fig. 7.2 and Fig. 7.3 respectively. The figures show the effect on LCC with increase of MTTF and MTTR values from low to high levels.

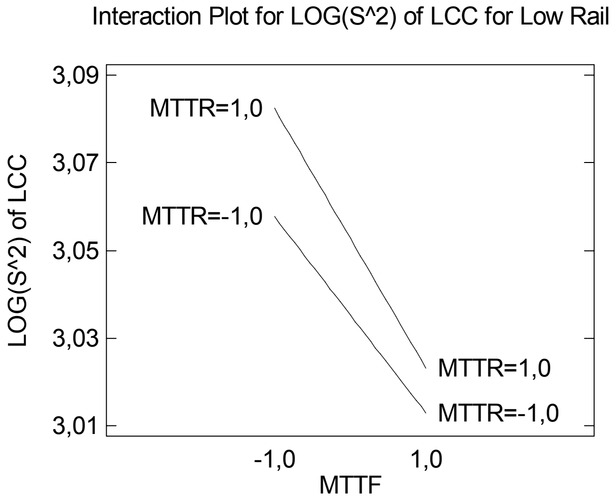

Figure 7.2: Interaction plot showing variability in LCC for low rail

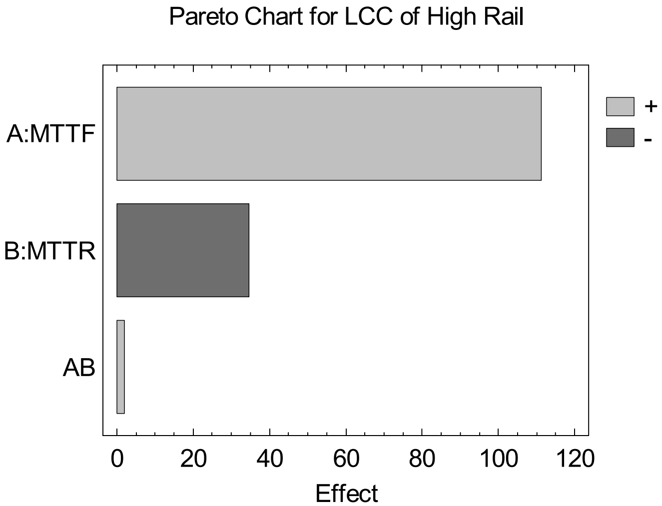

Figure7.3: Effect of MTTF and MTTR on uncertainty of LCC for high rail

As shown in Fig. 7.3 and 7.4, MTTF has a positive effect on LCC and MTTR has a negative effect. The magnitudes of the effects imply that the uncertainty in MTTF has more impact on the change in LCC than the uncertainty in MTTR. Two possible reasons for these differences in magnitudes are uncertainty levels in the parameters and given importance levels in the LCC formulation. The interaction between MTTF and MTTR is not significant in any of the cases.

