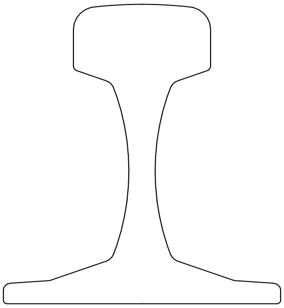
DOCTORAL THESIS

# Operation and Maintenance Performance of Rail Infrastructure

*Model and Methods*

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# Operation and Maintenance Performance of Rail Infrastructure

## Model and Methods

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Abstract

Congestion of roads and sky, increasing energy costs and a demand to reduce emissions, have created a need to shift transportation from road and air to rail. Consequently, rail utilisation is increasing, adding stress to the rail infrastructure and time constraints to maintenance. At the same time, the performance and capacity of rail infrastructure are expected to be preserved or even improved. Railway performance and capacity can be enhanced by: expanding infrastructure; introducing better technology; and improving the efficiency and effectiveness of operation and maintenance. Performance measurement has shown to improve the efficiency and effectiveness of organisations, but the development and integration of performance measurements are essential. A key issue in performance measurement is the process of collecting, storing and converting data into information and knowledge, i.e. data analysis and presentation. Organisations use various systems and methods to collect and analyse data, but the analysis of the collected data to extract relevant information is often a challenge. With improved data analysis and performance measurement, rail transportation can meet the requirements of performance and capacity. Specifically, maintenance planning and optimisation of preventive maintenance can be made more effective, which can decrease interruptions of train operation, reduce costs and ensure safety.

In this thesis, a model for monitoring and analysis of operation and maintenance performance of rail infrastructure is developed. The model includes various methods for analysis of operation and maintenance data. The work aims to facilitate improvements and optimisation of decision-making in railways.

The thesis consists of two parts. The first part gives an introductory summary of the subject and research, followed by a discussion of the appended papers, an extension of the research and conclusions. The second part consist of five appended papers. The first paper concerns the development of a model for improving performance measurement of rail infrastructure. The second paper is a study of indicators related to rail infrastructure performance. The three subsequent papers are development of data analysis methods for: operational availability of rail infrastructure, composite indicators and maintenance costs.

**Keywords:** operation and maintenance, indicators, performance measurement, maintenance cost, rail infrastructure, linear assets, preventive maintenance, corrective maintenance, aggregation, composite indicators, cost-benefit analysis, decision support

# List of appended papers

## Paper A

Stenström, C., Parida, A., Galar, D. and Kumar, U. (2013) Link and effect model for performance improvement of railway infrastructure. *Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, vol. 227, no. 4, pp. 392-402.

## Paper B

Stenström, C., Parida, A. and Galar, D. (2012) Performance indicators of railway infrastructure. *International Journal of Railway Technology*, vol. 1, no. 3, pp. 1-18.

## Paper C

Stenström, C., Parida, A. and Kumar, U., Measuring and monitoring operational availability of rail infrastructure. Accepted for publication in: *Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*.

## Paper D

Stenström, C., Parida, A., Lundberg, J. and Kumar, U., Development of an integrity index for monitoring rail infrastructure. Submitted for publication in: *International Journal of Rail Transportation* (under review).

## Paper E

Stenström, C., Parida, A., and Kumar, U., Preventive and corrective maintenance: Cost comparison and cost-benefit analysis. Submitted for publication in: *Structure and Infrastructure Engineering* (under review).

# List of related papers

**Journal publications**

Stenström, C., Parida, A., Kumar, U. and Galar. D. (2013) Performance indicators and terminology for value driven maintenance. *Journal of Quality in Maintenance Engineering*, vol. 19, no. 3, pp. 222-232.

Stenström, C. and Parida, A. (2014) Measuring dependability of linear assets considering their spatial extension. *Journal of Quality in Maintenance Engineering*, vol. 20, no. 3, pp. 276-289.

Parida, A., Stenström, C. and Kumar, U. (2014) Performance measurement for managing railway infrastructure. *International Journal of Railway Technology*, vol. 2, no. 4, pp. 888-901.

**Technical reports**

Stenström, C. and Parida, A. (2013) Link and effect model for maintenance of railway infrastructure. Luleå University of Technology, Sweden, ISBN 978-91-7439-724-6.

Stenström, C. and Parida, A. (2013) Åtgärds- och effektmodell för effektivare underhåll av järnvägar. Luleå University of Technology, Sweden, ISBN 978-91-7439-720-8.

Stenström, C. (2012) Maintenance performance measurement of railway infrastructure with focus on the Swedish network. Luleå University of Technology, Sweden, ISBN 978-91-7439-460-3.

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Finally, I wish to express my sincere gratitude to my daughters and my partner for always being there, supporting and understanding, and to extend my gratitude to my parents, siblings and close relatives for being role models.

Christer Stenström
October, 2014
Luleå, Sweden

# Abbreviations and notations

The abbreviated version of a term is sometimes more common than the full spelling. Thus, terms that only appear once in the thesis are still presented together with their abbreviations for clarification, but these words are not included in the list below.

| | |
|---|---|
| CI | Composite indicator |
| CM | Corrective maintenance |
| CMMS | Computerised maintenance management system |
| CSF | Critical success factor |
| DEA | Data envelopment analysis |
| EU | European Union |
| GUI | Graphical user interface |
| HSE | Health, safety and environment |
| IM | Infrastructure manager |
| KPI | Key performance indicator |
| KRA | Key result area |
| LCC | Life cycle cost |
| NS | Network statement |
| OEE | Overall equipment effectiveness |
| PM | Preventive maintenance |
| PI | Performance indicator |
| RAMS | Reliability, availability, maintainability and maintenance supportability |
| RQ | Research question |
| S&C | Switches and crossing (turnout) |
| TTR | Time to restoration |
| TTT | Train time table |
| $A(t)$ | Point availability |
| $A_O$ | Operational availability |
| $A_{SA}$ | Service affecting availability |
| $R^2$ | Coefficient of determination |
| $t_{Active}$ | Active repair time |
| $t_{Min}$ | Minimum time for maintenance |
| $\eta$ | Efficiency, equals ${}^{Output}/_{Input}$ |

# Contents

# Part I

# Chapter 1

# Introduction

*"The rolling stock and the permanent way*
*will be in a similar condition"*

*Railway Economy (1850)*
*by Dionysius Lardner*

This chapter gives a short description of the research area, along with the purpose, research questions, scope and limitations, and thesis outline.

## 1.1 Background

### 1.1.1 The need for rail transport

Rail transport has increased over the last decade and it is likely to further increase as passenger and cargo transportation shift from road and air to rail, due to rising energy costs, congestion of roads and sky, and the demand to reduce emissions (EC, 2001b, 2006, 2011). As for the European Union (EU), the key goals of the White Paper 2011 on the European transport system include a 50 % shift of medium distance intercity passenger and freight journeys from road to rail and waterborne transport, and a 60 % cut in transport $CO_2$ emissions by 2050 (EC, 2011). At the same time, the crude oil (conventional reservoirs) output reached its all-time peak in 2006 (IEA, 2010). Thus, the capacity of rail transport needs to be enhanced with preserved or increased availability to meet the new demands in the transport sector.

### 1.1.2 The need for measuring performance and maintenance of rail transport

As rail transport is capital intensive and has a long life span, its operation and maintenance require a long term and sustainable strategy. Strategic planning involves collecting information, setting goals, translating goals to specific objectives and setting up activities to achieve the objectives (Armstrong, 1982, Parida and Chattopadhyay, 2007). For further discussion of developing maintenance strategies for rail infrastructure, see Espling and Kumar (2004).

To monitor and steer the performance of rail infrastructure according to objectives, the effect of maintenance need to be measured; this is carried out through indicators, such as indicators of reliability, availability, maintainability and maintenance supportability (RAMS). These indicators, in turn, are a central part of performance measurement. Measuring entails data collection, but since raw data do not give any information by themselves, they need to be processed. This consumes resources, especially if wrong data are collected, i.e. those not aligned to the overall organisational objectives, or if data quality is poor (Parida and Chattopadhyay, 2007, Karim et al., 2009).

Rail infrastructure are large, geographically spread out technical systems, also known as linear assets. Rail infrastructure include system, subsystem and component levels, and infrastructure managers (IMs) are involved with each of these levels, i.e. IMs have strategic, tactical and operational levels. Furthermore, numerous stakeholders give rise to conflicting requirements that need to be met, complicating the assessment and monitoring of rail infrastructure and its maintenance. Also, due to organisational changes, technology development, changes in objectives and policies, the performance measurement system need to be robust to accommodate continuous improvements.

### 1.1.3 The need for harmonisation and standardisation in rail transport

Mobility is vital for the economy and society in general, facilitating economic growth, job creation, cultural learning and leisure. Harmonisation and standardisation of strategic planning and performance measurement enables the use of comparison to determine performance, both internally and across countries and continents. Standardisation can also reduce the need for discussions of definitions and practices (Kahn et al., 2011). The International Union of Railways (UIC) and European Committee for Standardization (CEN) are important contributors to and promoters of the standardisation of operation, maintenance and RAMS of rail transport (UIC, 2010, CEN, 1999). Considering the European transport system, increased interoperability and building a trans-European rail network are goals of the EU (EC, 1991, 1996). This has resulted in a necessity to harmonise and standardise the operation and maintenance of rail transport, by creating and using common standards across the EU.

## 1.2 Problem statement

Congestion of roads and sky, increasing energy costs and a demand to reduce emissions, have led to a need to shift transportation from road and air to rail (EC, 2011). Consequently, rail capacity utilisation is increasing, adding stress to the rail infrastructure and time constraints to maintenance. At the same time, it is expected that the performance and capacity of rail infrastructure will be preserved or even improved. Railway performance and capacity can be enhanced by: expanding infrastructure; introducing better technology; and improving the efficiency and effectiveness of operation and maintenance. Performance measurement has shown to improve efficiency and effectiveness of organisations (Kaplan and Norton, 1992, 1993, Klefsjö et al., 2001). However, the development and integration of performance measurement methods are critical for their success (Schneiderman, 1999, Bourne et al., 2002, Kumar, 2006). A key issue in performance measurement is the process of collecting, storing and converting the data into information and knowledge, i.e. data analysis and presentation, e.g. Murthy et al. (2002). Organisations use various systems and methods to collect and analyse data, but the analysis of the collected data to extract information is often a challenge. With improved data analysis and performance measurement, rail transportation can meet the requirements of performance and capacity. Specifically, maintenance planning and optimisation of preventive maintenance can be made more effective, which can decrease interruptions of train operation, reduce costs and ensure safety.

In this thesis, a model for monitoring and analysis of operation and maintenance performance of rail infrastructure is developed. The model includes various methods for analysis of operation and maintenance data. The work aims to facilitate improvements and optimisation of decision-making in railways.

## 1.3 Purpose statement

The purpose of the research is to develop a model for monitoring and analysis of operation and maintenance performance of rail infrastructure.[1]

## 1.4 Research questions

To fulfil the above purpose, the following research questions (RQs) have been formulated:

**RQ 1** How can operation and maintenance of rail infrastructure be improved through a performance measurement model?

**RQ 2** Which indicators are used by infrastructure managers and researchers for operation and maintenance of rail infrastructure?

**RQ 3** How can operation and maintenance data be aggregated for monitoring and analysis of rail infrastructure?

[1]For definition of model and related terminology, see Section 2.5.

## 1.5 Linkage of research questions and appended papers

The main linkage between the research questions and the appended papers is shown in Table 1.1.

*Table 1.1: Linkage of the research questions (RQs) and appended papers (A-E).*

| | **A** | **B** | **C** | **D** | **E** |
|---|---|---|---|---|---|
| **RQ 1** | × | | | | |
| **RQ 2** | | × | | | |
| **RQ 3** | | | × | × | × |

## 1.6 Scope and limitations

### 1.6.1 Scope

The scope of the work includes the operation and maintenance performance of rail infrastructure. The purpose is to develop a model. A model can be described as a simplified description of a system or process, used to study its characteristics and to assist calculations and predictions (Table 2.2). Thus, the model to be developed in this work is for measuring the performance of rail infrastructure operation and maintenance, for studying its characteristics and to assist calculations and predictions. The model will consist of a framework, for planning and follow up of performance, and methods for data analysis.

Emphasis is on operation and maintenance as it is regarded as a means to increase performance. Performance, in turn, considers technical performance, and especially for dependability and RAMS, i.e. reliability, maintainability, availability and supportability. Supportability, or maintenance supportability, is an organisational aspect, but as reliability and maintainability are inherent properties of items and railway systems are not easy to replace, supportability is essential.

As humans have a limited perception and capability to process information, the number of indicators one person can monitor is limited. Therefore, the research also includes data aggregation, to reduce the number of indicators, with minimum loss of information. Aggregation also facilitates comparison, as the output is an overall indicator or index.

The research includes case studies with the scope to verify the developed methods. See Section 4.2.3 and Appendix A of Paper E for details and summary statistics.

### 1.6.2 Limitations

The research is limited to rail infrastructure within the area of operation, i.e. design, construction and reinvestment are not considered. Aspects like rolling stock, maintenance contracting and climate variations are not considered.

The case studies are limited to certain railway lines, with the primary aim of verifying the methods; i.e. the resulting performance of the rail lines is primarily used for discussion purposes.

## 1.7 Authorship of appended papers

The contribution of each author to the appended papers is shown in Table 1.2, divided as per the following activities:

1. Formulation of the fundamental ideas of the problem
2. Performing the study
3. Drafting the paper
4. Revising for important intellectual content
5. Final approval for submission

*Table 1.2: Contribution of the authors of the appended papers (A-E).*

| | **A** | **B** | **C** | **D** | **E** |
|---|---|---|---|---|---|
| **Stenström, C.** | 1-5 | 1-5 | 1-5 | 1-5 | 1-5 |
| **Parida, A.** | 1,4,5 | 1,4,5 | 4,5 | 1,4,5 | 1,4,5 |
| **Kumar, U.** | 1,4,5 | | 4,5 | 1,4,5 | 1,4,5 |
| **Galar, D.** | 1,4 | 4 | | | |
| **Lundberg, J.** | | | | 1,4,5 | |
| **Norrbin, P.** | | | | | 1,4 |

## 1.8 Outline

Problem description and justification of the research appear in this chapter. Basic concepts and definitions are given in Chapter 2, followed by a literature review in Chapter 3. Chapter 4 contains the research methodology. Chapter 5 summarises the appended papers. Results and research questions are discussed in Chapter 6, together with linkage between the developed model and methods used (Section 6.4). Chapter 7 is an extension of the research. Lastly, the work is concluded in Chapter 8.

# Chapter 2

# Basic concepts and definitions

*"Have you heard of the wonderful one-horse shay,*
*That was built in such a logical way,*
*It ran a hundred years to a day,*
*And then, of a sudden,*
*...*
*it went to pieces all at once,*
*All at once, and nothing first,*
*Just as bubbles do when they burst."*

*The Deacon's Masterpiece (1858)*
*by Oliver Wendell Holmes, Sr.*

This chapter provides some basic concepts and definitions.

## 2.1 Operation and maintenance engineering

Maintenance can be described as the combination of all technical and administrative actions, including supervision actions, intended to retain an item in, or restore it to, a state in which it can perform a required function (IEC, 1990, CEN, 2010). Pintelon and Parodi-Herz (2008) describe the goal of maintenance as total life cycle optimisation of an asset. Maintenance differs from other business functions due to its multidisciplinary characteristics. Although it deals with engineering aspects, its value is hard to measure in simple financial terms (Murthy et al., 2002). Moreover, with technological advancement and globalisation, systems have become increasingly complex in an effort to increase their quality, efficiency and availability. Consequently, maintenance has become increasingly sophisticated, moving from purely corrective to preventive and predictive (Pintelon and Parodi-Herz, 2008). Accordingly, the cost of maintenance can be significant; see Section 3.2.3. Maintenance is part of operations as it intends to retain items in or restore them to an operational status. A related term is systems engineering; this is a methodical, disciplined approach to the design, realisation, technical management, operations and retirement of a system (NASA, 2007); i.e. it concerns systems' life cycle processes (ISO/IEC, 2008). An example where both maintenance engineering and systems engineering disciplines are integrated is offered by Utne (2010), who used them as tools for developing maintenance strategies, including availability indicators and maintenance cost.

## 2.2 Performance measurement

Performance measurement can be described as the process of quantifying the efficiency and effectiveness of action (Neely et al., 1995) or the study of whether outcomes (of operation and maintenance) are in line with set objectives. This process can be illustrated by an input-process-output (IPO) model, as shown in Figure 2.1; the feedback loop represents the performance measurement process or system.

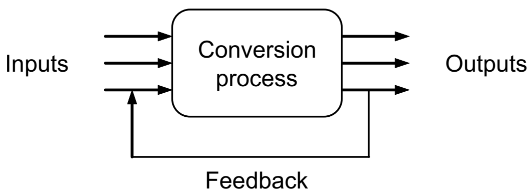


*Figure 2.1: General input-process-output (IPO) model.*

The tools to measure performance within performance measurement systems are various kinds of indicators. Examples of classifications are: performance indicators (PIs) and key performance indicators (KPIs); financial, technical and HSE (health, safety and environment); leading, coinciding and lagging indicators; and individual and composite indicators (Stenström et al., 2013). Indicators grouped together form scorecards, and an entity for describing the whole performance measurement process/system is commonly called framework or model.

Measuring can result in large savings and business safety, if measuring leads to more proactive operation. However, additional costs are associated with measuring. It is therefore important to thoroughly analyse what, where, when, how and for whom to measure (Parida, 2006b).

## 2.3 Dependability and RAMS

Dependability and RAMS are central terms in maintenance that demonstrates its complexity in a dense form. A common description is given by International Electrotechnical

Commission (IEC, 1990); see Figure 2.2. Another description is given by European Standards EN 13306:2011 (CEN, 1999); see Figure 2.3.

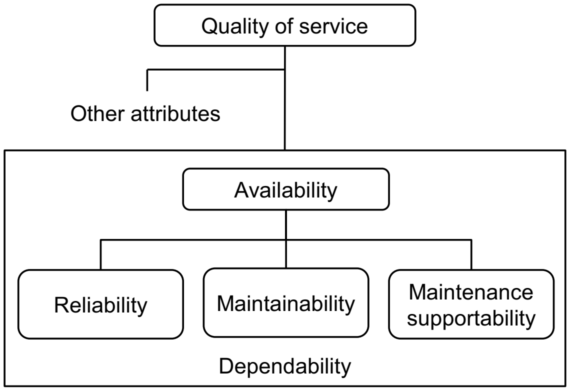


*Figure 2.2: Dependability as described by IEC (1990).*

Reliability, availability, maintainability and maintenance supportability, are attributes of dependability. Written as an acronym, it becomes RAMS, i.e. dependability and RAMS are similar terms used in operation and maintenance. However, the letter S in RAMS can stand for supportability, safety, sustainability or security, i.e. RAMS[4]. In Figures 2.2 and 2.3 the letter stands for maintenance supportability, but in railways it stands for safety (CEN, 1999, Morant et al., 2014).

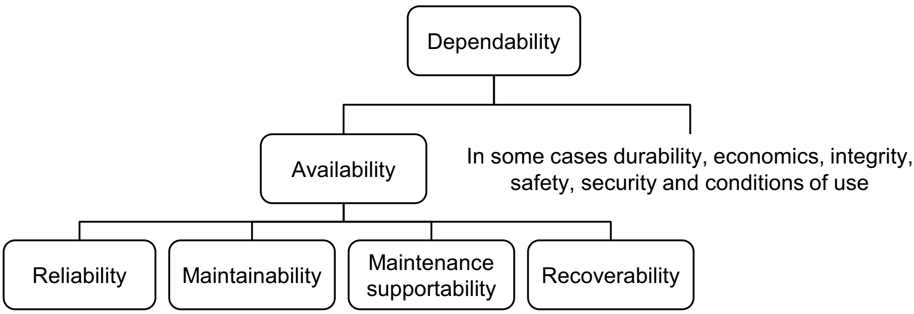


*Figure 2.3: Dependability according to EN 13306:2011 (CEN, 2010).*

Reliability, availability, maintainability can be described both qualitatively and quantitatively; see Paper C for details.

## 2.4 Strategic planning

The performance measurement of organisations need to be aligned with the organisational strategy (Kaplan and Norton, 2001, Eccles, 1991, Murthy et al., 2002). Strategic planning can be described as the process of specifying objectives, generating strategies, evaluating strategies and monitoring results (Armstrong, 1982). Strategic planning involves collecting information, setting goals, translating goals to specific objectives and setting up activities to achieve the objectives. Following the formulation of the strategy, objectives are broken down into tactical and operational plans. The outcomes of the strategy are continuously assessed by collecting data, aggregating the data into information and reporting the resulting information back to the strategic, tactical and operational planning. Components of strategic planning are described in Table 2.1.

## 2.5 Thesis purpose related terminology

Subject related terminology is found in EN 13306: Maintenance terminology (CEN, 2010) and in IEC 60050-191: International Electrotechnical Vocabulary (IEC, 1990). Additional terminology is related to the thesis purpose and research questions, i.e. model and methods.

A model can be described as a simplified description of a system or process, used to study its characteristics and to assist in calculations and predictions (Table 2.2). Thus, the link and effect model (Paper A) can be interpreted as a description of the performance measurement of rail infrastructure operation and maintenance. Moreover, performance measurement can, within an organisation, be seen as a process or a system (Table 2.2); i.e. the link and effect model can be seen as a process model or system model. Nevertheless, this model can also be seen as a framework integrating various methods and processes (Table 2.2).

The link and effect model is a model for monitoring and analysis of operation and maintenance performance of rail infrastructure (Paper A). Calling the link and effect model a performance measurement system would not be wrong, but a distinct name makes references more precise and, thus, easier. An alternative name could be a cause and effect model, but this might be misleading. See Table 2.2.

*Table 2.1: Components of strategic planning.*

| **Term** | **Description** |
|---|---|
| Vision statement | A statement of what an organisation, or organisational unit, hopes to be like and to accomplish in the future (U.S. Dept of Energy, 1993), e.g. zero machine breakdown. |
| Mission statement | A statement describing the key functions of an organisation (U.S. Dept of Energy, 1993), e.g. a dependable mode of transport. Note: vision and mission are set on the same hierarchical level, since either can come first; e.g. an authority has a vision, and determines a mission to start a business; the business can then develop its own vision later on. |
| Goals | A goal is what an individual or organisation is trying to accomplish (Locke et al., 1981). Goals are commonly broad, measurable, aims that support the accomplishment of the mission (Gates, 2010), e.g. rail availability of 99 %. |
| Objectives | Translation of ultimate objectives (goals) to specific measureable objectives (Armstrong, 1982), or targets assigned for the activities (CEN, 2010), or specific, quantifiable, lower-level targets that indicate accomplishment of a goal (Gates, 2010), e.g. less than one failure per track-km and year, and less than 2 % of failures with more than two hours train delay. |
| Strategy | Courses of action that will lead in the direction of achieving objectives (U.S. Dept of Energy, 1993), e.g. various analysis, resource allocation and investments. |
| Key result areas (KRAs) | Areas where results are visualised (Boston and Pallot, 1997), e.g. maintenance cost, and maintenance callbacks & backlog. |
| Critical success factors (CSFs) | Those characteristics, conditions, or variables that when properly managed can have a significant impact on the success of an organisation (Leidecker and Bruno, 1984), e.g. minimum number of failures, and fast repair of failures. |
| Key performance indicators (KPIs) | Actual indicators used to quantitatively assess performance against the CSFs (Sinclair and Zairi, 1995). A KPI is a PI of special importance comprising an individual or aggregated measure, e.g. failures, maintenance time, and availability. |
| Performance indicators (PIs) | Parameters (measurable factors) useful for determining the degree to which an organisation has achieved its goals (U.S. Dept of Energy, 1993), or numerical or quantitative indicators that show how well each objective is being met (Pritchard et al., 1990), e.g. failures per item, logistic time and repair time. |
| Indicator | A thing that indicates the state or level of something (Oxford Dict., 2011). |

*Table 2.2: Terminology related to the thesis purpose.*

| **Term** | **Description** |
|---|---|
| Model | A standard for imitation or comparison (The Century Co., 1889), or a schematic description of something, especially a system or phenomenon, that accounts for its properties and is used to study its characteristics (American Heritage Dict., 2011). Such a model can be a mathematical one (Oxford Dict., 2011). |
| System model | A model of a system, e.g. performance measurement system models (Toni and Tonchia, 2001) and climate system models (Gent et al., 2011). |
| Process model | A model of processes, such as a performance-based process model (Jones and Sharp, 2007). |
| Conceptual model | A model of concepts (general or abstract ideas/understandings), e.g. a system model, or as a more specific example, a conceptual model of performance measurement (Theeranuphattana and Tang, 2008). |
| System | Things connected so as to make one complex whole, e.g. infrastructure (The Century Co., 1889) |
| Framework | A basic structure underlying a system, concept, or text (Oxford Dict., 2011), or a set of assumptions, concepts, values, and practices that constitutes a way of viewing reality (American Heritage Dict., 2011). |
| Conceptual framework | A conceptual framework explains, either graphically or in narrative form, the main things to be studied, the key factors, constructs or variables, and the presumed relationships among them (Miles and Huberman, 1994). |
| Process | A set of interrelated tasks that together transform inputs to outputs (Pall, 1987, Davenport and Short, 1990, EIA, 1999). |
| Method | A method is a systematic and orderly procedure or process for attaining some objective (Baskerville, 1991), or an orderly regulation of conduct with a view to attaining an end (The Century Co., 1889). |
| Methodology | The study or description of methods (Baskerville, 1991), or the science of method in scientific procedure (The Century Co., 1889), e.g. Chapter 4 of this thesis. |
| Tool | Any instrument, apparatus, etc. necessary to the performance of some task (Baskerville, 1991). |
| Cause and effect | Principle of causation; relationship between cause and effect (Oxford Dict., 2011); within engineering, cause and effect diagrams (Ishikawa, 1986). |
| Link and effect model | A model for monitoring and analysis of operation and maintenance performance of rail infrastructure (see Paper A). |

# Chapter 3

# Literature review

This chapter gives a review of the literature related to the research questions (RQs). Since each appended paper includes a literature review, parts of the review given below are found in the appended papers. Nevertheless, the goal of this chapter is to give a review following the RQs and provide a context for the appended papers.

## 3.1 Performance measurement of rail transportation

With increasing competition, globalisation and legislation of health, safety and environment (HSE), traditional accounting with only financial measures (indicators) has been shown to be insufficient for assessing business performance (Johnson, 1983, Kaplan, 1984). Consequently, new performance measurement models and scorecards have been developed to take into account quantitative and qualitative non-financial measures, including efficiency, effectiveness, internal and external perspectives (Keegan et al., 1989, Fitzgerald et al., 1991, Kaplan and Norton, 1992, 1996). Likewise, scorecards and performance measurement systems are important for grasping a large number of indicators and identifying the most important ones.

As maintenance constitutes a key element in many organisations (Swanson, 2001, Tsang, 2002, Parida and Kumar, 2006), it has benefited from the development of more holistic and balanced performance measurement.

For performance measurement of rail transportation, studies commonly starts from a certain perspective, like: rolling stock, operators, infrastructure, passengers, freight or infrastructure managers (IMs). Depending on the perspective, the project output in terms of indicators can have different focus areas.

Several EU projects have reviewed indicators from rolling stock and operators perspectives. EQUIP (2000) has developed a 'Handbook for self-assessment of the internal performance of local public transport operators' suggesting indicators related to contracting, passengers, vehicles, employees, delays and cost. IMPROVERAIL (2003) gives indicators related to: utilisation (train-km per track-km); safety; service quality and reliability (train delay); efficiency (man-hours per track- or train-km), innovation and growth; finance; and accessibility. UTBI (2004) reviewed common indicators of urban transport systems, primarily for utilisation and cost. SuperGreen (2010, 2013) reviewed indicators in the European transport sector. Key indicators are of cost, transportation time, reliability (train punctuality), utilisation and environment aspects. The projects EQUIP, IMPROVERAIL and SuperGreen also categorised the indicators according to type and hierarchical level.

Work on performance measurement from a rail infrastructure perspective can also be found. INNOTRACK (2009, 2010), focused more on the rail infrastructure and its maintenance. With aim on life cycle cost (LCC) and RAMS, examples of indicators are cost of down time, failure rate and repair time. In the joint project "Asset management club project" (BSL, 2009), eight European IMs compared their information systems, key performance indicators (KPIs) and scorecards for managing rail infrastructure. The Swedish IM, Trafikverket (Swedish Transport Administration), is one of the IMs that took part of the Asset management club project. Trafikverket's indicators for rail infrastructure have been reviewed by: Åhrén and Parida (2009a); Åhrén (2008); and Söderholm and Norrbin (2013). In another IMs project, initiated by UIC - LICB (2008), 14 IMs maintenance costs were harmonised and compared, but details of the harmonisation process are left out.

Quite extensive work has been carried out on identifying indicators for measuring performance of rail transportation. Some reviews take the perspective of rolling stock and operators, but do not provide a structured list; nor are they in detail, like EN 15341: Maintenance Key Performance Indicator (CEN, 2007) or SMRP Best Practice Metrics (SMRP, 2011). For rail infrastructure, various indicators have been identified as important, but no review is available, except from a single IM, namely Trafikverket (Åhrén and Parida, 2009a).

The above mentioned research work is assembled in the thesis related technical report (ISBN 978-91-7439-460-3), together with other related work by academics and IMs. Within the report, identified indicators are briefly discussed with examples in Chapter 4, and Chapter 5 gives a similar review of scorecards, with examples. Using the technical report as a background, Paper B answers RQ 2, works as a reference for IMs and provides a basis for a possible future standard on railway indicators.

Further discussion and review of performance measurement in general are found in work by Neely et al. (2000), Bourne et al. (2003), IDeA (2006), Taticchi et al. (2010) and Nudurupati et al. (2011). For performance measurement of maintenance, reviews are given by Parida and Chattopadhyay (2007), Kumar and Parida (2008), Simões et al. (2011), Kumar et al. (2013) and Parida et al. (2014b).

When it comes to models for performance measurement of rail infrastructure, studies are lacking. The International Union of Railways (UIC) has given out asset management guidelines (UIC, 2010), as a seven-step procedure based on British Standards Institute's PAS 55 (BSI, 2008), the International Infrastructure Management Manual (IIMM) from New Zealand (INGENIUM and NAMS, 2006) and the Asset Management Overview by the U.S. Federal Highway Administration (FHWA, 2007). PAS 55 has been superseded by

ISO 55000 (ISO, 2014). General performance measurement and maintenance performance measurement models are shown in Figure 3.1.

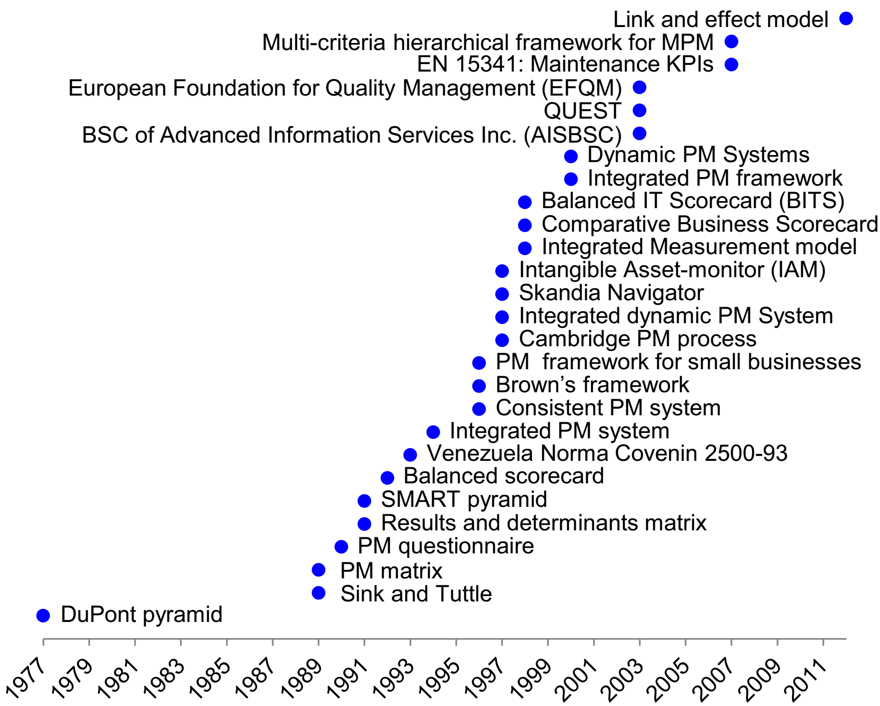


*Figure 3.1: Performance measurement models (Parida et al., 2014b).*

### 3.1.1 Challenges in the implementation process

Performance measurement has been shown to increase the performance and competitiveness of organisations by providing more balanced metrics, e.g. see Kaplan and Norton (1992, 1993), but there are implementation issues. Some claim that 70 % of scorecard implementations fail (McCunn, 1998). In a review, Kumar (2006) identified three main issues of implementation: human involvement, including managers and employees; integration and linkage of strategic goals and vision to the operational level; and development of effective indicators. Other researchers have noted the following issues in the implementation of performance measurement initiatives (Bourne et al., 2002):

- A highly developed information system is called for
- The process can be time-consuming and expensive

- Management involvement and commitment is required
- Resistance to change
- Vision and mission are not actionable
- Strategy may not be linked to resource allocation
- Goals may be negotiated rather than based on stakeholder requirements
- State of the art improvement methods are not always used
- Striving for perfection can undermine success
- Strategy is not always linked to department, team and individual goals
- A large number of measures dilutes the overall impact
- Indicators are often poorly defined
- There is a need to quantify results in areas that are more qualitative in nature

Kaplan and Norton (2000) listed several of the issues recorded by Bourne et al. (2002) and stressed problems which result first from hiring inexperienced consultants and second from overlooking strategy and instead introducing a rigorous data collecting computer system. Davenport et al. (2001) carried out case studies and interviews with 20 companies and found that a major concern in the information age is that most companies are not turning data into knowledge and then results. Karim et al. (2009) made similar observations in maintenance data processing; the gap between data processing and knowledge is too large, probably due to an inability to identify stakeholder requirements.

Concerning the problem caused by having too many measures, The Hackett Group found that companies report, on average, 132 measures to senior management each month, about nine times the recommended number, thereby confusing detail with accuracy (Davis and Davis, 2010). The number of strategic level indicators depends on the number of senior managers. Therefore, data aggregation is needed, but care must be taken as some information will always be lost and the underlying factors can be forgotten.

### 3.1.2 Link and effect model

Following the development of performance measurement models that include both financial and non-financial measures, and their extension to maintenance, Liyanage and Selmer (1999) and Liyanage and Kumar (2003) applied these concepts to the oil and gas industry. The authors constructed an initial model, called link and effect model (Figure 3.2), which was later developed to a process map, described as a value based operation and maintenance performance concept (Liyanage and Kumar, 2003).

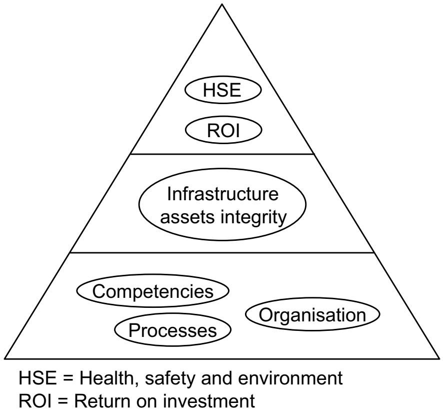


*Figure 3.2: The initial link and effect model. Adapted from Liyanage and Selmer (1999).*

These ideas were further developed by Kumar (2006) and Parida (2006a) (Figure 3.3). With this model as a background, in collaboration with organisations from the hydropower industry and mining industry, Parida and Chattopadhyay (2007) constructed a model following the link and effect approach, described as a multi-criteria hierarchical maintenance performance measurement framework; see Figure 3.4.

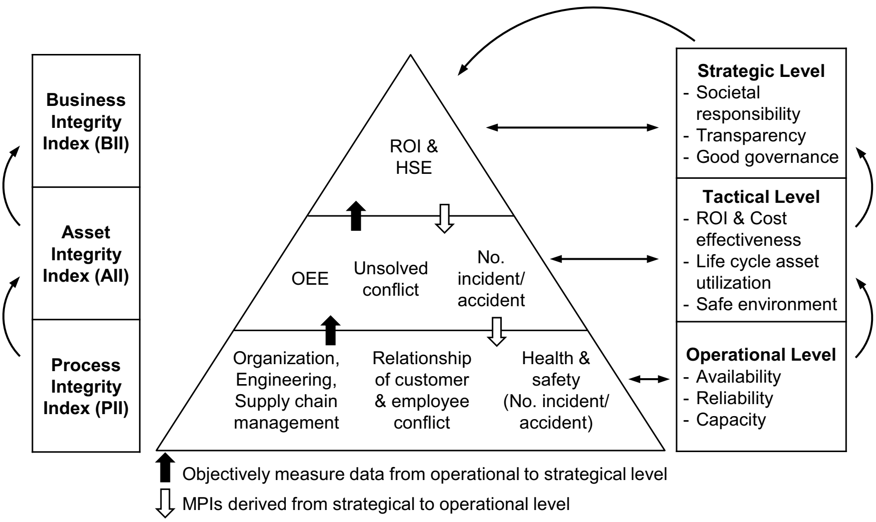


*Figure 3.3: Link and effect model. Adapted from Parida (2006a).*

***Front-end process:***
- *Timely delivery*
- *Quality*
- *HSE issues*

**External effectiveness:**
- Customers/ stakehodlers
- Compliance with regulations

**Internal effectiveness:**
- Reliability
- Productivity
- Efficiency
- Growth and innovation

***Back-end process:***
- *Process stability*
- *Supply chain*
- *HSE*

| Hierarchical level / Multi-criteria | Level 1<br>Strategic/Top management | Level 2<br>Tactical/Middle management | Level 3<br>Functional/ Operational |
|---|---|---|---|
| **Equipment/ process related** | - Capacity utilization | - Availability<br>- OEE<br>- Production rate<br>- Quality<br>- Number of stops | - Production rate<br>- Number of defects/rework<br>- Number of stops/downtime<br>- Vibration and thermography |
| **Cost/finance related** | - Maintenance budget<br>- ROMI | - Maintenance production cost per ton<br>- Maintenance/production cost | - Maintenance cost per ton |
| **Maintenance task related** | - Cost of maintenance tasks | - Quality of maintenance task<br>- Change over time<br>- Planned maintenance task<br>- Unplanned maintenance task | - Change over time<br>- Planned maintenance task<br>- Unplanned maintenance task |
| **Learning, growth & innovation** | - Generation of a number of new ideas<br>- Skill improvement training | - Generation of number of new ideas<br>- Skill improvement training | - Generation of number of new ideas<br>- Skill improvement training |
| **Customer satisfaction related** | - Quality complaint numbers<br>- Quality return<br>- Customer satisfaction<br>- Customer retaintion | - Quality complaint numbers<br>- Quality return<br>- Customer satisfaction<br>- New customer addition | - Quality complaint numbers<br>- Quality return<br>- Customer satisfaction |
| **Health, safety & security, environment** | - Number of accidents<br>- Number of legal cases<br>- HSSE losses<br>- HSSE complaints | - Number of accidents/incidents<br>- Number of legal cases<br>- Compensation paid<br>- HSSE complaints | - Number of accidents/incidents<br>- HSSE complaints |
| **Employee satisfaction** | - Employee satisfaction<br>- Employee complaints | - Employee turnover rate<br>- Employee complaints | - Employee absentees<br>- Employee complaints |

*Figure 3.4: Multi-criteria hierarchical maintenance performance measurement framework; a link and effect approach. Adapted from Parida and Chattopadhyay (2007).*

The concept was adapted to railways by Åhrén (2008). Åhrén mapped maintenance performance indicators (17 in total) used by the Swedish infrastructure manager (Trafikverket), linked them to objectives, balanced scorecard, and identified key result areas and critical success factors. Åhrén also developed an example of how a link and effect model can be constructed (Table 3.1). Furthermore, Åhrén and Parida (2009a,b) studied maintenance performance indicators of the Swedish and Norwegian infrastructure managers for comparing performance and development of a composite indicator for overall railway infrastructure effectiveness (ORIE).

The concept of a link and effect model has been used by several researchers, but application to real operation and maintenance data are lacking, something generally true for performance measurement models. Thus, this is an area of further research.