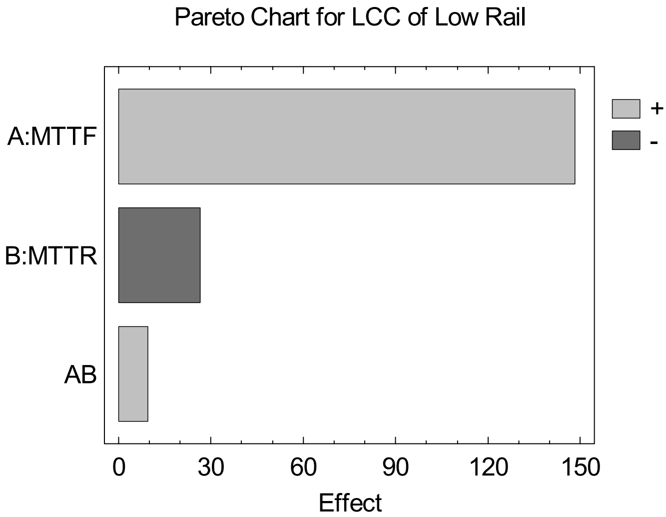

Figure 7.4: Effect of MTTF and MTTR on uncertainty of LCC for low rail

Monte Carlo simulation was used to determine the probability distribution of LCC and estimate the associated variability cost. A two-sided 90% confidence level was considered for this distribution. LCC figures were generated by nine combinations of upper, mean and lower limits of MTTF and MTTR that were generated by Monte Carlo simulation. As shown in Table 7.5, the difference between upper and lower limits can provide the variability cost associated with LCC. The negative sign on the costs indicate that they were calculated as Total Present Value (TPV).

Table 7.5: Simulated probability distribution of LCC

		High Rail	Low Rail
LCC (SEK)	Probability distribution	Weibull- 3 parameter (η=219.6026, β=3.0731, γ=815.1878)	Weibull- 3 parameter (η=170.7607, β=2.2115, γ=1049.3146)
	Upper Limit	-1024.8602	-1214.6553
	Mean	-1011.5003	-1200.5471
	Lower Limit	-998.9916	-1187.6428

For better estimation of uncertainty in LCC, this chapter outlines a methodology based on a combination of Monte Carlo simulation and DoE. This combination gives a possibility to identify parameters that are influential on the LCC estimation and its variability. The simulations are used to make the deterministic LCC equations probabilistic. DoE is applied to guide how the RAM parameters should be varied in a systematic way.

Chapter 8

Discussions and Conclusions

This chapter discusses the findings of the present research. Furthermore, it presents the research contributions and the scope for future research

8.1 Discussion

The purpose of this research work is to develop an approach for track maintenance planning based on the RAMS and LCC analysis of the track. There are three research questions that have been formulated. The differences between the research questions are on the level of analysis. The first research question is in an aggregated level of defining RAMS and LCC for track maintenance while the second research question looks into the applications of RAMS and LCC in track maintenance planning. The third research question is on a more detailed level that supports the LCC analysis in track maintenance planning by looking into uncertainty.

The research presents a survey of current practices of RAMS and LCC for railway track in Europe. The survey looks into the rules and standards being followed by different infrastructure managers and railway suppliers. Different models and tools being used are also described (Chapter 5). A few improvement areas on the rules and models are discussed, which will be incorporated in the later part of the project. The research also presents the fundamental concepts of RAMS and LCC and the factors influencing them for railway track scenario. Processes of RAMS and LCC analysis in the operation and maintenance phase of the system life cycle have been looked into. The first research question is answered in chapters 3, 4 and 5. As discussed in the chapters it can be seen that RAMS analysis for the railway track is at a primary phase. The European standard (EN 50126) on RAMS for railway discusses RAMS in general. It can be seen that no standard discusses railway track nor the factors associated with it from RAMS and LCC perspective. In this research, RAMS analysis for the track has been studied and the factors influencing RAMS for track have been discussed. A process for RAMS analysis in operation and maintenance phase has been derived. Different cost models have been discussed in the thesis. But the life cycle approach of these cost models are still lacking. Few shortcomings of the existing cost models have been addressed in the thesis and improvement areas have been identified. Finally, a LCC process in the operation and maintenance phase has been illustrated (Chapter 4).

An approach for track maintenance planning based on RAMS and LCC analysis has been developed and described (see Chapter 6). The issues related to generating RAMS database for effective RAMS analysis and taking maintenance decisions based on RAMS analysis have been discussed. Maintenance decision optimisation by LCC with respect to system-effectiveness and cost-effectiveness has been looked into. Chapter 6 tries to answer the second research question of this thesis. Maintenance planning in railway context has long been done based on past experience and experts' judgement. Maintenance planning based on RAMS and LCC analysis is quite limited for track in the current scenario (see chapter 5). Chapter 6 tries to answer the research question two by developing an approach for track maintenance planning based on RAMS and LCC analysis.