As discussed in Section 3.1, many models measure performance. The general agenda for all of these, including the link and effect model, is continuous improvement (Bhuiyan and Baghel, 2005), also known as kaizen or as the plan-do-study-act cycle. See for example six sigma (Klefsjö et al., 2001), balanced scorecards (Kaplan and Norton, 1992) or ISO 55000 (ISO, 2014). Nevertheless, the approach and focus areas vary between the

*Table 3.1: Example of a link and effect (L&E) model. Adapted from Åhrén (2008).*

| L&E model CSA | CSF | KRA | KPI examples |
|---|---|---|---|
| ROMI | Budget deviation | Permanent way, catenary/power supply, signalling/telecom, and other objects | Budget deviation from permanent way, catenary/power supply, signalling/telecom, and other objects |
| | Overall railway infrastructure effectiveness (ORIE) | Infrastructure availability, infrastructure performance, and infrastructure quality | Availability rate, performance rate, and quality rate |
| HSE | Health index | Reported 3rd party disturbances due to maintenance activities | Amount of reported disturbances due to noise, vibrations, platform lights, platform snow removal, and fallen tree protection programme |
| Railway Infrastructure Integrity (RII) | Infrastructure quality index | Permanent way | Level of track quality, urgent inspection remarks, Q-factor, and amount of defect sleepers |
| Processes | Internal process index | Information and analysis | Share of IT-system availability, confidence, and usefulness |
| Competences | Strategic competence provision index | IM organization | Strategic competence provision index |

models, and an individual model is not effective for every organisation. Consequently, hybrid models have been developed (Bhuiyan and Baghel, 2005). With reference to the challenges of implementation (Section 3.1.1), successful implementation depends on organisations' experience and the complexity of the model to be implemented. From Section 3.1.1, we can also conclude that keeping the implementation issues in mind and following a structured approach are more important than the choice of model.

Given the need to measure operation and maintenance performance of rail infrastructure, along with the lack of such models for railways and known implementation issues, RQ 1 adopts the concept of continuous improvement and the link and effect model, focusing on implementation issues and strategic planning. Paper A answers RQ 1.

## 3.2 Data aggregation in rail transportation

Data aggregation is needed since humans have limited perception and capability to process information. Parida (2006a) found data aggregation to be a critical issue in organisations, along with data islands and data overload. The aim of data aggregation and RQ 3 is to reduce the number of indicators with minimum loss of information. Besides, aggregation facilitates comparison of performance.

Data aggregation can be described as combination of measurements (data). Combinations can be of data with the same unit or with different units. It can be as an individual indicator over a group of items, e.g. failures and train delays, or as a combination of several indicators, forming an index, e.g. overall equipment effectiveness (OEE). A type of index is composite indicators (CIs); Saisana and Tarantola (2002) describe a CI as: a mathematical combination (or aggregation) of a set of individual indicators with no common meaningful unit of measurement and no obvious way of weighting them. Another approach is to aggregate using monetary costs.

Availability is an important concept within engineering (Section 2.3), but has not been scientifically applied in the operation and maintenance of rail infrastructure. Hence, operational availability is studied in RQ 3. Data aggregation is further examined through composite indicators, as a method for combining individual indicators. Lastly, maintenance cost have been used as a means to data aggregation.

### 3.2.1 Availability

Availability is a function of reliability, maintainability and maintenance supportability; i.e. it depends on how often an item fails, the time it takes to restore the function by carrying out maintenance, and the time it takes for the supporting organisation to react on failures. Therefore, availability measures include critical aspects of both technical and organisational perspectives in a single measure. Availability measures are used in various fields of design, operation and maintenance for measuring and monitoring performance, such as electronics (U.S. Dept of Defense, 1995), electricity generation (IEEE, 2007), mining (Kumar and Klefsjö, 1992) and maintenance (Jardine and Tsang, 2013). It is often considered a key performance indicator (CEN, 2007, SMRP, 2011), and is used in calculation of overall equipment effectiveness (OEE).

In railways, the European Standards EN 50126 (CEN, 1999) gives guidelines for RAMS (reliability, availability, maintainability and safety) specification. The standard defines availability in accordance with other standards. However, as the standard concerns RAMS specification, monitoring performance during operation is only mentioned briefly. Patra and Kumar (2010) develop a Petri net model that can be used for RAMS specification. The model takes failure rates and down times as inputs and gives the availability as an output. Utilising increased availability is a main goal of timetabling, punctuality and delay time modelling (Huisman et al., 2005, Vromans et al., 2006, Wang et al., 2011). Similarly, reliability modelling (Carretero et al., 2003, MacChi et al., 2012) and maintenance (Zoeteman, 2006, 2001) aim at increased availability.

For monitoring of availability during operation and maintenance, Mahmood et al. (2013) studied reliability, availability and maintainability of frequency converters in railways using the IEEE Std 762 (IEEE, 2007). The data stretched over four years and cover 46 frequency converter stations.

For availability of rail infrastructure and train operation, Nyström (2009) reviewed indicators related to availability. Examples of indicators reviewed are measures of punctuality, track condition and disabled state (down state). Nyström further constructed two measures to be used as measures of availability in rail infrastructure: obtained capacity

/ planned capacity, and 1 - slack time / total travel time. Availability of rail infrastructure has been studied in the INNOTRACK project; a part of EU's Sixth Framework Programme. Indicators related to the availability of railway infrastructure include: train delay, obtained capacity divided by the planned capacity, up time and down time, and arrival punctuality (INNOTRACK, 2009, 2010). In addition, the definition of availability in railways needs to be sorted out if it is a function of capacity utilisation, along with what data are required and how it relates to train delays (INNOTRACK, 2009). Further, availability is defined differently between IMs. For RAMS analysis, availability should be studied for the system/track to understand the extent to which it is available for operation. This for example can give a guarantee of track availability without traffic interruptions (INNOTRACK, 2010). For this, Söderholm and Norrbin (2014a) used the share of successful train passages as a measure of availability.

As the studies above suggest, monitoring availability in the operation and maintenance phase of rail infrastructure needs to be studied further to comply with common practice. Thus, the aim of Paper C is to apply availability to the operation and maintenance of rail infrastructure.

### 3.2.2 Composite indicators

Composite indicators are used for aggregating data, thereby simplify monitoring, and for internal and external comparisons.

Comparison of individual indicators in rail transport is common (UIC, 2012, Åhrén and Parida, 2009a, IMPROVERAIL, 2001, SuperGreen, 2010, UTBI, 2004). As an example, UIC railway statistics (UIC, 2012) give indicators of train-km, passenger-km, tonnes-km, punctuality, cost, energy, etc., for various countries. However, composite indicators (CIs), often called indices, are not common in railways.

In a study of rail infrastructure condition, Uzarski et al. (1993) suggested condition indices for: rail, joints and fastenings; ties; and ballast, subgrade and sideway components. These indices are primarily based on visual inspection surveys using scoresheets, and are combined to create an overall track structure condition index (TSCI).

Åhrén and Parida (2009b) proposed an overall railway infrastructure effectiveness (ORIE), a CI that resembles overall equipment effectiveness (OEE). OEE is the product of availability (uptime), performance (production speed), and quality (product quality). Another such indicator is the overall factory vibration level (Galar et al., 2012). However, classifying these indicators as CIs depends on how a CI is defined. Saisana and Tarantola (2002) describe a CI as: a mathematical combination (or aggregation) of a set of individual indicators with no common meaningful unit of measurement and no obvious way of weighting them. OEE and vibration based indices would then be more of aggregated data.

Using the description of a CI by Saisana and Tarantola, data envelopment analysis (DEA) comes under CIs, but as a special form due to relative weights and a specific method. DEA is a non-parametric statistical method for evaluating the productive efficiency of a set of peer entities called decision-making units (DMUs), which convert multiple inputs into multiple outputs (Cooper et al., 2011, Seiford, 1990). A major difference of DEA from other performance comparison techniques is that relative weights are used in this method, thus, the most favourable weights for each unit subject to other units are calculated, making comparison possible. George and Rangaraj (2008) applied DEA to Indian railway zones to compare their performance, using the following inputs: operating expenses, tractive effort (total horse power consumed by locomotives), equated track kilometres (total km of track), number of employees, number of passenger carriages and number of wagons. Passenger kilometres and ton kilometres are used as outputs. Similar studies have been carried out on the North American freight railroads (Malhotra et al., 2009), on the London Underground (Costa and Markellos, 1997) and on data from the Urban Public Transport Statistics (Graham, 2008).

Regarding CIs at a general level, Bandura (2008) reviewed some well-known composite indicators and found 178 CIs, e.g. by the World Bank, European Commission, UNESCO and OECD, measuring, for example, education, science, technology, economy, sustainability and peace. Studying some of these CIs, it reveals that each CI is more or less unique. However, the general method for construction of CIs has been described by Freudenberg (2003), Jacobs et al. (2004) and OECD & JRC - EC (2008), which is applied in the appended Paper D.

### 3.2.3 Maintenance cost

The balance between preventive and corrective maintenance (PM and CM) within an organisation depends on a number of factors: cost of down time, redundancy and items' reliability characteristics. Consequently, the balance between PM and CM for minimising costs varies between organisations and assets.

Finding the ratio of PM to CM in an organisation or system is complicated as there are numerous influencing factors. Firstly, it needs to be clear what activities belong to PM or CM. Secondly, the resources spent on each activity need to be registered, which includes data quality issues (Davenport et al., 2001, Karim et al., 2009). Thirdly, some cost objects are hard to estimate, especially indirect and outsourcing costs. Consequently, there are few studies on the shares of PM and CM costs.

While studies on PM to CM costs are lacking, a common rule of thumb for evaluating performance says we should aim for a PM to CM share of 80/20 in general (Wireman, 2003), i.e. following the Pareto principle. However, such rules of thumb may not be useful if proposed by a person outside the organisation in question. On the other hand, there are numerous studies of maintenance optimisation models and maintenance cost models; see reviews by Dekker (1996), Garg and Deshmukh (2006), and Sinkkonen et al. (2013). Dekker (1996) noted a gap between theory and practice in maintenance optimisation modelling, likely because of the mathematical purpose and stochastic nature of many models, and the traditional focus on deterministic approaches in mechanical engineering. In addition, few companies are interested in publishing. Garg and Deshmukh (2006) and Sinkkonen et al. (2013) made similar observations; maintenance optimisation models and cost models applications are limited.

Some studies on industrial equipment have presented case studies with the aim of optimising PM and CM costs (Charles et al., 2003, Khalil et al., 2009). These considered single machineries and details were left out for demonstration purposes.

However, studies on the total maintenance cost in relation to production are available. For example, Mobley (1990) states that maintenance costs can represent 15-60 % of the cost of goods produced, depending on the specific industry. Coetzee (1997) states that 15-50 % of the total cost of production is spent on the maintenance of equipment, while Bevilacqua and Braglia (2000) state that maintenance department costs can represent from 15-70 % of total production costs. Meddaoui and Bouami (2013) analysed data from a company whose maintenance expenses represent 45 % of their total expenses. However, information is left out in these studies since their aims were not to quantitatively find the cost of maintenance in comparison to production.

For infrastructure, the total cost of maintenance has been considered. For example, OECD (2006) estimated road infrastructure will need a global investment of USD 220-290 billion/year from 2010-30 (maintenance and net additions). For rail infrastructure, the estimate is USD 49-58 billion/year. Annual investment for road, rail, telecoms, electricity (transmission and distribution) and water is estimated to account, on average, for about 2.5 % of world gross domestic product (GDP); it sum up to USD 37 trillion from 2010-30. In the US, ASCE (2011) found that to resolve existing deficiencies in highways, bridges and transit, USD 74 billion was needed in 2010. If present trends continue, the funding gap will be USD 3.6 trillion (55 % unfunded) in 2040. Deteriorating conditions are estimated likely to impose cumulative costs on American households and businesses of USD 2.9 trillion by 2040.

Concerning life cycle costing (LCC) in infrastructure, extensive work has carried out, including costs and benefits to society, owners, users and the environment (Thoft-Christensen, 2012). Studies have considered investments, reinvestments, related induced user costs, and maintenance work. Many models take a stochastic approach, with some practical applications available (Thoft-Christensen, 2012).

In Paper E, we focus solely on comparing PM and CM, taking a deterministic approach and using historical maintenance data. A similar approach to the analysis of historical maintenance data was used by Nissen (2009b). Nissen constructed a life cycle cost (LCC) model for switches and crossings (S&Cs) and carried out a case study. The model includes cost of acquisition, PM, CM and reinvestments. The PM consist of track recording car inspections, rectification of inspection remarks, ballast tamping and rail grinding. Details on the cost of PM relative to CM are not discussed, but from the figures given, CM is about 10 % of the maintenance cost when cost of acquisition is disregarded. Patra et al. (2009) suggested a similar model for railway tracks and used a case study over the life of rails. Maintenance costs where treated as labour costs.

In conclusion, some work has been done on the maintenance cost of rail infrastructure. The focus of these studies have been over the life length of S&Cs and rails. The share of PM and CM, and the benefit of PM have not been studied. Therefore, RQ 3 addresses this issue; see appended Paper E.

# Chapter 4

# Research methodology

Scientific research, also known as scientific inquiry, scientific method, or simply research, comprise creative work undertaken on a systematic basis to increase the stock of knowledge, including knowledge of man, culture and society, and the use of this stock of knowledge to devise new applications (OECD, 2002). Research, in its simplest form, can consist of three steps (Creswell, 2011):

1. Posing a question
2. Collecting data to answer the question
3. Presenting an answer to the question

Research is often misrepresented as a fixed sequence of steps; rather, it is a highly variable and creative process (AAAS, 2001). The choice of steps in research can therefore vary between subjects and researchers. For further discussion, see for example Hugh (2002).

## 4.1 Research design

The research in this thesis takes the following steps, using deductive reasoning, i.e. moving from general to specific:

1. Background: identifying the research problem, using a literature review in the subject area to identify gaps in the knowledge
2. Problem statement: presenting the problem and possible solution, as postulated by this study
3. Purpose statement: presenting the overall goal of the study
4. Research questions: specifying the purpose

5. Scope and limitations: specifying what is to be studied

6. Collecting data: both quantitative and qualitative data are collected for analysis, including case studies

7. Analysis of data: transforming data into information

8. Discussion and conclusions: deduced from the information

An alternative research design is to use hypotheses. Research questions and hypotheses are similar in that both narrow the purpose statement (Creswell, 2008). However, hypotheses are predictive, proposed explanations subject to testing.

Research steps 1-5 have been reviewed in Chapter 1. Step 6: 'Collection data', included a literature review, interviews and infrastructure manager's operation & maintenance databases. The literature review and interviews were used to build a foundation for the further work and to answer RQ 2, resulting in a technical report (ISBN 978-91-7439-460-3) and Paper B. The link and effect model described in Paper A, responding to RQ 1, was developed after further literature study and collection of historical rail operation and maintenance data. The process was repeated for RQ 3 and Papers C-E. Matlab software was used for the data analysis and case studies in Papers A and C-E. Microsoft Excel and Minitab software were used to verify the algorithms written in Matlab. MaxDEA software was also used in Paper D.

## 4.2 Data collection

Data were collected from a literature review, interviews and railway operation and maintenance historical data.

### 4.2.1 Interviews and information from experts

In the early phase of the project, 14 people at the Swedish infrastructure manager (IM) Trafikverket (Swedish Transport Administration), were interviewed to explore and map the Swedish rail infrastructure maintenance system. The interviews were carried out in person using open-ended questions, allowing freedom for both the interviewer and the interviewee in terms of asking supplementary questions (interviewer) and responding more freely (interviewee). The interviews complemented the literature study, as it related to Trafikverket and the rail network in Sweden. The questions included the following:

- Can you tell me about the strategic planning process, e.g. break down of goals to operational objectives?

- Can you tell me about the planning of maintenance of the rail infrastructure?

- Is there any documentation related to the strategic planning and planning of maintenance, e.g. policies, handbooks, strategies?
- How is railway infrastructure performance measured?
- What performance indicators are used?
- Can you tell me about the outsourcing of maintenance?

See Table 4.1 for interviewees' positions at Trafikverket. In addition to interviews, meetings with concerned personnel from Trafikverket took place to discuss the progress, clarifying issues and future directions.

*Table 4.1: Interview respondents at Trafikverket. The asterisk indicates the new organisational structure.*

| Interviewee | Position | Section | Unit | Division | Department |
|---|---|---|---|---|---|
| 1 | Head | | | Tactical planning | Operation |
| 2 | Supervisor | Assets | Operation - North | Railways | Operation |
| 3 | Head | Staff support function | Maintenance | Railways | Operation |
| 4-9 (6 persons) | Analyst, business | | Analysis | Tactical planning | Operation |
| 10 | Quality controller | Staff support function | Operation - Mid | Railways | Operation |
| 11 | Head | | Analysis | Tactical planning | Operation |
| 12 | Analyst, track | Rail systems | Railways and roads | Technology | Operation |
| 13 | Analyst, contracting | | Staff support function | Procurement | Operation |
| 14 | National research coordinator | | Development | Infrastructure development | Maintenance* |

### 4.2.2 Literature review

For the references used; see the appended papers, related technical reports and Chapters 2 and 3 of this thesis. The following types of literature related to operation, maintenance and performance of railways have been reviewed:

- Railway peer review journal and conference papers
- Maintenance engineering, performance measurement and strategy peer review journal and conference papers
- European Union project reports, such as the Framework Programmes
- European White Papers on transport
- Swedish and European legislations
- Published books
- Documents of the Swedish IM, e.g. handbooks, policies and standards
- International, European and Swedish standards
- Consultancy reports

### 4.2.3 Collection of operation and maintenance data

Rail infrastructure operation and maintenance historical data have been collected from Trafikverket. The data include seven railway lines in Sweden, which come to about 3 400 km of track and 4 000 switches & crossings (S&Cs), see Figure 4.1. The data includes all rail infrastructure systems, i.e. substructure, superstructure, electrification, signalling, information and communication technology (ICT) and rail yards.

The data consist of preventive maintenance (PM), corrective maintenance (CM), train delays and asset structure data. The PM data includes inspections data and rectification of inspection remarks data. The CM data, also known as failure data, consist of urgent inspection remarks reported by the maintenance contractor, as well as failure events and failure symptoms identified outside the inspections, commonly reported by train drivers, but occasionally reported by the public. The train delay data, in turn, is the trains' deviation in minutes from the time table at a given point, recorded through the track circuits and signalling systems (Söderholm and Norrbin, 2014b). For details, see appended Papers A and C-E, and especially Appendix A of Paper E for summary statistics.

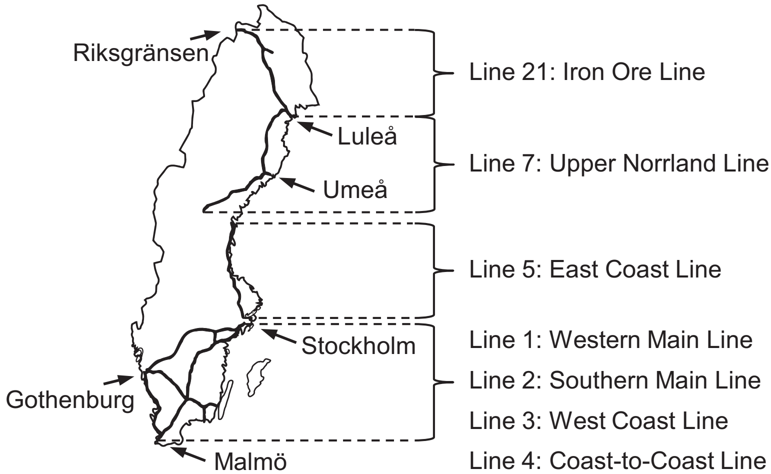


*Figure 4.1: Railway lines 1-5, 7 and 21 of the Swedish network.*

## 4.3 Analysis of operation and maintenance data

Operation and maintenance data were collected from four databases of Trafikverket, corresponding to the PM, CM, train delays and asset structure. A key concern for analysis is the quality of data; high-quality data are commonly defined as data that are appropriate for use (Strong et al., 1997, Wang and Strong, 1996). Issues that were encountered in the data analysis are:

- Highly skewed distribution of train delays due to extraordinary events/failures
- Highly skewed distribution and unrealistic low values of logistic and repair time of CM data
- Length of railway sections registered in the asset structure database not conforming with asset structure documents
- Change of database affecting the registration of train delay data
- Data not specifying the subsystem or component under CM and PM
- Missing data

These issues were met by: considering a certain percentage of train delays as outliers; limiting allowed logistic and repair times to certain values; applying the log-normal mean and/or median to logistic and repair times; separating the data analysis before and after the change of database at the end of 2009; comparing track lengths of database with documents and geographical maps; avoiding analysis where subsystems and components data were lacking; and excluding missing data. Further details for each analysis are found in Papers A and C-E.