To assist the track maintenance planning more effectively, uncertainty associated with LCC estimation has been discussed and calculated (Chapter 7). Design of Experiment (DoE) and Monte Carlo simulation methodologies are used to calculate the uncertainty in LCC estimation due to RAMS parameters. The failure and maintenance data for the analysis have been extracted from Banverket's databases and qualitative data where obtained through consultations with experts in Banverket. The third research question has been answered in chapter 7 of the thesis. This chapter discusses the different uncertainties associated with LCC analysis. An approach has been developed to calculate uncertainty in LCC due to uncertainty in RAMS variables. Variable costs calculated in LCC will help in making effective decisions for track maintenance planning.

This research provides a better understanding of RAMS and LCC methodologies in the railway track maintenance planning. If RAMS and LCC are integrated, decisions will be made based on facts often representing real situations.

8.2 Research Contributions

The research provides state of the art RAMS and LCC methodologies being followed by infrastructure managers and railway suppliers in Europe. These methodologies will help in developing effective rules and models for RAMS and LCC analysis by finding the shortcomings in the current practices. The factors influencing RAMS and LCC analysis have been discussed.

An approach has been developed for track maintenance planning with the utilisation of RAMS and LCC analysis. The study depicts how RAMS analysis helps in track maintenance decisions and LCC helps in optimisation of maintenance decisions.

An approach has been developed to calculate uncertainty in LCC analysis due to RAMS parameters by using methodologies of DoE and Monte Carlo simulation.

8.3 Scope for Further Research

Based on the research conclusions and issues, the following points can be suggested for future research:

- Development of a model for track maintenance decision support utilising RAMS and LCC methodologies.

- Detailed estimation of the variable cost in LCC by considering different uncertainties as mentioned in the thesis. Risk analysis need to be considered in LCC calculation. Risk can be defined as the additional cost associated with LCC due to unforeseen failures in the future. Necessary actions must be taken well in advance in order to identify the risks associated with LCC and the methodologies to estimate those risks

- Development of a framework for defining RAMS and LCC in contracts.

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Appendix 1

Table 1: Time To Failure (rail break) data in MGT for curves of radius 450-600 metres

High Rail	Low Rail
400	325
350	350
250	150
425	225
300	275
325	425
150	300
350	125
150	150
400	400
275	300
575	

Table 2: Time To Repair (to correct rail break) data in minutes for curves of radius 450-600 metres

High Rail	Low Rail
159	258
120	154
480	216
149	240
270	169
547	75
340	340
43	202
228	202
202	216
240	240
218	169