As previously mentioned, algorithms for data analysis were written in Matlab software and verified through spot checks in input spreadsheets, Microsoft Excel and Minitab. Some spot checks where carried out using manual calculations. The results of analysis were verified through comparison with properties and utilisation of the railway lines and sections under analysis. Results were also compared with alternative analysis methods; the availability indicator in Paper C was compared to train delays, and the composite indicator in Paper D was compared with data envelopment analysis (DEA). Results were also compared to previous published research as well (Paper E).

As an example of the input data, a simple data quality check of CM data is shown in Figure 4.2. Each work order consists of 71 fields. Fields with 100 % usage means that all work orders have some text or numbers filled in. Therefore, a data field with low usage can mean that the data quality is low, or it may just not be applicable for every work order. The data are from railway section 111, between 2001-2010, and consist of 7 476 work orders.

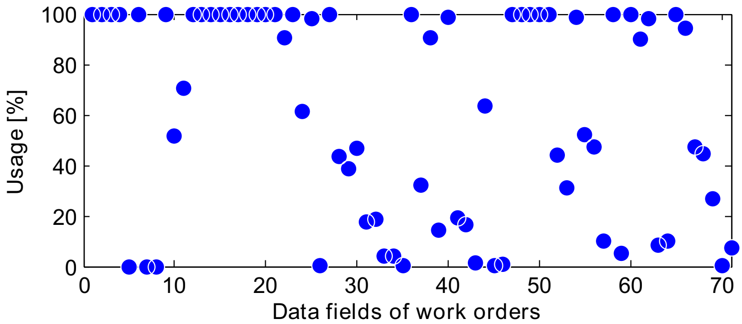


*Figure 4.2: Usage of work order fields. 34 fields are used in over 90 % of the work orders.*

An example of an algorithm is shown in Figure 4.3. The flowchart shows how train delays and failure work orders are integrated.

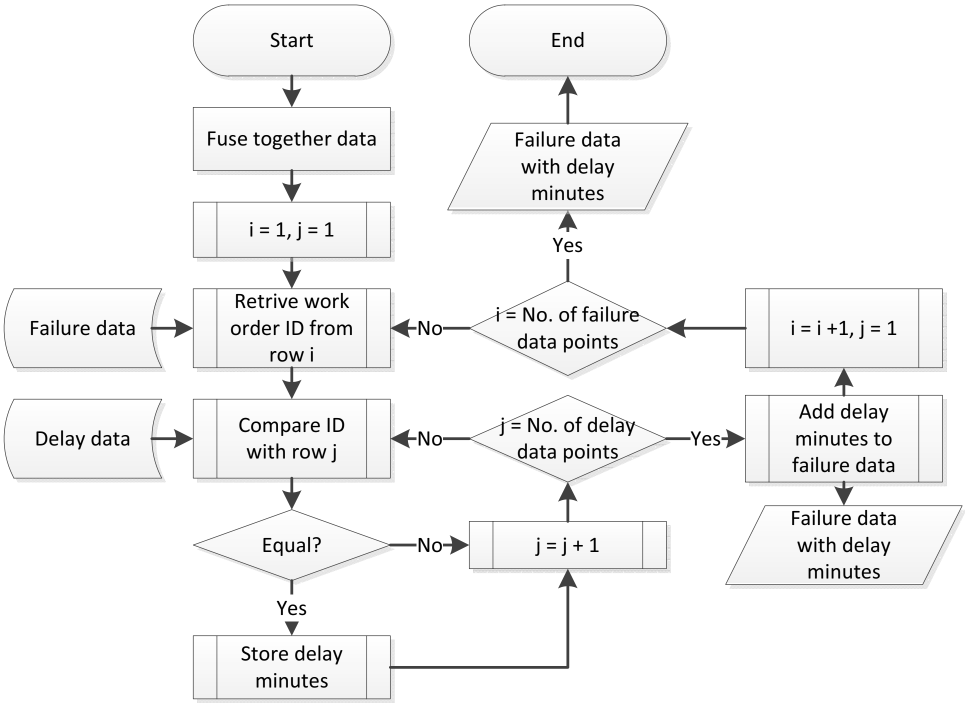


*Figure 4.3: Flowchart of the integration of data algorithm.*

# Chapter 5

# Summary of the appended papers

## 5.1 Paper A

**Title** – Link and effect model for performance improvement of railway infrastructure

**Purpose** – To develop a model for monitoring and analysis of operation and maintenance performance of rail infrastructure.

**Methodology** – With increasing competition, internationalisation, and legislation on health, safety and environment, financial data have been shown to be insufficient for assessing business performance. Accordingly, new performance measurement models and scorecards have been developed that consider non-financial data. This subject was reviewed for best practice, followed by construction of a model, called link and effect model, for developing performance measurements systems. The model is verified in a case study, linking European Union transport goals to operational performance. An index of operational risk was also developed using consequence-probability matrices.

The case study was carried out on data from railway section 111 of the Iron Ore Line in Sweden. The data consists of train delays and infrastructure corrective maintenance work orders (i.e. failures) between 2001.01.01-2009.12.01.

**Findings** – Previous studies have shown that performance measurement initiatives often fails in practice, e.g. due to time and cost constraints. The paper finds that performance measurement initiatives need to be dynamic/versatile. Further, it was found that components of strategic planning are used differently between organisations, which makes it hard to link stakeholders' requirements to strategic, tactical and operational planning, e.g. linking EU transport goals to IMs and measures in railway track. Another issue is indicators traceability; merely following an indicator such as train delay does not indicate where the delay comes from and where to improve. In addition, improvement initiatives need to be understood by all stakeholders, regardless of organisational levels, both internally and externally. Given these findings, the link and effect model was constructed as a four step continuous improvement (kaizen) process, with focus on the components of strategic planning, traceability, ease of use and the underlying factors of indicators; see Figure 5.1.

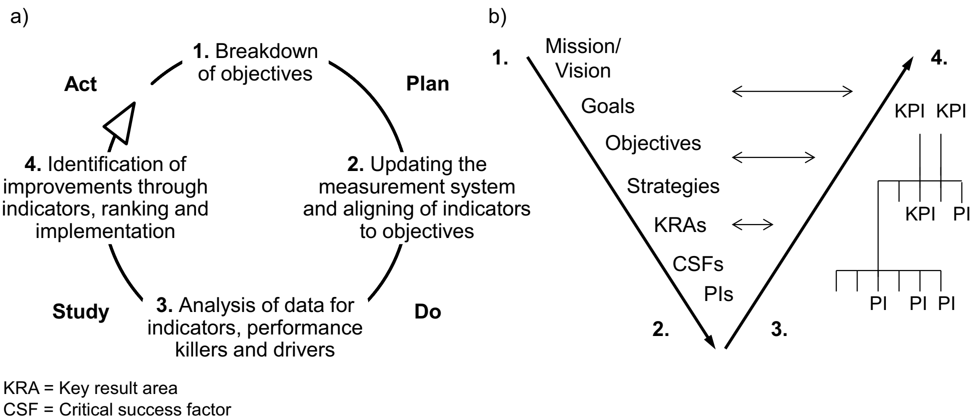


*Figure 5.1: The link and effect model based on (a) a four-step continuous improvement process and (b) a top-down and bottom-up process. The numbers in (b) represents the steps in (a).*

In the case study and the rail infrastructure studied, poor performing systems were found to be the track and switches & crossings. The subsystems responsible for the poor performance were found to be switch motors, switch controls, switch point blade connectors, switch point drives, as well as track rails and joints.

Furthermore, it was found that consequence-probability matrices can be used to visualise performance and rank systems as a function of failure frequency and train delay.

**Practical implications** – The construction of the performance improvement model as a four steps process with a focus on traceability and usability should simplify and make effective both the implementation and use of performance measurement. The case study demonstrates how performance measurement models can be applied to rail infrastructure operation and maintenance data in practice, which is believed to be of interest to infrastructure managers as such case studies are lacking.

**Originality/value** – The link and effect model developed extends the work on models for measuring performance of rail infrastructure, as it demonstrates how such models can be applied to rail infrastructure and operation and maintenance data. In the case study, the EU's vision of a sustainable transport system is linked to the performance of specific components in the railway track, through application of technical standards. It also includes and stress common implementation issues that should be considered at an early phase. This is considered to be significant practical implications of the work.

## 5.2 Paper B

**Title** – Performance indicators of railway infrastructure

**Purpose** – To map and group indicators of rail infrastructure and to compare them with the indicators of European Standards EN 15341: Maintenance Key Performance Indicators, EN 15341 (CEN, 2007).

**Methodology** – Performance indicators (PIs) were identified by reviewing research papers, European railway project reports and documents of the Swedish infrastructure manager (IM), Trafikverket, e.g. policy documents and handbooks. The PIs are categorised into a scorecard according to European Standards EN 15341 (CEN, 2007), and the infrastructure asset structure of Trafikverket.

**Findings** – About 120 indicators were identified and mapped; similar indicators are treated as the same, but some indicators are found twice, e.g at system and component level. Figure 5.2 shows the structuring of the indicators, following EN 15341 and the asset structure of Trafikverket. Eleven key performance indicators (KPIs) of EN 15341 are found to be similar to the identified railway indicators.

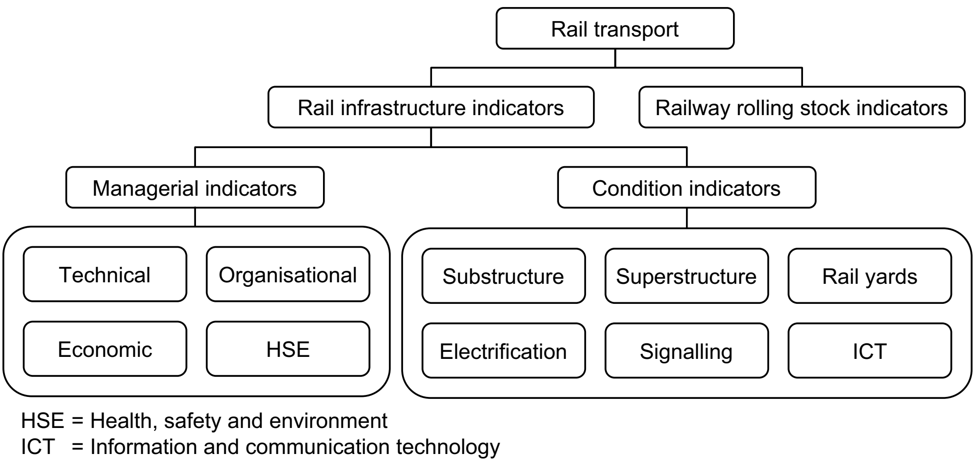


*Figure 5.2: Structure of the rail infrastructure indicators.*

**Practical implications** – IMs use performance measurement to study whether results are in line with set objectives, for predicting maintenance need and for comparison purposes. The identified indicators can therefore be used by IMs for reviewing and improving their performance measurement system. The work also provides a background for possible future standardisation of railway indicators. However, harmonising between IMs for comparison is a challenge, since the operational and geographical conditions vary extensively.

**Social implications** – As IMs improve their use of operation and maintenance data and monitoring of rail infrastructure, resources can be used more effectively, and the rail capacity and reliability can increase. Consequently, more traffic can shift from road to rail, emissions are reduced and government expenditure on transport is made more effective.

**Originality/value** – The presented study gives a thorough mapping of rail infrastructure indicators.

## 5.3 Paper C

**Title** – Measuring and monitoring operational availability of rail infrastructure

**Purpose** – To measure operational availability of rail infrastructure using technical standards.

**Methodology** – Availability depends on the combined aspects of reliability, maintainability and maintenance supportability. Operational availability ($A_O$) includes corrective maintenance time, preventive maintenance time and maintenance support delay, i.e. it is the real availability under given operation environment and maintenance support. However, we do not include preventive maintenance in the calculation of $A_O$ as it does not affect train operation in normal circumstances. Therefore, $A_O$ is estimated based on the time to restoration (TTR) of failures in the rail infrastructure.

TTRs are typed in by train dispatchers and by the maintenance support, and thus, they present only approximate values. Moreover, the TTRs are highly skewed due to certain extraordinary events, like tear down of contact wire. Therefore, the log-normal mean and median are applied to the TTRs.

All failures will not affect the trains since railways are operated irregularly. Hence, including the down time (i.e. the TTR) from all failures will give the availability experienced by the IM, while only including train-delaying failures will give the availability experienced by train operators, freight and passengers. The former measure is the $A_O$, while we call the latter measure service affecting availability ($A_{SA}$).

There is also a probability of faults taking place simultaneously depending on the length of the railway section under consideration (Figure 5.3); this needs to be taken into account.

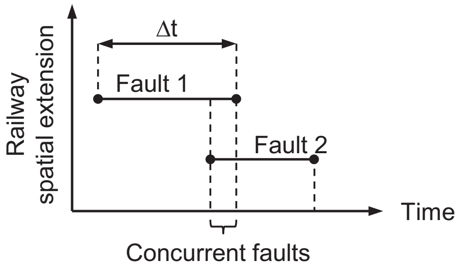


*Figure 5.3: Sketch of concurrent failures.*

Data come from seven railway lines in Sweden. The lines connect the three largest cities of Sweden; Stockholm, Gothenburg and Malmö, as well as the iron ore line in the north of Sweden. The collected failure data are between 2013-14, i.e. one year. Reported number of failures is 24 816, with 25 % of the failures resulting in train delays.

In conclusion, $A_O$ and $A_{SA}$ equals $^{Uptime}/_{Uptime + Downtime}$, where the down time is the sum of the log-normal or median TTR of failures, counting concurrent faults once.

**Findings** – The resulting availability measure gives a higher correlation with train delays ($R^2 = 0{,}94$) than failures with train delays ($R^2 = 0{,}73$); see Figure 5.4. The result is reasonable since availability is a function of reliability, maintainability and maintenance supportability, i.e. it includes failures, repair time and logistic delay. Furthermore, the case study shows it is preferable to use the median or log-normal of the maintenance time data for calculating availability, as it yields better results than using the registered TTRs.

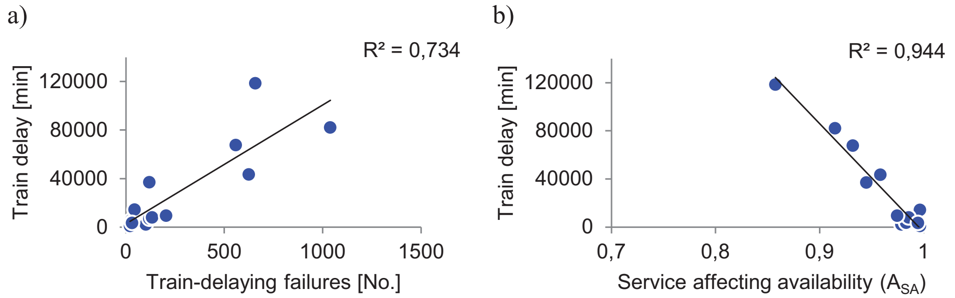


*Figure 5.4: Comparison of correlation of failures and availability with train delays. The data points corresponds to different systems, such as track and switches & crossings.*

**Practical implications** – Availability is a better indicator than the individual indicators: failure frequency, logistic time and repair time, in the sense that it is a measure of all three indicators; i.e. it includes both technical and organisational aspects. An indicator that gives the percentage of time a system has been operational may also be more intuitively appealing, or less abstract than a figure telling that a system has failed $x$ times.

**Social implications** – Indicators that are easy to interpret and reflect upon can be of public interest. In contrast, the significance of, for example, $x$ train-delay minutes can be hard for a layman to interpret.

**Originality/value** – This study has scientifically applied the concept of operational availability to rail infrastructure.

## 5.4 Paper D

**Title** – Development of an integrity index for monitoring rail infrastructure

**Purpose** – To develop a method for monitoring and comparing rail infrastructure using composite indicators.

**Methodology** – Rail transport requires comprehensive monitoring due to its complexity, and since humans have a limited perception and capability to process information, the number of indicators that one person can monitor is limited. Consequently, identification of the most important indicators and data aggregation is needed. Composite indicators (CIs) can simplify the performance measurement by summarising the overall performance of a complex asset into a single number; which is easier for decision-makers to interpret than multiple indicators and plots.

A CI, called rail infrastructure integrity index, is constructed based on: failure frequency, train delays, logistic time, and active repair time. Broadly speaking, the method applied follows OECD & JRC - EC (2008):

1. Theoretical framework
2. Data selection
3. Imputation of missing data
4. Multivariate analysis
5. Normalisation
6. Weighting and aggregation
7. Uncertainty and sensitivity analysis

8. Back to data
9. Links to other indicators
10. Visualisation of results

Data come from seven railway lines in Sweden. The lines connect the three largest cities of Sweden; Stockholm, Gothenburg and Malmö, as well as the iron ore line in the north of Sweden. The collected failure data are between 2010-14, i.e. four years. Reported number of failures is 97 105, with 22 % of the failures resulting in train delays.

The method includes study of: correlation and variance; three normalisation procedures; four weighting procedures; and geometric and additive aggregation.

The CI results were also compared to data envelopment analysis (DEA). In DEA, efficiency is defined as $\eta = {}^{Output}/_{Input}$. Inputs are the logistic time and repair time (resources), while the output is train delay caused by switches & crossings (S&Cs) per S&Cs and train delay caused by remaining systems per track-km. Since less train delay means higher output, the train delay is normalised and inverted, i.e. $1 - I_{qi}$, where $q$ is either delay per S&Cs or per track-km.

**Findings** – Depending on the normalisation, weighting and aggregation techniques chosen, the resulting CI will change, often slightly but sometimes extensively. Therefore, when CIs are being implemented into an IM's computerised maintenance management system (CMMS), it is useful to let data users study sensitivity by choosing factors within the graphical user interface (GUI). The same is true for decomposing a CI; the GUI of a CMMS implementation should let data users decompose the indicator for root cause analysis.

The correlation matrix shows a high correlation between failures and train delay ($R^2 = 0.87$). In addition, pairwise comparison following expert opinion leads to a low weight on failures and a higher weight on train delays. Therefore, the individual indicator of failures can be neglected in the construction of a rail infrastructure integrity index.

Comparing the CI result with DEA showed a high correlation ($R^2 = 0.80$), indicating that both methods for comparing performance give similar results; see Figure 5.5.

In the case study results, railway lines 1 and 3 have the best CI result, while line 21 lags behind the other lines. Given the Arctic climate and higher axle load of line 21 (Iron Ore Line), results are sound. In addition, lines 1 and 3 have a higher safety inspection classification, as they have higher train speed limits. Finally, lines 1 and 3 are double track railways, making them less sensitive to failures than line 21 which is a single track line.

**Practical implications** – Composite indicators, also known as indices, are widely used as tools for comparing performance, e.g. by the World Bank, European Commission, UNESCO and OECD, measuring, for example, education, science, technology, economy, sustainability and peace. Thus, IMs can use CIs as a method for comparing performance within railways.

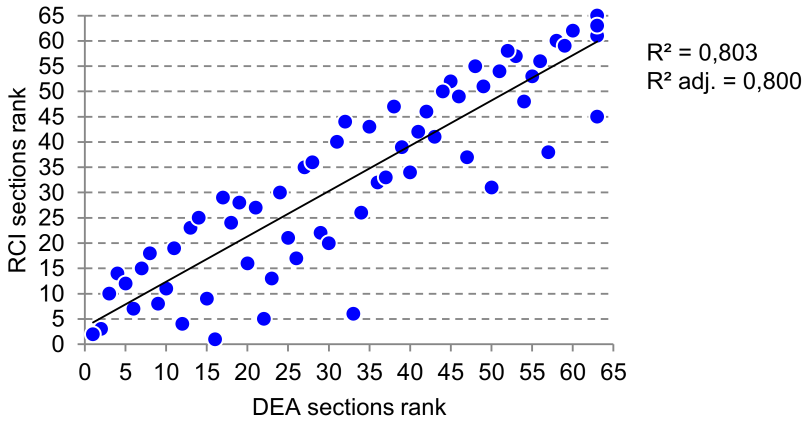


*Figure 5.5: Comparison of RCI and DEA results.*

**Originality/value** – The application to rail infrastructure, using common procedure for construction of CIs, is believed to be new.