Appendix 2

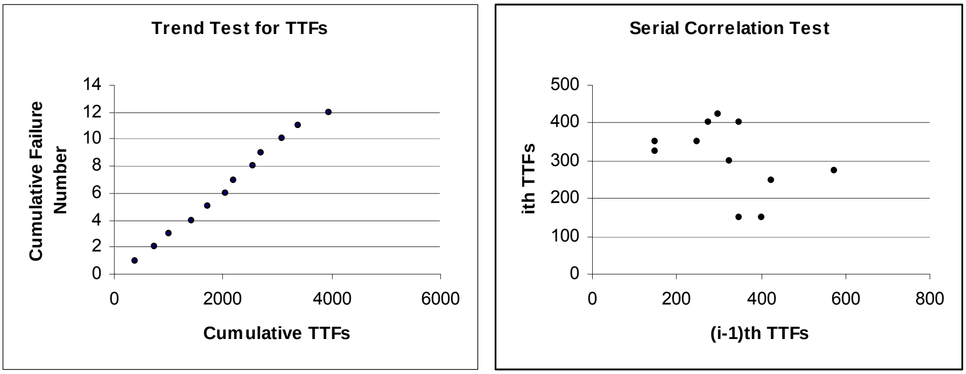

Figure 1: Test for IID for TTFs of the High Rail

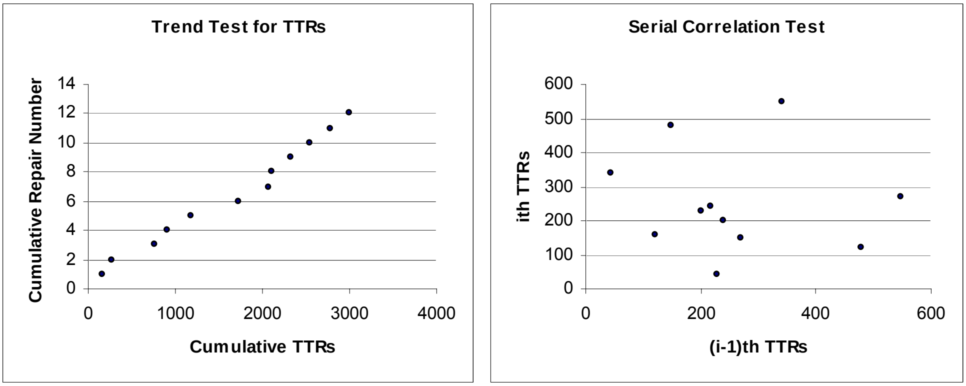

Figure 2: Test for IID for TTRs of the High Rail

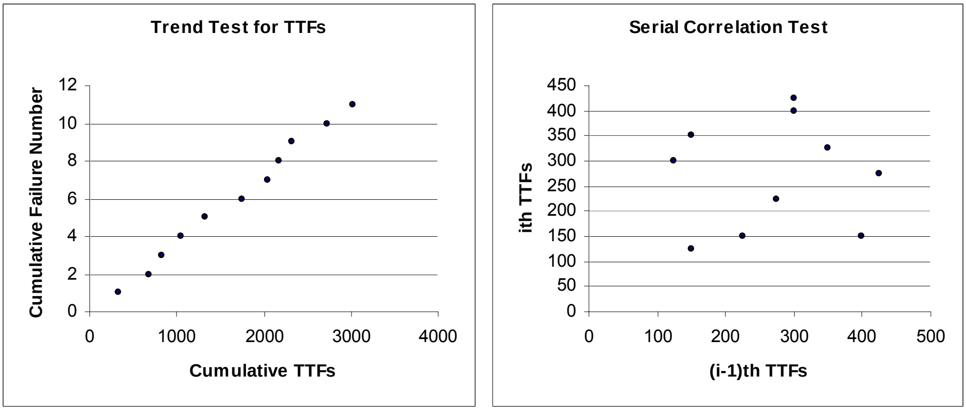

Figure 3: Test for IID for TTFs of the Low Rail

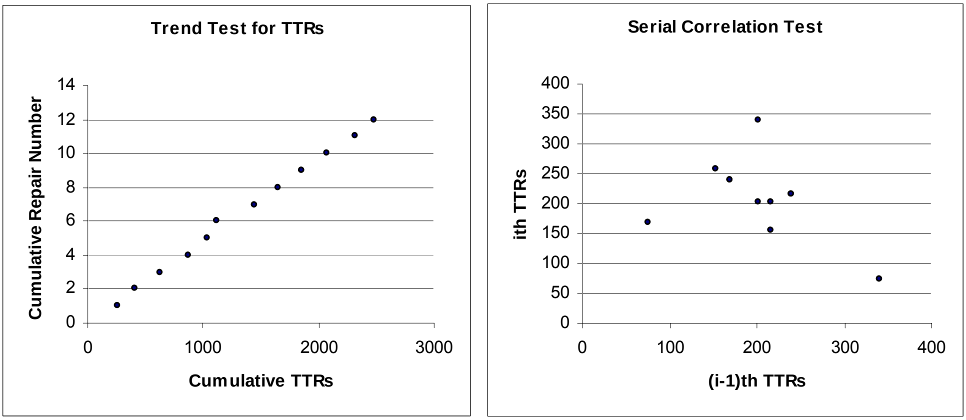

Figure 4: Test for IID for TTRs of the Low Rail