## 5.5 Paper E

**Title** – Preventive and corrective maintenance: cost comparison and cost-benefit analysis

**Purpose** – To compare preventive and corrective maintenance (PM and CM) costs of rail infrastructure.

**Methodology** – Formulations for estimation of maintenance costs are set up including: frequencies of failures, inspections and inspection remarks; logistic and repair times; resources; and costs.

PM and CM data come from seven railway lines in Sweden, consisting of 65 sections. The lines connect the three largest cities of Sweden; Stockholm, Gothenburg and Malmö, as well as the iron ore line in the north of Sweden. The failure data are of 2013-14, i.e. one year. Reported number of failures is 24 816, inspections equal 352 679, inspection remarks equal 52 854 and the rectified inspection remarks equal 28 704.

PM and CM costs of the 65 railway section were compared by fixating relevant constants, such as the cost of train delay. For comparing the 65 railway sections, estimated maintenance costs were normalised according to switches and crossings (S&Cs) and track length.

The benefit of PM was estimated by setting up a benefit-cost ratio as $B/C = {}^{Benefit\ of\ PM}/_{Cost\ of\ PM}$. Cost of PM equals the costs of inspections and rectification of inspections remarks, while the benefit of PM equals cost saved by avoiding failures.

**Findings** – In the case study, PM costs represent about 10-30 % of the total maintenance cost, including cost of train delay (Figure 5.6). If the cost of train delays is disregarded, PM stands for about 30-50 % of the maintenance cost. The study indicates that the railway sections with the lowest total maintenance cost have the highest share of preventive maintenance (Figure 5.6). Furthermore, the railway sections with the highest maintenance cost carried twice the number of trains and transported three times the tonnage compared to the least costly railway sections.

The benefit-cost ratio of PM was estimated at 3.3. This is highly dependent on the input data, especially the cost of train delay. The train delay cost represented about 60 % of the CM cost. Consequently, the feasibility of maintenance investment and component replacement projects is highly dependent on the cost of train-delays.

The resulting costs of maintenance were also compared to transported tonnage. However, the correlation between maintenance costs and transported tonnage was at the same level as the correlation between failure frequency and transported tonnage, i.e. not high.

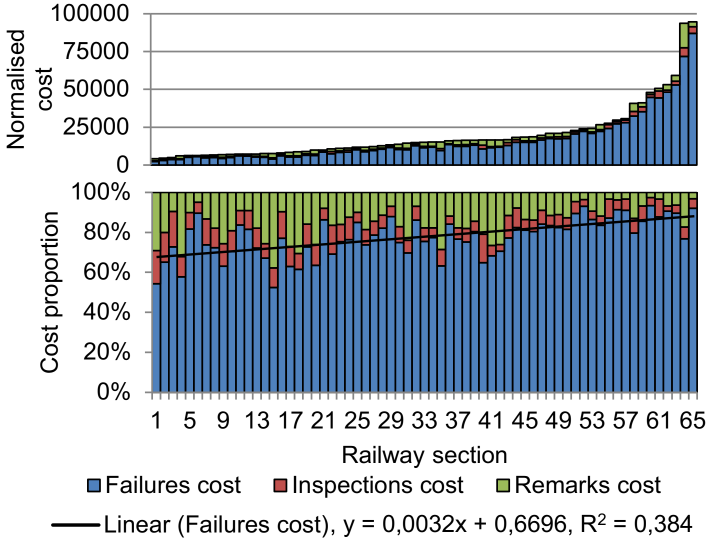


*Figure 5.6: Normalised maintenance cost and cost proportion of the 65 railway sections.*

**Practical implications** – The method makes it possible for IMs' to estimate their PM to CM ratio, comparing their railways, and to calculate the benefit of PM, besides using it for maintenance strategy formulation. However, as the cost of train delay influences the result to a large extent, the discussion of the cost of train delays may be expanded.

**Social implications** – If it is possible to show the benefit of PM in figures, the public's acceptance of reactive maintenance in a railway line widely known to induce high train delay costs can decrease.

**Originality/value** – Studies on the ratio between PM and CM, as well as the benefit of PM are lacking. This article looks into these aspects.

# Chapter 6

# Results and discussion

## 6.1 First research question

**RQ 1:** How can operation and maintenance of rail infrastructure be improved through a performance measurement model?

RQ 1 is answered in Paper A, with the purpose to develop a link and effect model for monitoring and analysis of operation and maintenance performance of rail infrastructure. The model was constructed as a four step continuous improvement process, with a focus on the components of strategic planning, traceability, ease of use and the underlying factors of indicators (Figure 5.1). There are many other models for performance measurement similar to the link and effect model, however they do not offer it from a railway perspective. In railways, International Union of Railways (UIC) has given out asset management guidelines (UIC, 2010), as a seven-step procedure based on British Standards Institute's PAS 55 (BSI, 2008), the International Infrastructure Management Manual (IIMM) from New Zealand (INGENIUM and NAMS, 2006) and the Asset Management Overview by the U.S. Federal Highway Administration (FHWA, 2007). PAS 55 has been superseded by ISO 55000 (ISO, 2014). These models, as well as the link and effect model, are based on or includes continuous improvement concept, i.e. kaizen and the plan-do-study-act (PDSA) cycle. While they all represent improvement initiatives, there are differences in their focus and elaboration. The link and effect model is focused more on performance measurement and offers more flexibility as it has fewer steps. Still, the essential components are in place, together with the terminology. It is believed that the flexibility makes implementation easier, as it is more concerned with improving IMs' current practices and processes for measuring performance than replacing them. Actually, a significant step in good practice in measuring performance is likely to structure the data, databases, analysis and indicators already in place (Figure 6.1), which relate to information logistics (Morant et al., 2013). However, it may bring more enjoyment to a small group of people to implement something new rather than improve the existing.

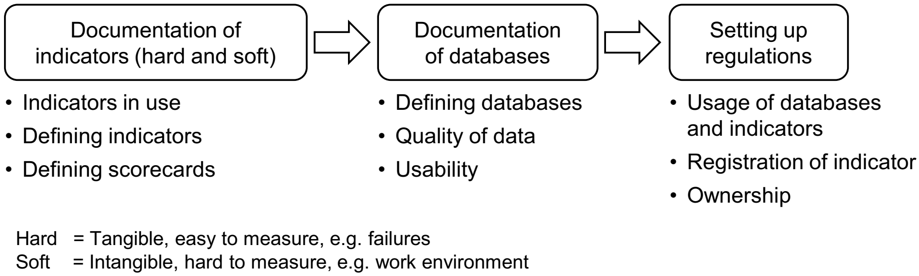


*Figure 6.1: Requirements for measuring performance.*

Nevertheless, the asset management guidelines by UIC (2010) also offers a simplified and concise approach to performance measurement and asset management in railways, together with appropriate terminology. Hence, the difference between UIC's asset management guidelines and the link and effect model is that the link and effect model demonstrates how such models can be applied to rail infrastructure and operation and maintenance data. The model is verified in a case study, linking the EU's vision of a sustainable transport system (EC, 2011) to the operational performance of rail infrastructure items, through application of technical standards. If similar terminology is used (Paper A: Table 1), the components of strategic planning can be extracted from EU's White Paper on transportation (EC, 2011) and linked to maintenance terminology (IEC, 1990, CEN, 1999, 2010). Thus, the method is believed to be reproducible under similar terminology.

The concept of link and effect model is adopted from previous research in industries of oil and gas, mining, hydro power and railway (Section 3.1.2). Compared to these studies, it is mainly the application to real operation and maintenance data that is new in Paper A.

Concerning the case study, consequence-probability matrix, or risk matrix, (ISO/IEC, 2009) has been applied. Failures in terms of corrective maintenance work orders are put on the $y$-axis, and the corresponding total train delay is on the $x$-axis (Paper A: Figure 7). An alternative approach is to divide the train delays with the failures to receive a mean value. As train delays do not have a normal distribution, however, applying the arithmetic mean may not be appropriate. Also, data points associated with many failures are shifted more than data points associated with fewer failures, causing the upper right corner of the first quadrant (the so-called red zone or high risk zone) more or less empty. Consequently, the function of the matrix is disturbed. Finally, if a data user is given the mean train delay, s/he may want to know the total and vice versa.

The risk matrix was used to calculate a risk index using the length of the hypotenuse, i.e. the length of the vector from the origin to the data points. Weighting constants were added since one of the two individual indicators (failures and train delay) can be considered more important than the other. Train delays are often considered more important than failures as the cost of delay can be high. Example figures are £32, €53 and up to €200 per minute (Nissen, 2009a). However, equal weighting was used in the case study; i.e. a high risk index does not tell if it is due to many failures or long train delay. An alternative to using weights is to add cost to failures and delay, to create a cost model. This is addressed in Paper E.

Many other risk assessment technique are available besides risk matrix. ISO/IEC (2009) lists 31 techniques divided into five categories: look-up methods, supporting methods, scenario analysis, function analysis, control assessment and statistical methods. Examples of supporting qualitative methods are brainstorming, interviews and delphi method. Examples of scenario methods are root cause analysis, fault tree analysis, event tree analysis and cause-and-effect analysis. In root cause analysis, losses of function are studied one at a time. Fault tree analysis is commonly used in system design and for major failures in the operation phase. Event tree analysis is used for accident scenarios, often including multiple safeguards. Cause-and-effect analysis, or fishbone diagram, is a qualitative technique for mapping effects' contributory factors. An example of function analysis is failure mode effect analysis (FMEA); a technique for identification of failures modes and their effects. Including criticality analysis; the technique is called FMECA. FMEA gives a list of failure modes, mechanisms and effects. Cause and consequence information is commonly also given. FMECA also gives likelihood of failure (failure rates) and quantitative consequences. FMECA can be used to calculate a criticality index, by taking the product of the likelihood, detectability and consequence, i.e. similar to the index used in the risk matrix method in Paper A. Risk matrix is used in FMECA ISO/IEC (2009). Some examples of statistical methods are Markov analysis, Petri net analysis and Monte Carlo method. Advantages of Markov and Petri net analyses are their ability to calculate probabilities of a system to be in various states, e.g. gives failure probability and availability measures. Monte Carlo method can be used to study output distributions, such as reliability and availability. Drawbacks of these methods include that they can be resource intensive and difficult to communicate to personnel not involved in the analysis. Resource consumption is related to: the need of clear understanding of system transitions and states in Markov and Petri net analyses, and the complexity of large Monte Carlo models. The aim of the case study of Paper A was to link strategic goals to operational performance on system, subsystem and component levels. With failure rates and train-delays as the consequence of failures, risk matrix was considered as an appropriate tool. The risk matrix of Paper A give information on poor performing items. This information can be used as input to other risk assessment techniques, such as brainstorming and root cause analysis.

In the perspective of Trafikverket, they find the work of Paper A interesting as it shows how strategic planning of railways, such as EU's White Paper on transportation (EC, 2011), can be linked to activities on the operational level of railways and to engineering terminology, e.g. RAMS parameters. The risk matrix has also been found interesting as a tool for visualising performance.

## 6.2 Second research question

**RQ 2:** Which indicators are used by infrastructure managers (IMs) and researchers for operation and maintenance of rail infrastructure?

RQ 2 is answered in Paper B, with the purpose to map and group indicators of rail infrastructure and to compare them to EN 15341 (CEN, 2007).

The listed indicators form a basis for constructing a performance measurement system for rail infrastructure. However, the focus has been on the railway track. Some parts of the overhead contact system have been considered, but other systems have not, e.g. bridges, tunnels, and signalling. Rolling stock has also been left out. Studies have shown that the rail infrastructure is responsible for 20-30 % of the train delays, while train operating companies (TOCs) are responsible for 30-40 % of the train delays (Espling, 2007, Nyström and Kumar, 2003, Olsson and Espling, 2004). The studies also showed that the rolling stock, i.e. vehicle failures, is responsible for 10-20 % of the delay. Indicators for assessing the performance of rolling stock and operations are therefore likewise important for rail transportation, which extensive work have been carried for (Section 3.1). In a future study, a handbook or technical standard on rail transport PIs, these studies could be incorporated with the presented study. In addition, as railways are operated semi-continuously, indicators of opportunistic maintenance (Utne et al., 2012) is another interesting area to include in a future study of indicators, both regarding rail infrastructure and rolling stock.

The review includes both research work and documents by IMs, but it is not clear which indicators are really applied and used in railways; this is another topic for future study. Details regarding indicators are not given. Within an IM or in a technical standard, the indicators need to be explained further, e.g. for calculation procedure, advantages, disadvantage, target values and maintenance limits. Especially maintenance limits deserves attention as research in railways have shown promising cost-effective results; see Bergquist and Söderholm (2014) and Khouy et al. (2014).

By comparing the identified indicators to EN 15341 (CEN, 2007), it was found that 11 PIs are similar. A number of the indicators in the technical standard are general for any maintenance functions. Nevertheless, it has to be kept in mind that the standard is mainly for manufacturing businesses, not for linear assets. Thus, many railway indicators cannot be found in the standard. The comparison of railway indicators to EN 15341 shows similarities between performance measurement practices between railways and manufacturing. Moreover, with the comparison, it is known which indicators in railways that can be used for benchmarking with other industries, e.g. indicators of maintenance cost, safety, times and backlog. On the other hand, operation and maintenance practices differ significantly between industries, which may limit such application.

The scorecard in Paper B has a group called availability. Availability related indicators include indicators of punctuality, regularity, failures, delay and temporary speed restrictions. However, any general availability indicators for railways could not be found, such as uptime measures, or like indicator T1 of EN 15341: Total operating time / Total

Operating time + Down time due to maintenance. Availability is studied in Paper C.

A previous study on indicators of rail infrastructure performance have been carried out by Åhrén and Kumar (2004) and Åhrén (2008), who mapped 17 indicators through interviews with Trafikverket and review of Trafikverket documents. It was found that 10 of these indicators were used within Trafikverket. Paper B extends this work by including research articles and EU projects.

By comparing the results of Paper B with EN 15341 (CEN, 2007), we see that both studies are limited in the details regarding the indicators. However, EN 15341 is more detailed in defining the meaning of each indicator, i.e. providing a short description of what each indicator mean. In comparison with SMRP best practice metrics (SMRP, 2011), it is seen that those indicators are structurally defined and explained more than those of Paper B and EN 15341. The SMRP indicators include: definition, objectives, formula, component definitions, qualifications, sample calculation, harmonisation (with EN 15341) and references. Moreover, Trafikverket has supported several studies on structuring and use of indicators (Åhrén, 2008, Jonsson, 2010), besides continuously working with their internal scorecard called quality of service. The work of Paper B has also been presented in a workshop at International Union of Railways (UIC), Paris, by Trafikverket. Nevertheless, for the work to be adopted, it is believed that the indicators need to be studied and documented in more detail. SMRP best practice metrics can work as a good example for this.

## 6.3 Third research question

**RQ 3:** How can operation and maintenance data be aggregated for monitoring and analysis of rail infrastructure?

RQ 3 is answered in Papers C, D and E, which are discussed separately below. Paper C is a study of availability, i.e. an aggregate of maintenance down time, Paper D is a study of the feasibility of using composite indicators in railways, and Paper E is regarding cost of corrective and preventive maintenance.

### 6.3.1 Paper C

The purpose of Paper C is to measure operational availability in the operation and maintenance phase of railways using common definitions. The resulting availability measure give a higher correlation with train delays ($R^2$ = 0,94) than failures with train delays ($R^2$ = 0,73); see Figure 5.4. The result is reasonable since availability is a function of reliability, maintainability and maintenance supportability; i.e. it includes failures, repair time and logistic delay.

A main concern in constructing availability measures is how to treat down time distributions, i.e. the time to restoration (TTR). TTR is the time interval during which an item is in a down state due to a failure (IEC, 1990), i.e. administrative delay, logistic delay and repair time, or just the latter two. A term sometimes used as a synonym for the time to restoration is time to repair; however, it has been deprecated (IEC, 1990).

Maintenance times often have a log-normal distribution (U.S. Dept. of Defense, 1997, O'Connor and Kleyner, 2012), and thus, railway TTR data may be positively skewed, i.e. have long right tails. Consequently, consideration has to be taken regarding limits, percentiles and mean values. The effect of applying a percentile is seen in Figure 6.2, together with a log-normal fit. The failure work orders included are up to the 95$^{\text{th}}$ percentile with respect to the TTR length in minutes. TTR equals logistic time (LT) and repair time (RT) added together. The log-normal mean equals 410 minutes and the median equals 171 minutes.

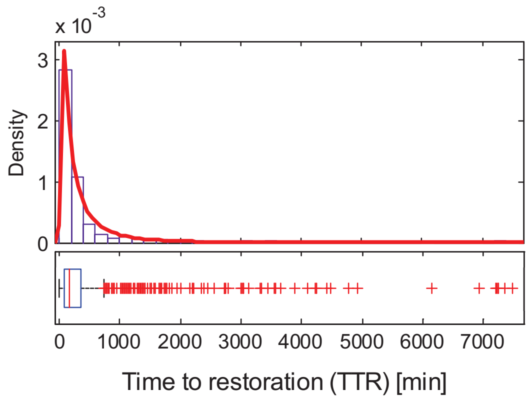


*Figure 6.2: Percentile applied to TTR of Swedish Iron Ore Line, section 111, 2010-14.*

Alternatively, time limits can be applied instead of a percentile. Figure 6.3 shows the same data, but instead of applying a percentile, time limits have been set; that is including data only fulfilling $5 < LT < 240$ minutes and $10 < RT < 600$ minutes. The log-normal mean equals 204 minutes and the median equals 147 minutes.

Which method to use for the exclusion of data depends on the aim of the analysis. Having long TTRs does not necessarily mean the data have been incorrectly typed in. It can be due to severe failures, such as tear down of the overhead contact wire, derailments or fires. Thus, excluded data, i.e. outliers, need to be analysed separately. Exclusion rules, therefore, depend on the aim of the measure. To measure only frequent failures, effective limits can be set, which can be to exclude 10 % of the data or applying time limits. As a result, the log-normal mean of the TTR data will be less affected by outliers, and in the case of measuring availability, it will increase. Similar effects are achieved by the use of the median. Less effective limits will not miss as many severe failures, but at the same time, the log-normal mean of the TTR data will be less robust (Paper C: Figure 7). Regardless limits, outliers should be included in a separate analysis

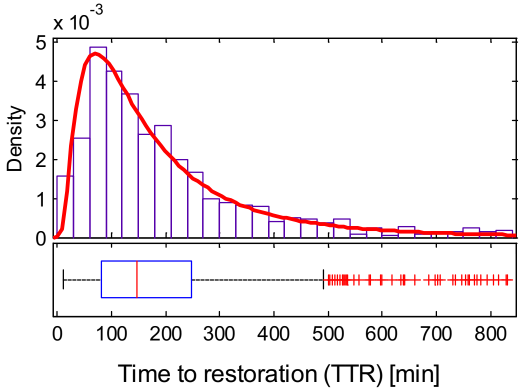


*Figure 6.3: Time limits applied to TTR of Swedish Iron Ore Line, section 111, 2010-14.*

as they can have a large effect on performance, but this is beyond the scope of this study. Examples of outliers are given in Appendix A: Table A.6 of Paper E.

The effect of applying percentiles to TTR data is shown in Figure 6.4. The median is stable, while the log-normal mean is affected by the positively skewed data. Concurrent faults are as well shown, but the availability measures are adjusted to only count concurrent faults once.

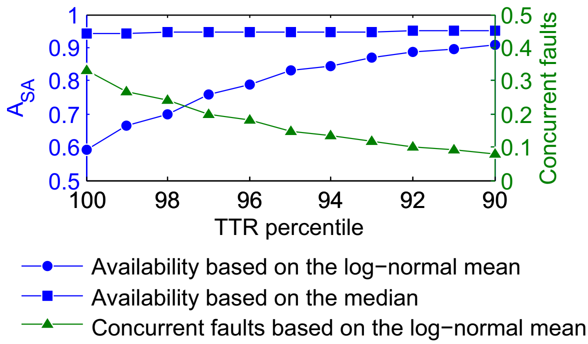


*Figure 6.4: Service affecting availability ($A_{SA}$) as a function of TTR percentile of railway section 111.*

For further explanation of the results in Paper C, a visualisation is added in Figure 6.5. The figure shows the service affecting availability ($A_{SA}$) over one month of rail section 111, of the Swedish Iron Ore Line. $A_{SA}$ means only train-delaying failures are included. The grey and white areas represent the instantaneous, or point, $A_{SA}$; grey is up state and white is down state. More specifically, it is the $A_{SA}$ per minute. The solid line is the daily mean $A_{SA}$, and the dashed line is the month mean $A_{SA}$. The mean availability is given by:

$$\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} A(t)dt \tag{6.1}$$

where $A(t)$ is the point availability, and the $\Delta t$, i.e. $t_2 - t_1$, is day or month considering Figure 6.5. The availability measures in the three plots of the figure are based on the same data but using different ways of assessing TTR. The median is used in the top, the log-normal i used in the middle, and the registered TTR is used in the bottom. In the top, the down state windows (or TTR windows) are the same size since the median of all TTRs over one year is applied to all failures. The same is true for the middle plot of the figure, except the log-normal i used instead of the median. In the bottom plot, each window differs in size as the registered TTRs are used.

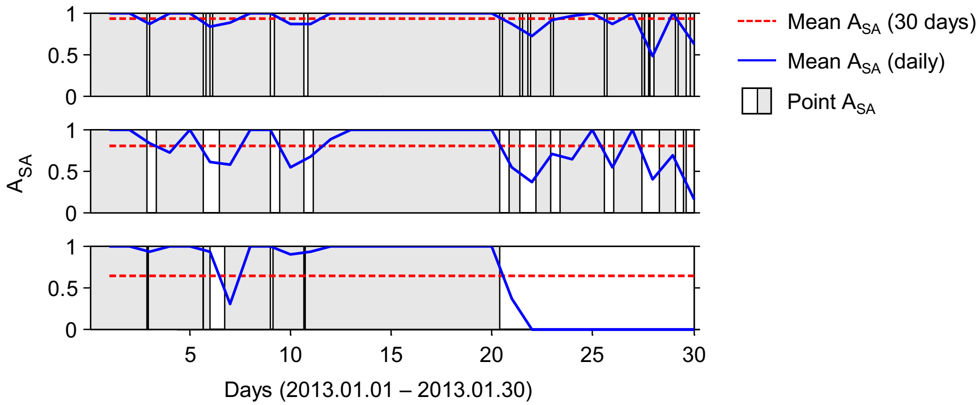


*Figure 6.5: Mean and instantaneous (point) service affecting availability ($A_{SA}$) of railway section 111. Based on the median (top), log-normal mean (middle) and registered TTR (bottom).*

Söderholm and Norrbin (2014a) used the share of successful train passages as a measure of availability. The availability measure of Paper C does not include information regarding the number of trains affected by a failure. On the other hand, the measure used by Söderholm and Norrbin (2014a) does not include the extent of down time. Thus, the indicators measure different but dependent aspects, and thus, would be interesting to study together. Moreover, the indicator studied by Söderholm and Norrbin (2014a) is used within Trafikverket, which further makes such a study interesting. Also, previous studies have raised the issue of measuring availability of railways; see Paper C: Section 1.

Studying the resulting availability measures of Paper C, it is seen that the track and

S&Cs have the lowest availabilities; see Paper C: Figure 7. These results are in line with Paper C: Figure 5. Note that 'no fault found' does not have any availability since TTR data is put to zero for these failures in the database of Trafikverket. If we study the subsystems of the S&Cs in Paper C: Figure 10, the four items: switch control, switch motor, point drive and connector, are in line with the results of Paper A: Figure 8. However, studying the subsystem 'frog' in Paper C: Figure 10, it has the lowest availability of the S&Cs' subsystems. But in Paper A: Figure 8a, it is not performing poor according to the risk matrix. Studying the active repair box plot (Paper C: Figure 8a), it is seen that the median repair time is long compared to the other subsystems. This shows that the service affecting availability ($A_{SA}$) of the frog does not give a correct picture of the availability experienced by trains. The $A_{SA}$ only includes train-delaying failures, but since frog failures give many short train delays, but takes long time to repair, it gives a low $A_{SA}$. This issue can be solved by only using the operational availability ($A_O$), i.e. the availability experienced by the infrastructure manager. Alternatively, $A_{SA}$ can be used where limits can be chosen for inclusion of train-delaying failures, e.g. only including failures with train-delay below or above a certain number of minutes. Outliers can also be studied in such a way. This is possible in a software implementation.

### 6.3.2 Paper D

The constructed composite indicator (CI) includes four individual indicators: failure frequency, train delays, logistic time (LT) and repair time (RT), i.e. corrective maintenance data. It was assumed that the data quality is similar for all the 65 railway sections. However, some failure work orders missed the time when repair was finished and, therefore, were not included in the calculation of log-normal mean LT and RT. The precision of the log-normal mean LT and RT depends on the data available. It was seen that missing repair times varied with some percentage points between the railway sections. This was not studied further since available data were quite large: about 21 000 train-delaying failures (22 % of 97 000 failures) over 65 railways sections.

The railway sections' CI result in Paper D: Figure 6, with related discussion, shows the method to be interesting for comparison of performance. For example, four out of seven sections of railway Line 1 are in the top ten, while five out of six sections of railway Line 21 is in the bottom ten. Comparing the city sections 655 and 112, which are in each end of the CI result: both have low logistic time, but section 655 has 349 failures (S&Cs excluded) over 6 km of track and section 112 has 839 failures over 2 km of track (S&Cs excluded). Studying the asset register of these section may bring answer to this difference. Moreover, comparing the results with performed preventive maintenance and transported volume would also be interesting.

The CI results were compared with data envelopment analysis (DEA), but it would be interesting to compare the CI with input measures, like transported tonnage, preventive maintenance and costs.

Famurewa et al. (2014) studied CIs using a similar approach as Paper D, but applied fuzzy logic for aggregation of individual indicators. The individual indicators were: failure frequency per train-km, train delay per train-km, inspections per tonne-km and track quality index, i.e. the included indicators and normalisation procedure also differed. One of the railway sections studied was section 111 of the Iron Ore Line. The CI results of both studies found section 111 to have the poorest performance. It would be interesting to compare the method used by Famurewa et al. (2014) and the method of Paper D. This would require new data to be collected as the studies do not include the same railway sections. Not all of the sections in Paper D has known transportation volumes.

Another CI has been developed by Duranton et al. (2012), based on the individual indicators: passenger-km, tonne-km, punctuality, percent high speed rail, accidents and fatalities. The results show an interesting correlation with public subsidies and investments of railways. However, details regarding the method is not given which makes comparison with other CIs hard.

### 6.3.3 Paper E

In the case study, 70-90 % of the maintenance cost comes from corrective maintenance (CM), which in turn constitutes 61 % of down time/delay cost (Paper E: Figures 3 and 4). Consequently, the result strongly depends on the cost of down time. If the down time cost is disregarded in the case study, CM stands for 50-70 % of the maintenance cost.

The travel speed for preventive maintenance (PM) was set rather high and would therefore affect the results with a few percentage points if set lower; the size of the logistic time is shown in Paper E: Figure 3.

It was also found that the railway sections with the lowest total maintenance cost had the largest share of PM; 30 % PM as compared to 10 % PM for the most costly sections (Paper E: Figure 4). This does not mean that the railway sections with the lowest total maintenance cost invest more resources into PM in monetary terms; rather the result shows that the railway sections with the lowest cost have both lower PM and CM costs. Generally, within maintenance, it is argued that there is an optimum balance of PM and CM (Lyngby et al., 2008). Therefore, if PM is feasible and introduced to a system with 100 % CM, the total maintenance cost should be lower than when only CM was used. If this relationship is plotted, with the PM to CM share on the $x$-axis and costs on the $y$-axis, we should be able to find a minimum total cost at a specific share of PM. However, in Paper E, the railway sections with the lowest cost have lower PM and lower CM costs. By plotting total cost, PM cost and CM cost as a function of PM share, all three costs would go down with a higher PM share. This means the concept of PM/CM balance is not related to what is actually seen. This effect is rather due to the different production of the sections and their maintenance classification.

It should be noted that the presented method does not include all costs related to maintenance, such as procurement, planning, administrative and readiness costs. Logically, planning costs should be higher for preventive maintenance than corrective maintenance, while readiness costs should be higher for corrective maintenance.

## 6.4 Linkage between the developed model and methods used

The link and effect model of Paper A forms the foundation of the research. Paper B gives a mapping of indicators, and the subsequent papers studies various methods for monitoring and analysis of rail infrastructure performance. The methods studied in Papers C-E are availability measures, composite indicators and maintenance costs. In addition, risk matrix method is studied in the case study of Paper A, while maintenance between trains are considered in Chapter 7 of this thesis. Moreover, graphical representation has been studied in a related paper (Stenström and Parida, 2014). These studies together form the research carried out, or version 2 of the link and effect model. Figure 6.6 shows how the work is linked together. As in the link and effect model of Paper A, the model consist of a four steps continuous improvement cycle. The intention is that the cycle should be carried out on a yearly basis. The four steps/numbers in the cycle to the left of Figure 6.6 correspond to the v-representation to the right of the figure. In step 1, the text box 'Components of strategic planning' refers to Table 2.1. In step 2, the text box refers to Figure 6.1, and thus Paper B for documentation of indicators. Step 3 is analysis of data; here, the methods to use depend on the user's objectives, e.g. infrastructure manager. Results are evaluated in step 4, which the developed methods can be used for.

The presented research, is limited to rail infrastructure. However, rail infrastructure and rolling stock are subsystems of rail transportation, and together responsible for its performance (Section 6.2). Interdependency of both systems needs to be considered in performance measurement. The wheel-rail interface and vehicle dynamics play an important role in such studies (Pombo and Ambrósio, 2012), as well as the pantograph-catenary interaction (Pombo and Ambrósio, 2013).

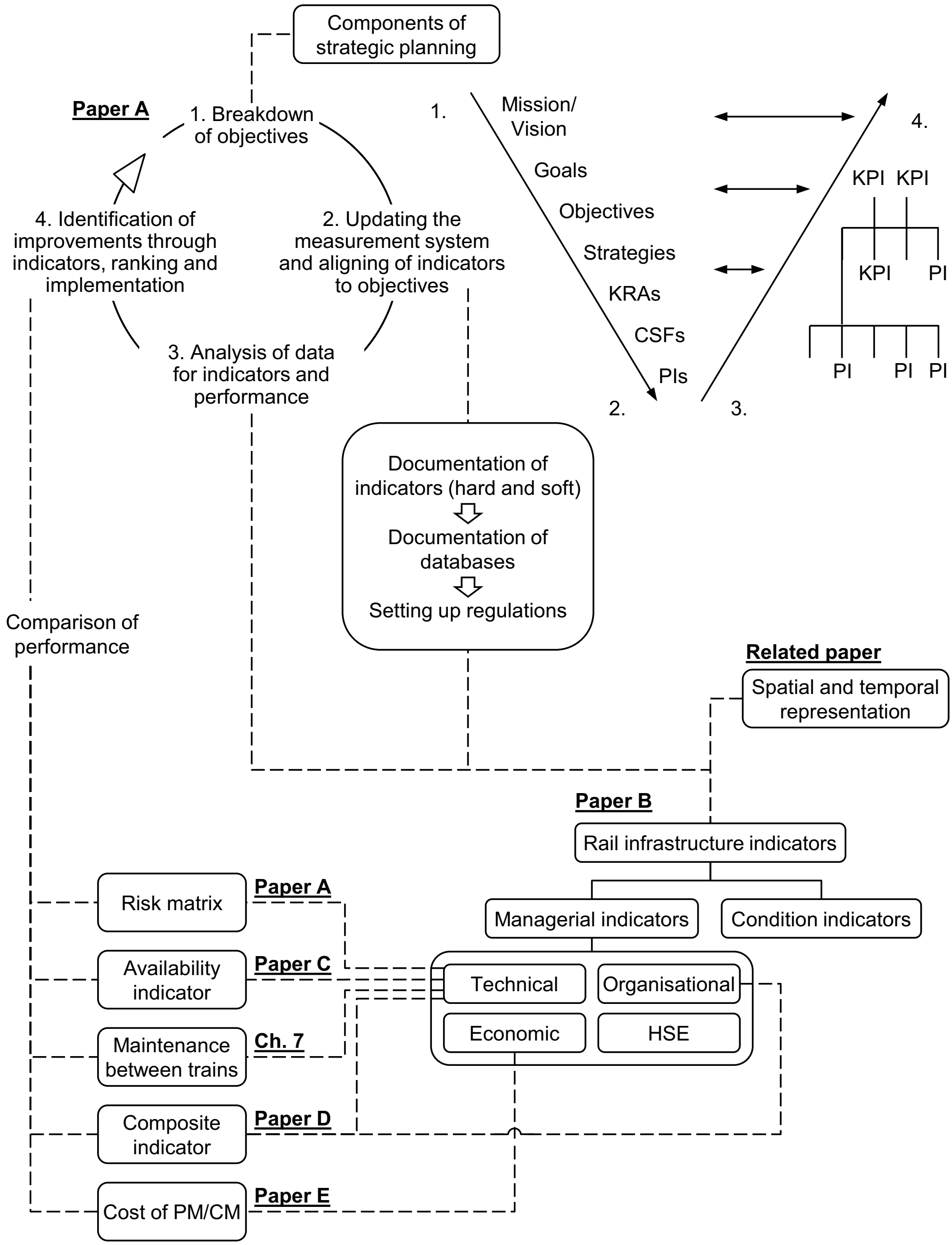


*Figure 6.6: The link and effect model; framework and methods linked together.*

# Chapter 7

# Extension of the research

The aim of rail infrastructure maintenance planning is to minimise the effect on traffic. Therefore, infrastructure managers (IMs) start planning their maintenance work far ahead of time to fit with the planning of train time tables. In the European Union (EU), each IM is obligated to publish a Network Statement (NS) (EC, 2001a) with all the information needed for train operators interested in capacity. The NS must be published about one year before a new year and a new train time table comes into force. Consequently, the planning of major maintenance work starts about 1½-2 years before a new train time table. Maintenance work that is planned after submission of the NS has to compete with or be fitted into operators' applications for capacity. However, some work is planned only a few weeks before execution, and depending on the railway line in question, a few hours during night can be available for maintenance. Besides late planned maintenance work, failures in track normally require repair immediately or within one day. In addition, with increasing rail transportation (Chapter 1) it becomes harder to find time in track for maintenance. Therefore, it is of interest to simulate maintenance tasks between trains. Such simulation can be used to:

- Study maintenance work in train time tables with random train passages to find suitable time windows, e.g. freight trains
- Study maintenance work in train time tables with regular train passages/departures, i.e. urban areas. As an example, a certain maintenance work can take a very long time to complete at a train frequency of 10 minutes, while cancelling a group of trains or running one train out of three may be impacting the train service unnecessary negatively; i.e. cancelling each second train may then be the most optimal choice.
- Study the effect of exceeding allocated maintenance windows. As an example, the available maintenance window may be four hours, but it is known from experience and historical data that the work in question takes five to six hours. Possible solutions are: carry out the work in one shift, exceeding the four hours, and do the

last work between the trains; do the work in two shifts, i.e. eight hours over two days; or increase the number of personnel in the maintenance team if possible.

- Study the effect on maintenance of future increases in the frequency of trains. This is especially important in maintenance contracting, as contracts are often performance based and stretch over several years (Famurewa et al., 2013). If a possible increase in the numbers of trains running is not properly taken care of within the maintenance contracts, the infrastructure manager and contractor may end up in a disagreement.

In short, the research of this thesis has studied performance measurement models, indicators, operational availability, composite indicators and maintenance costs. These methods are for monitoring, analysing and comparing performance of rail infrastructure. The methods can improve maintenance planning, preventive maintenance and reinvestments. However, ad hoc planning and corrective maintenance will always be present, and, in some cases, is a cost-effective approach. The study of maintenance between trains was initiated in the AUTOMAIN project (Juntti et al., 2013, Parida et al., 2014a). In the AUTOMAIN project, the effect of exceeding an allocated maintenance window was studied by comparing an alternative maintenance approach. Specifically, the simulation concerned the decision to use one or two welding teams for frog (common crossing) replacement of switches & crosssings. Maintenance work between regular train departures, i.e. urban areas, was also studied in an attempt to balance maintenance cost and train services. As a continuation of the study of maintenance between trains and as an extension of the thesis research, the effect on maintenance between trains from an increase in train frequency is studied in this section.

## 7.1 Theoretical framework

Maintenance time in terms of travel, preparation, repair and clearance can be estimated through experience and use of historical work order data. However, the actual time to complete a particular maintenance task depends on the train time table and safety regulations governing entrance to and closure of the railway section in question. With these inputs, the actual time to maintenance can be estimated. Matlab software is used for model construction and Monte Carlo simulation. Monte Carlo method is used to predict increases in maintenance time by sampling random train time tables (TTTs). The model has a number of input and output parameters. The input parameters are as follows:

- Train time table (TTT)
- Non-value adding (NVA) time ($t_{NVA}$): Consist of preparation, confirmation, communication, waiting and lost time, for entrance to and closure of track
- Active repair time ($t_{Active}$)

- Minimum time for maintenance ($t_{Min}$)
- Arrival point in the time table

Minimum time for maintenance ($t_{Min}$) can be set as a fixed value or based on $t_{Active}$. As an example, if the required time for a maintenance activity is 150 minutes and $t_{Min}$ is set to 10 % of that time, i.e. 15 minutes, then no maintenance will be carried out if the time left for maintenance between two trains is less than 15 min.

The output parameter is the (actual) maintenance time: the time from the arrival of the maintenance team until the work is finished and the track is cleared.

Figure 7.1 demonstrates the model. Given that $t_{NVA}$ equals 10 minutes, $t_{Active}$ equals 50 minutes and $t_{Min} = 0.1 \times t_{Active} = 5$ minutes, the maintenance time becomes 109 minutes, i.e. 118 % more than the 50 active minutes required.

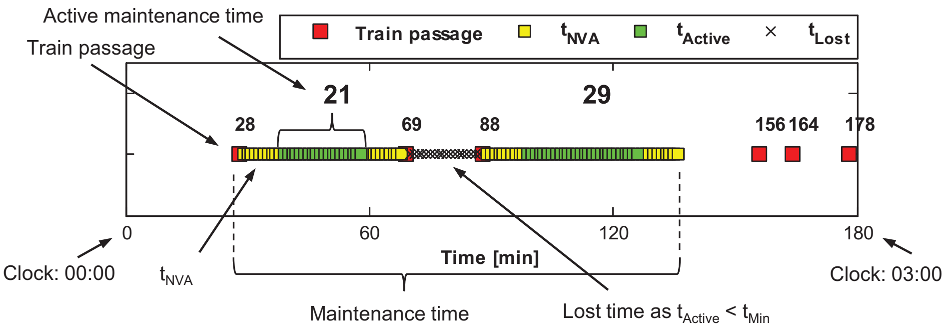


*Figure 7.1: Demonstration of model.*

Random TTTs are generated using a uniform distribution, with the exception that adjacent trains must have a minimum distance in time of $x$ minutes. An example of a 120 minutes maintenance task in randomly drawn TTTs is shown in Figure 7.2.

## 7.2 Prediction of increase in maintenance time

The number of trains occupying the Iron Ore Line between Kiruna, Sweden, and Narvik, Norway, is predicted to increase from 42 trains per day in 2014 to 50 trains per day in 2020 (Boysen, 2013); see Figure 7.3.

For the simulation: operating time is set to 18 hours per day; the number of trains per day is set to range from 10 to 60; a random uniform distribution is used to set out trains passages; an exception is added whereby adjacent trains must have a minimum distance in time of five minutes; $t_{NVA}$ is set to 5 and 10 minutes, giving two different cases; $t_{Active}$ equals 120 minutes; $t_{min}$ equals 10 minutes; and the number of random TTTs

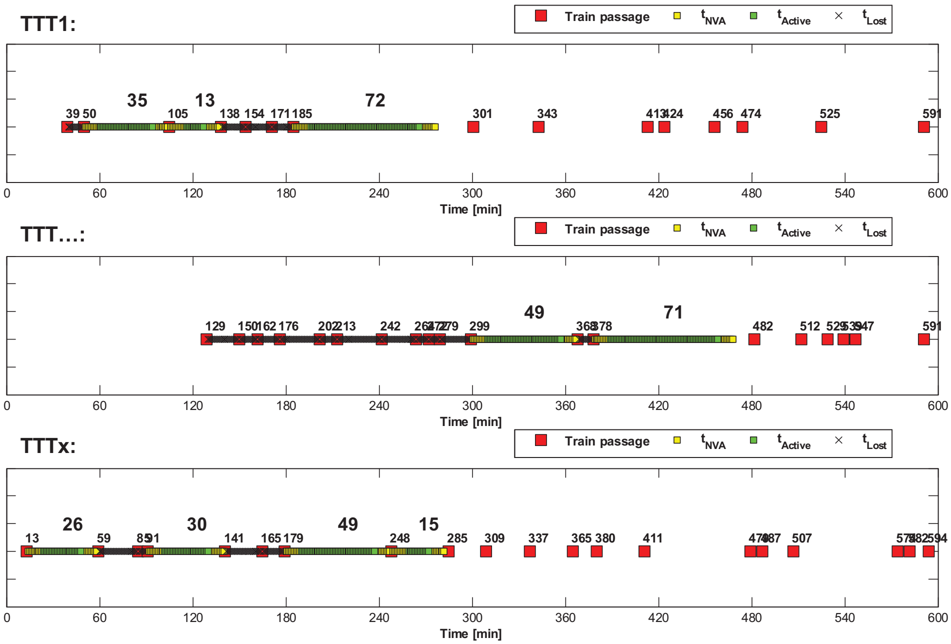


*Figure 7.2: Example of random drawn TTTs with a 120 minutes maintenance work.*

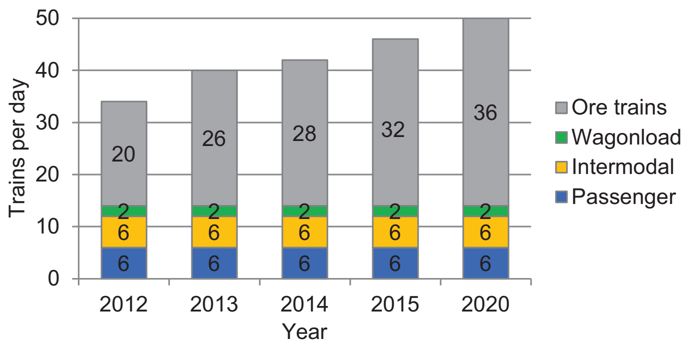


*Figure 7.3: Predicted increase in train frequency of the Iron Ore Line (Boysen, 2013).*

is set to 1000 for each train frequency and $t_{NVA}$. The result is shown in Figure 7.4: the data points are the mean values; their whiskers are the standard deviations; and the density function and box plot, with whiskers of 1.5 IQR (interquartile range), are for the highest data point. As indicated in the figure, the maintenance time has an exponential or polynomial growth as the train frequency increases.

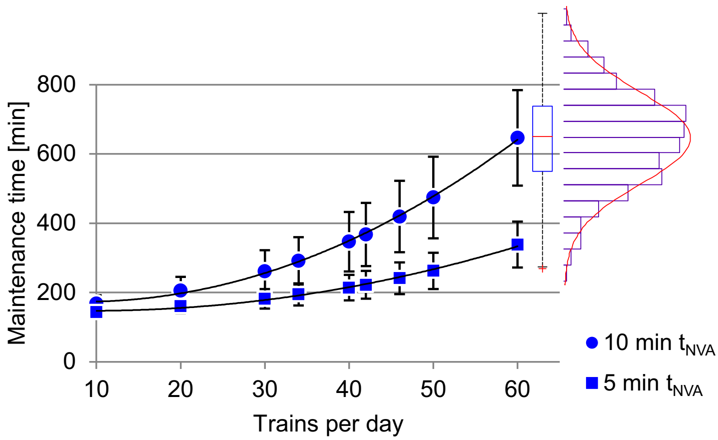


*Figure 7.4: Predicted increase in maintenance time with increase in train frequency.*

By comparing the results with the predicted increase in trains, it is found that the average maintenance time increases with 29 % ($t_{NVA}$ = 10 minutes) when the number of trains per day increases from 42 to 50; see Figure 7.5. With $t_{NVA}$ of 5 minutes, the maintenance time increases with 18 %.

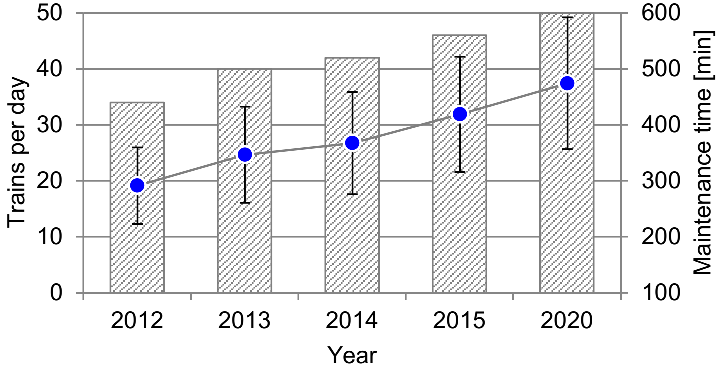


*Figure 7.5: Predicted train frequency and maintenance time.*

## 7.3 Discussion

In addition to $t_{NVA}$, the result depends likely on other inputs, such as the operating time, $t_{min}$ and $t_{Active}$; these relationships need to be studied further. The simulation considered a 120 minutes maintenance work ($t_{min} = 120$) that can be temporarily stopped to let trains pass. Other maintenance work can include work steps that have to be finished before trains can pass. As an example, frog replacement requires two out of four welds to be completed before trains can pass. This type of maintenance must be put into allocated maintenance windows, e.g at night, or in sufficiently large windows within the TTT. This kind of works can be simulated by sampling random TTTs with a fixed maintenance window.

Including the various types of maintenance work lead to a final predicted increase in the maintenance time. Historical maintenance data can be used for this purpose, together with expert judgement. It should also be noted that adding the logistic time (travel time) will reduce the increase in maintenance time as the logistic time is unaffected by the train frequency.

The method for predicting increase in maintenance time, as a function of increase in train frequency, is based on random drawn TTTs with uniform distributions. However, depending on the railway line in question, the configuration of a future TTT, with more trains, can be known. It is still not known, however, when a failure will take place, i.e. randomness. Thus, the presented method can alternatively be used with a fixed TTT and some distribution for failures. Sampling TTTs or sampling failures will, to a certain extent, yield similar results. As an example, randomly setting out a failure in a TTT is analogous to randomly setting a TTT to a failure.

## 7.4 Conclusions

Monte Carlo method can be used to predict maintenance time as a function of train frequency.

Specific to the case study, with the model input values used, the average maintenance time on the Iron Ore Line in Sweden, will increase by ~20-30 % from year 2015 to 2020. Nevertheless, expert opinion and parameter study can improve the prediction, and is required if the method is applied in practice.

# Chapter 8

# Conclusions, contributions and further research

Following the problem statement, purpose and research questions, the research continued with literature review, interviews and mapping of operation and maintenance indicators of rail infrastructure. After further literature review, a model, called link and effect model, for improving operation and maintenance performance of rail infrastructure was developed and applied in a case study. The research continued with three additional methods, including case studies, for measuring operation and maintenance of rail infrastructure: operational availability, composite indicators and cost modelling with cost-benefit analysis. Lastly, conclusions, contributions and the scope of further research are devised below.

## 8.1 Conclusions

The following conclusions have been reached:

- Previous studies have showed that performance measurement initiatives often fail in practice. Thus, performance measurement initiatives need to be versatile, the related components of strategic planning need to be clear, indicators need to be traceable, and performance measurement initiatives need to be easy to understand. (Paper A)

- Probability-consequence matrices are a useful graphical tool for assessing operation and maintenance performance of rail infrastructure. If they are used as a tool to devise an index, this should be done together with the graphical representation as the individual indicators, represented by the ordered pair $(x, y)$, result in the same index value when the first and second coordinates are interchanged. Nevertheless, such interchange depends on the weights of the individual indicators. (Paper A)

- About 120 operation and maintenance indicators of rail infrastructure were found through review of literature. In addition, 11 key performance indicators (KPIs) of EN 15341 (CEN, 2007) are found to be similar to the identified railway indicators. (Paper B)

- Operational availability of rail infrastructure has a higher correlation with train delays ($R^2 = 0{,}94$) than failures have with train delays ($R^2 = 0{,}73$) (Figure 5.4 and Paper C: Figure 8). Thus, operational availability can be used for railways as an overall measure of reliability, maintainability and maintenance supportability.

- Results of the constructed composite indicator (CI) were in line with rail lines and sections' characteristics and utilisation (Paper D: Table 9 and Figure 6); e.g. logistic time has little influence on city tracks' CI results, and the single track Iron Ore Line (Line 21) shows poor performance compared to lines with a double track, less load and higher inspection classification. Additionally, CI and DEA comparison showed a high correlation ($R^2 = 0.80$) (Figure 5.5, and Paper D: Figure 7). Thus, CIs can be used as an overall measure of rail infrastructure performance for internal comparison.

- Within the case study of the maintenance cost model, preventive maintenance (PM) costs represent about 10-30 % of the total maintenance cost, including cost of train delay (Figure 5.6, and Paper E: Figure 4). If the cost of train delays is disregarded, PM stands for about 30-50 % of the maintenance cost. Note that, the case study excludes PM planning cost and readiness cost for corrective maintenance (CM). The study also indicates that the railway sections with the lowest total maintenance cost had the highest share of preventive maintenance (Figure 5.6, and Paper E: Figure 4). Finally, the railway sections with the highest maintenance cost carried twice the number of trains and transported three times the tonnage compared to the least costly railway sections.

- Within the case study of the maintenance cost model, the benefit-cost ratio of PM was estimated at 3.3 (Paper E: Figure 7). This is highly dependent on the input data, especially regarding the cost of train delays. The train delay cost represented about 60 % of the CM cost. Consequently, the feasibility of maintenance investment and component replacement projects is highly dependent on the cost of train-delays.

- Monte Carlo method can be used to predict maintenance time as a function of train frequency. Specific to the case study, with the model input values used, the average maintenance time on the Iron Ore Line in Sweden, increases by ~20-30 % from year 2015 to 2020. (Chapter 7)

## 8.2 Research contributions

Contributions are deduced according to: new findings and classifications from the literature review; development of new theoretical methods; application of existing theoretical methods; application of existing applied methods to a new data set; and introduction of existing methods to a new discipline. Accordingly, the research contributions are considered to be:

- The link and effect model developed extends the work on models for measuring performance of rail infrastructure, as it demonstrates how such models can be applied to rail infrastructure and operation and maintenance data. It also includes common implementation issues that should be considered at an early phase. This is considered to be a significant practical implication and contribution of the work. (Paper A)
- The literature review of operation and maintenance indicators of rail infrastructure has led to the identification and classification of indicators. The classification has a significant implication; it can act as a reference for a possible future technical standard and for IMs in their work on reviewing and improving their performance measurement. (Paper B)
- The application of operational availability to rail infrastructure is considered significant, as it had not been scientifically applied to rail infrastructure prior to the study of Paper C.
- The introduction of a generally accepted method for constructing composite indicators to rail infrastructure is considered new, as such an application has not been performed before. (Paper D)
- The operation and maintenance cost model extends the work on modelling maintenance costs in rail infrastructure by its application to preventive and corrective maintenance, with cost-benefit analysis. (Paper E)
- The application of Monte Carlo method to simulate increases in maintenance time in railway track as a function of capacity utilisation is considered as new in the planning of rail infrastructure maintenance work. (Chapter 7)

## 8.3 Further research

Further research could consider the following:

- Study the effect of outlier definitions and analysis methods for maintenance time and train delay distributions. Within the thesis, limits were set according to common practice, to hinder unusual behaviour and to minimise loss of information; e.g. train delay data were included up to the $98^{th}$ or $95^{th}$ percentile, and maintenance time was limited to $x$ minutes. An example of outliers' effects is given in Paper C: Figure 7.

- Within the presented research, indicators have been studied and developed on individual basis. Comparison of indicators was done only for verification; availability was compared to failures (Figure 5.4 and Paper C: Figure 8), and CI to DEA (Figure 5.5, and Paper D: Figure 7). Thus, an area of further research is to compare how various indicators rank systems, subsystems and components within the same railway section, e.g. failures, train delay, consequence-probability matrices, availability, CI and maintenance cost.

- Future work could study advantages and disadvantages of CIs and DEA; CIs and DEA were used for comparison in Paper D (Figure 5.5, and Paper D: Figure 7).

- Indicators for operation and maintenance of rail infrastructure have been reviewed (Paper B), but they have not been studied in detail; thus, the indicators need to be studied more closely, e.g. for purpose, importance, advantages, disadvantages, target levels, formula and frequency.

- The data set used in appended Papers D and E were divided into two groups; switches and crossings (S&Cs) and linear assets. Linear assets consisted of the remaining rail infrastructure systems after excluding S&Cs. This separation was carried out for normalisation to the number of S&Cs and track length. However, further separation and normalisation are interesting further research, e.g. for power converter, interlocking and stations.

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# Part II

# Paper A

# Link and effect model for performance improvement of railway infrastructure

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# Link and effect model for performance improvement of railway infrastructure

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**Abstract**

Railway traffic has increased over the last decade due to its fuel efficiency and the need to reduce emissions. The railway infrastructure performance needs to be measured to allow assets to be managed effectively against set objectives. Various systems are used to collect and store data on traffic, failures, inspections, track quality, etc. However, these systems are sometimes used in an ad hoc manner, partly because of the weaknesses of traditional performance measurement systems. This paper proposes a link and effect model which is focused on the areas of continuous improvement, the key elements of strategic planning and on the underlying factors responsible for the railway performance. The model provides information on the performance of railway systems and components, and how they are linked to each other and to the overall objectives, thereby facilitating proactive decision-making. The model is applied in a case study on the Iron Ore Line in Sweden. The performance of a section of the line is studied in terms of failures, train delays and repair times, and ranked through a risk matrix and composite indicator.

## 1 Introduction

The level of railway traffic has increased over the last decade and is likely to further increase as more goods are transported via rail rather than road due to soaring energy costs, road congestion and the demand to reduce emissions (EC, 2011). The key goals set by the European Union (EU) include a 50 % shift of medium distance intercity passenger and freight journeys from road to rail and waterborne transport, and a 60 % cut in $CO_2$ emissions generated by transport systems. These goals need to be met by 2050 and thus there is considerable interest in methods to increase the capacity of existing railways and make them more environmentally friendly.

Efficient and effective maintenance is essential to ensure maximum dependability and capacity of the existing railway infrastructure. To manage maintenance successfully within stated objectives, the infrastructure performance needs to be measured and monitored. Performance indicators (PIs) for reliability, capacity, punctuality, etc. are extensively used by infrastructure managers (IMs) in making maintenance decisions. However, they are sometimes used in an ad hoc manner and not properly defined. A proactive management approach using performance measurements can lead to savings and improve profitability. However, as additional costs are associated with the measurement processes, it is important to thoroughly analyse what, where, when and how to measure (Parida and Kumar, 2004). The efficiency and effectiveness of the railway infrastructure can be improved if an appropriate performance measurement (PM) system is selected. In traditional PM systems, PIs are given threshold values, indicating when an action needs to be taken, and since PIs commonly consist of aggregated data, e.g. total delay, PIs can appear to be abstract in nature. Therefore, aggregated PIs with thresholds can make the system reactive if not appropriately used. To meet these problems, in the proposed link and effect model, PIs are analysed for the underlying factors responsible for the performance, providing a starting point for improvements.

This paper studies the PM of railway infrastructure using the proposed link and effect model. The model uses continuous improvement through a top-down and bottom-up approach, with a focus on the key elements of strategic planning. Overall strategic goals are broken down into operational objectives, and this is followed by measuring and studying the outcomes in terms of railway infrastructure performance. The development of the model is a continuation of the research by Liyanage and Kumar (2003) and Åhrén (2008). The model is also verified in a case study on a section of track in Sweden. The strategic planning of transportation is reviewed with emphasis on European and Swedish national perspectives to identify goals and objectives. Then statistical analyses of operation and maintenance data are carried out to identify performance killers and drivers, i.e. the underlying factors that create poor and good performance, respectively. In brief, the link and effect model is a methodology for developing PM systems, that combines PM and engineering principles for proactive management of physical assets.

# 2 Performance improvement under a link and effect model

With increasing competition, internationalisation, and legislation on health, safety and environmental issues, traditional accounting using only financial indicators is insufficient to assess business performance (Johnson, 1983, Kaplan, 1984). Accordingly, new PM methods, scorecards and frameworks have been developed that consider non-financial perspectives (Keegan et al., 1989, Fitzgerald et al., 1991, Kaplan and Norton, 1992). For example, the maintenance function, a key element in the success of many organisations (Swanson, 2001, Tsang, 2002, Parida and Kumar, 2006), is now based on more holistic and balanced PM systems.

PM systems have been shown to increase the performance and competiveness of organisations through their use of more balanced indicators (Kaplan and Norton, 1992, 1993), however, there are some implementation issues. In a literature review, Bourne et al. (2002) listed the issues encountered in the implementation of a PM initiative:

- the time and expense required;
- lack of leadership and resistance to change;
- vision and mission may not be actionable if there are difficulties in evaluating the relative importance of activities and identifying true ‘drivers’;

- goals may be negotiated rather than based on stakeholder requirements;
- striving for perfection can undermine success;
- strategy may not be linked to department, team and individual goals;
- a large number of indicators dilutes the overall impact;
- indicators can be poorly defined;
- a highly developed information system is required and data may be hard to access;
- consequences of measurement.

The effects of a large number of poorly defined indicators on the planning and PM of railway infrastructures have been specifically recognised in several studies (Kumar et al., 2008, Berggren, 2010).

Kaplan and Norton (2000) discussed several of the issues noted by Bourne et al. (2002) and highlighted the problem of overlooking strategy planning and rather introducing a complex computer system to collect data. Davenport et al. (2001) carried out interviews with 20 companies and found that they shared the concern that they were not turning data into knowledge and action. Karim et al. (2009) made similar observations in a study of maintenance data, and highlighted a concern that the gap between data processing and knowledge management is large.

Concerning the problem of a large number of indicators, Davis and Davis (2010) noted that an average of 132 indicators are reported to senior management each month, about nine times the recommended number of indicators on a scorecard, thereby confusing detail with accuracy. A human can only monitor a limited number of indicators, and therefore the number of strategic-level indicators depends on the number of senior managers. Consequently, identification of the most important indicators and data aggregation is needed since there can be several hundreds of indicators at the operational level (Stenström et al., 2012). Aggregation of data, e.g. total train delay or total number of failures, is a weakness of traditional PM systems since it can make the indicators abstract and thus the underlying factors can remain obscured (Stenström et al., 2012, Stenström, 2012). The link and effect model tries to solve this problem by complementing indicators with the underlying factors responsible for the observed performance.

The expansion of the railways has resulted in an increased number of operation and maintenance practices in response to the specific needs of each IM and country. However, harmonisation and increased use of standards have occurred as a result of globalisation, especially in the EU where increased interoperability and the creation of a trans-European railway network are of prime interest (EC, 1996). Therefore, PM needs to be dynamic and versatile. Another important element in PM is the fast development of new technologies, including computers (hardware and software) and condition monitoring. Changes in the enterprise resource planning system or the computerised maintenance management system (CMMS) within an organisation can alter the PM practices and monitoring of historical asset condition data. In addition to globalisation and technology changes, organisational changes can also affect the success of a PM system. Overall, PM systems need to be proactive and dynamic to handle changes such as:

- change in business goals, objectives, strategy, policies, etc.;
- change in technology and communication;
- organisational changes;
- evolving regulations, e.g. health, safety, security and environment;
- stakeholder requirements;
- fluctuations in the economy, i.e. the business cycle.

The link and effect model aims to solve some of the problems encountered in traditional PM systems. More specifically, the model puts emphasis on:

- continuous improvement;
- the key elements of strategic planning;
- the underlying factors responsible for the performance.

# 3 The link and effect model

Many improvement methods have their basis in a continuous improvement process, for example, the plan-do-study-act (PDSA) cycle, also known as the Deming cycle, Shewhart cycle or kaizen cycle (Imai, 1986). Furthermore, it has been found that organisations use the key elements, or components, of strategic planning differently, e.g. vision, mission, goals, objectives, etc. (Stenström, 2012). The link and effect model is therefore based on the PDSA cycle with an emphasis on the key elements of strategic planning. The model has two main components: a four-step continuous improvement process and a top-down and bottom-up approach; see Figure 1. The methodology starts by breaking down the objectives, followed by updating the measurement system, analysis of data and finally identification and implementation of improvements. The model is preferably used on a yearly cycle as an IM's objectives commonly change in response to annual appropriation letters.

## 3.1 Step 1: Break down of objectives

The first step of the link and effect model concentrates on strategic planning, which also includes gathering stakeholders' objectives (usually conflicting) and assembling them into a common framework. For railways in the EU, aligning and harmonisation start at the European level and are broken down to national governmental and IM levels, i.e. from strategic to operational planning.

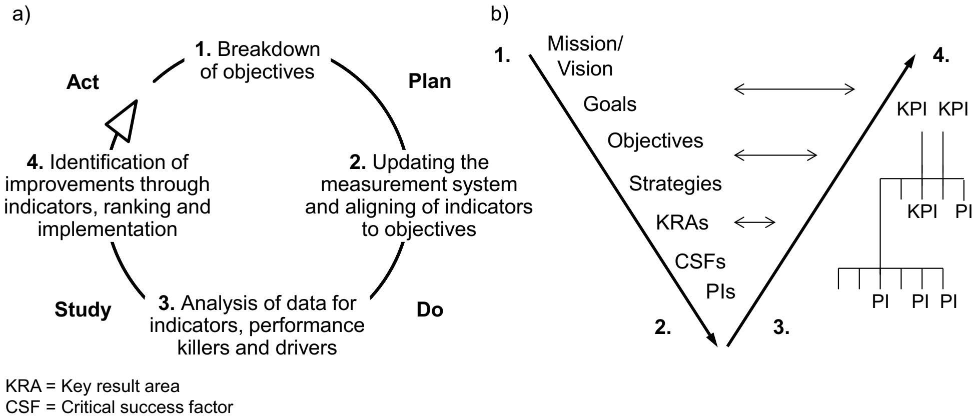



*Figure 1: The link and effect model based on (a) a four-step continuous improvement process and (b) a top-down and bottom-up process. The numbers in (b) represents the steps in (a).*

Strategic planning can be described as the process of specifying objectives, generating strategies, and evaluating and monitoring results (Armstrong, 1982). The terminology of strategic planning can vary between organisations and researchers; see discussion in the case study. Therefore, key elements, or components, of strategic planning are given in Table 1 to assist in understanding Step 1 of the link and effect model.

## 3.2 Step 2: Updating the measurement system and aligning of indictors

The PM system of an organisation is under constant pressure from strategic planning, organisational changes, new technologies and changes in physical asset structure. Therefore, Step 2 in the link and effect model concerns updating the measurement system based on new stakeholder demands and objectives. See Figure 2.

A good PM system does not necessarily require a high level of precision; it is more important to know the trend of the movement in an indicator, i.e. how the current value compares with historical values (Kaydos, 1991). The way that indicators are calculated can change in response to new and better ways of making measurements, changed objectives or organisational changes. It should be noted that the trend in a movement can be lost, and therefore the old calculation methods should be kept and presented alongside the new calculation method for a period of time, i.e. overlapping (Stenström, 2012). Some indicators can give a good record for trend studies quite quickly whereas others need several years to become trustworthy.

*Table 1: Key elements of strategic planning.*

| Term | Description |
|---|---|
| Vision statement | A statement of what an organisation hopes to be like and to accomplish in the future (U.S. Dept of Energy, 1993), e.g. zero machine breakdown. |
| Mission statement | A statement describing the key functions of an organisation (U.S. Dept of Energy, 1993), e.g. a dependable mode of transport. Note: vision and mission are set on the same hierarchical level, since either can come first, e.g. an authority has a vision, and gives a mission to start a business; the business can develop its own vision later on. |
| Goals | A goal is what an individual or organisation is trying to accomplish (Locke et al., 1981). Goals are commonly broad, measurable, aims that support the accomplishment of the mission (Gates, 2010), e.g. rail availability of 99 %. |
| Objectives | Translation of ultimate objectives (goals) to specific measureable objectives (Armstrong, 1982), or targets assigned for the activities (CEN, 2010), or specific, quantifiable, lower-level targets that indicate accomplishment of a goal (Gates, 2010), e.g. less than one failure per track-km and year, and less than two percent of failures with more than two hours train delay. |
| Strategy | Courses of action that will lead in the direction of achieving objectives (U.S. Dept of Energy, 1993), e.g. various analysis, resource allocation and investments. |
| Key result areas (KRAs) | Areas where results are visualised (Boston and Pallot, 1997), e.g. maintenance cost, and maintenance callbacks & backlog. |
| Critical success factors (CSFs) | Are those characteristics, conditions, or variables that when properly managed can have a significant impact on the success of an organisation (Leidecker and Bruno, 1984), e.g. minimum number of failures, and fast repair of failures. |
| Key performance indicators (KPIs) | The actual indicators used to quantitatively assess performance against the CSFs (Sinclair and Zairi, 1995). A KPI is a PI of special importance comprising an individual or aggregated measure, e.g. failures, maintenance time, and availability. |
| Performance indicators (PIs) | Parameters (measurable factor) useful for determining the degree to which an organisation has achieved its goals (U.S. Dept of Energy, 1993), or numerical or quantitative indicators that show how well each objective is being met (Pritchard et al., 1990), e.g. failures per item, logistic time, and active repair time. |

## 3.3 Step 3: Analysis of data for indicators, performance killers and drivers

Organisations collect vast amounts of data, but the ability to turn the data into information is often lacking (Davenport et al., 2001, Karim et al., 2009). Accordingly, analysis methodologies are developed in Step 3 that use various statistical methods to construct

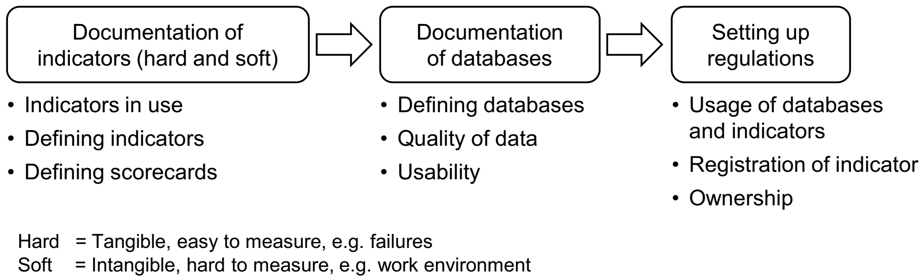



*Figure 2: Key requirements for PM.*

PIs and identify performance killers and drivers. Since data collection uses resources, another important aspect in Step 3 is to identify what data is required and what data is superfluous to requirements.

Aggregation of data is a weakness of traditional PM systems since it can make the indicators abstract and the underlying factors can become obscured (Stenström et al., 2012, Stenström, 2012), e.g. total train delay or total number of failures. Therefore, the link and effect model complements thresholds with the underlying factors responsible for the observed performance. Indicators with thresholds are commonly only given attention when some limit has been passed, making them reactive in nature. In contrast, the link and effect model gives the underlying performance drivers and killers, providing a starting point for improvements, i.e. more of a white box approach. See Figure 3.

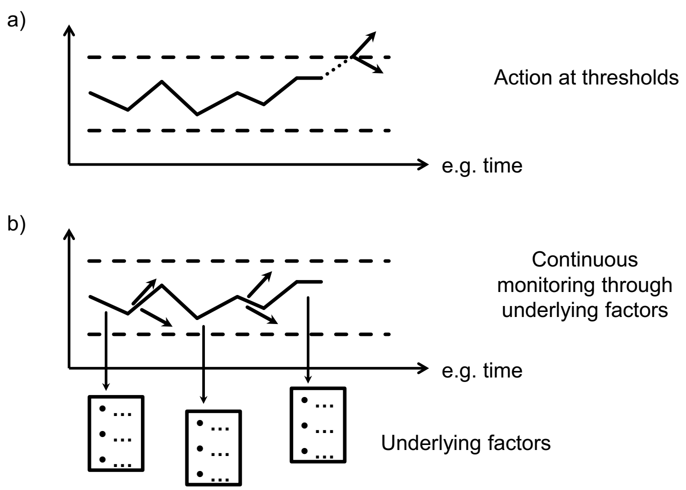



*Figure 3: (a) Traditional PM system with thresholds and (b) link and effect model complemented with the underlying factors of the indicator.*

### 3.4 Step 4: Identification of improvements, ranking and implementation

The link and effect model utilises continuous improvement with the ultimate goal of facilitating decision making, by providing an up-to-date PM system. Step 4 includes simulation, ranking, re-engineering physical assets and processes, implementing prognostic techniques and further defining indicators and databases.

## 4 Case study

A case study has been carried out to demonstrate and verify the link and effect model. The model begins by breaking down goals of transportation at the European level, followed by analysis at the national level of Sweden and the Swedish IM Trafikverket (Swedish Transport Administration).

### 4.1 Step 1: Breaking down objectives

The goal of Step 1 is to align the strategic planning of different stakeholders at the various organisational levels into a single framework. There are two challenges: first, identifying key elements and putting them into the same terminology; second, translating the high-level goals, which can be conceptual, into specific operational tasks. For a review of railway infrastructure management in Sweden, see Andersson (2002) and Stenström (2012).

The following elements of strategic planning were identified from the EU White Paper on the European transport system (EC, 2011):

- vision: towards a competitive and resource-efficient transport system;
- goals related to railways: by 2030, 30 % of road freight over 300km should shift to other modes such as rail or waterborne transport; by 2050, 50 % of medium distance intercity passenger and freight journeys should be shifted from road to rail and waterborne transport;
- objectives: 40 initiatives in four categories.

It should be noted that the vision and objectives were not explicitly stated in the White Paper, an experienced reader is required to interpret the meaning of the White Paper to create the stated vision and objectives. The mission could not be identified. However, the goals are stated clearly. Similarly, experience was required to find the elements of strategic planning at the national level (Sweden) since documents created by the Swedish IM Trafikverket and the Ministry of Enterprise had to be analysed.

The key elements of the strategic planning of transportation in Sweden are (vision and mission are left out):

- overall goal: to ensure an economic, efficient and sustainable provision of transport services for people and businesses throughout the country (Näringsdepartementet, 2009);

- objectives: railway operation and maintenance related objectives can be found in Trafikverket?s quality of service (QoS) scorecard (Söderholm and Norrbin, 2011).

By studying the QoS scorecard, we found two indicators of interest to this case study: first, train delay due to infrastructure problems and second, punctuality.

Once the goals and objectives were identified and put into a common framework, it is possible to align perspectives to operational measures. By studying the objectives, we found that QoS is a key facilitator at both the international and national level (EC, 2011, Söderholm and Norrbin, 2011). According to IEC 60050-191, QoS is the collective effect of service performance which determines the degree of satisfaction of a user of the service; see Figure 4, similar terminology can be found in European Standards EN 50126 and EN 13306 (IEC, 1990, CEN, 1999, 2010).

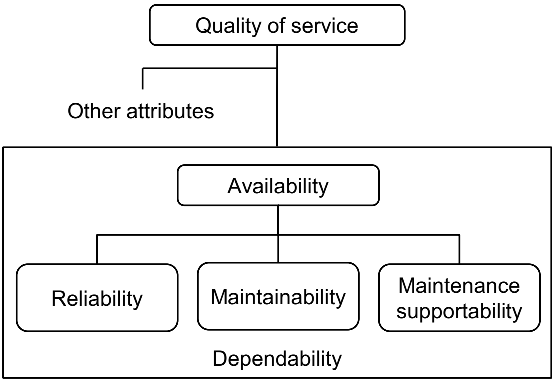



*Figure 4: Quality of service.*

As can be seen in Figure 4, availability is a vital component of service quality. The focus in this case study is on availability, more specifically, on failures and downtime in the railway infrastructure; see Figure 5.

## 4.2 Step 2: Updating the measurement system and aligning of indicators

Indicators need to be set up and aligned to measure the results. Indicators related to failures and down time specific to railways include (Stenström et al., 2012, Stenström, 2012, Åhrén and Kumar, 2004):

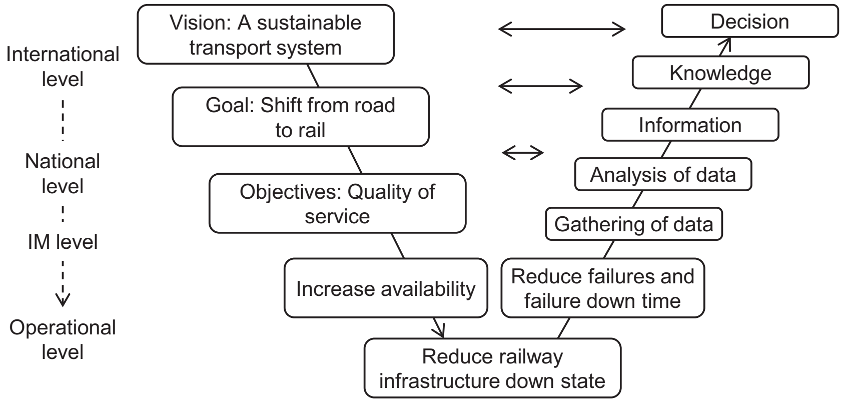



*Figure 5: Breaking strategy into failure and down time components.*

- failures or work orders (in total, per item, per track-km or per train-km);
- train delay (in total, per item, per track-km or per train-km);
- punctuality (per line, line class or area).

Punctuality, failures and train delay are included on Trafikverket's QoS scorecard, i.e. failures, work orders, and down time directly affect strategic objectives. However, indicators need to be further defined within an organisation after analysis has been carried out. Thus, an objective of the link and effect model is to present an indicator along with its underlying factors, not just as an aggregated measure.

## 4.3 Step 3: Analysis of data for indicators, performance killers and drivers

Operation and maintenance data of railway section 111 of the Iron Ore Line in Sweden, have been collected, verified and analysed. Section 111 is a 128 km 30 tonne mixed-traffic heavy haul line that runs from the city of Kiruna to Riksgränsen at the border with Norway (Figure 6). The collected data consists of train delay and infrastructure corrective maintenance work orders (WOs) generated between 01 January 2001 and 01 December 2009, i.e. 8 years and 11 months. Out of a total of 7 476 WOs, 1 966 WOs mentioned train delays, i.e. 26 %. This analysis is based on the 1 966 WOs connected to train delays, i.e. failures that have to be corrected immediately.

The corrective maintenance WO data consists of urgent inspection remarks reported by the maintenance contractor, as well as failure events and failure symptoms identified outside the inspections, commonly reported by the train driver, but occasionally reported by the public. Failures identified outside inspections include the following:

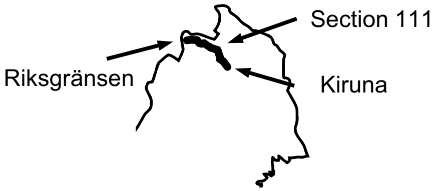



*Figure 6: Section 111 between the border of Norway, Riksgränsen, and Kiruna city.*

- actions taken after a report from train operators or the general public;
- inspections after wheel impact and failed pantograph events (both systems are in direct contact with the railway infrastructure);
- actions after alarms;
- accidents with animals.

Immediate action is required if the fault negatively affects safety, train delay, a third party or the environment.

Matlab software was used to integrate failure WOs with train delay data, to carry out basic data quality control and to perform data analysis. Starting at the system level of the railway infrastructure, WOs and delays were plotted in a risk matrix (Figure 7), also known as a consequence-probability matrix (ISO/IEC, 2009), which originated from the failure mode effect analysis approach in the standard MIL-P-1629 (U.S. Dept of Defense, 1949), and has previously been used to study railways in the standard EN 50126 (CEN, 1999). The whole data set of 1 966 WOs is used in Figure 7(a), whereas data only up to the 98$^{th}$ percentile, with respect to delays, can be seen in Figure 7(b). The 2 % longest delays are considered to be outliers. Outliers are preferably analysed before decision making, but that is beyond the scope of this research. All further analysis was based on WOs with delays up to the 98$^{th}$ percentile. In terms of WOs, 1 926 out of 1 966 WOs were considered; in terms of delay, this is 112 616 min out of 166 693 min.

The length of the hypotenuse in the risk matrix (Figure 7) is used for operational risk ranking. The figure shows that the poorest performing systems are the switches and crossings (S&Cs) and the track, together causing 45 470 min of delay out of the total of 112 616 minutes, i.e. 40 % (Figure 7(b)). These two systems are further analysed in Figure 8.

Figure 8(a) shows that two subsystems of the S&C, namely the switch control system and the switch motor system, deviate considerably from the other subsystems with respect to WOs and delays. The corresponding active repair times can be seen on the right-hand side of Figure 8(a) as box plot. On each box, the central mark is the median, the edges of the box are the 25$^{th}$ and 75$^{th}$ percentiles, and the whiskers extend to 1.5 IQR (interquartile range). Outliers are left out. The median time to repair the frog, i.e. the switch crossing point, is over 200 min, whereas other systems take about 50 min.

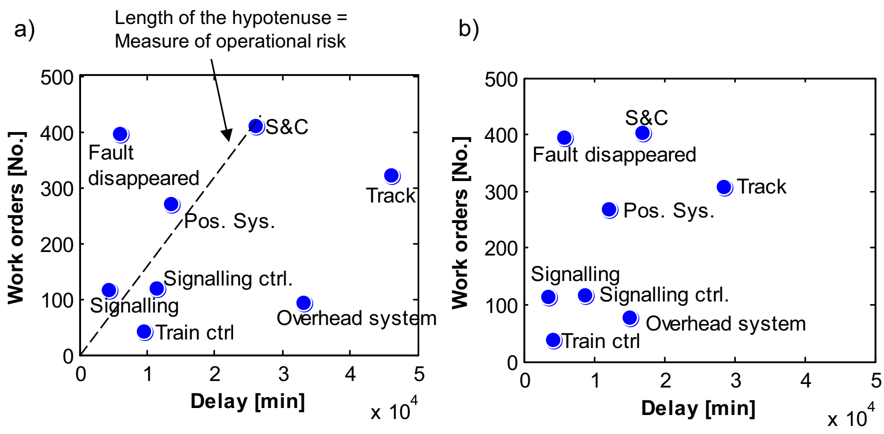



*Figure 7: Risk matrix at the system level, displaying WOs and corresponding train delays (a) complete data set and (b) data up to the 98th percentile for delays.*

The subsystems of the S&C are further broken down to the component level in Figure 8(b). Connectors and point drives, which are part of the switch control system and switch motor, are found to have a high risk ranking. In addition, the frog point and wing rail of the frog have high active repair times.

Lastly, analysis of the track subsystems appears in Figure 8(c). The figure shows that joints and rails are the subsystems responsible for the poor performance of the track. Interestingly, joints cause many WOs, but less delay (reliability problem). In contrast, the rail causes long delay but fewer WOs (maintainability problem). The box plot indicates that rail WOs takes three times longer to repair than the joints; a likely reason for the high delays. Joints consist of insulation pads and insulation rings causing short circuits, the main reason for WOs, whereas the main reason for rail WOs is breakage; a central safety risk due to the derailment hazard (Santos-Reyes et al., 2005).

Further breaking down of the track subsystems is not applicable since some of the subsystems are actually components, e.g. the rail.

Large savings would be obtained if the performance killers could be improved to meet the performance drivers. Table 2 lists WOs, train delays and operational risks. The operational risk equals the length of the hypotenuse:

$$R = \sqrt{(\alpha v_1)^2 + (\beta v_2)^2} \tag{1}$$

where $R$, $v_1$ and $v_2$ are the operational risk, the WOs and the train delay, respectively. $\alpha$ and $\beta$ are weighting constants. In this study we used an equal weighting, as is the case for most composite indicators (OECD & JRC - EC, 2008). By using the total numbers of WOs and train delays, $\alpha = 1$ and $\beta = 1\ 926/112\ 616 = 17 \times 10^3$.

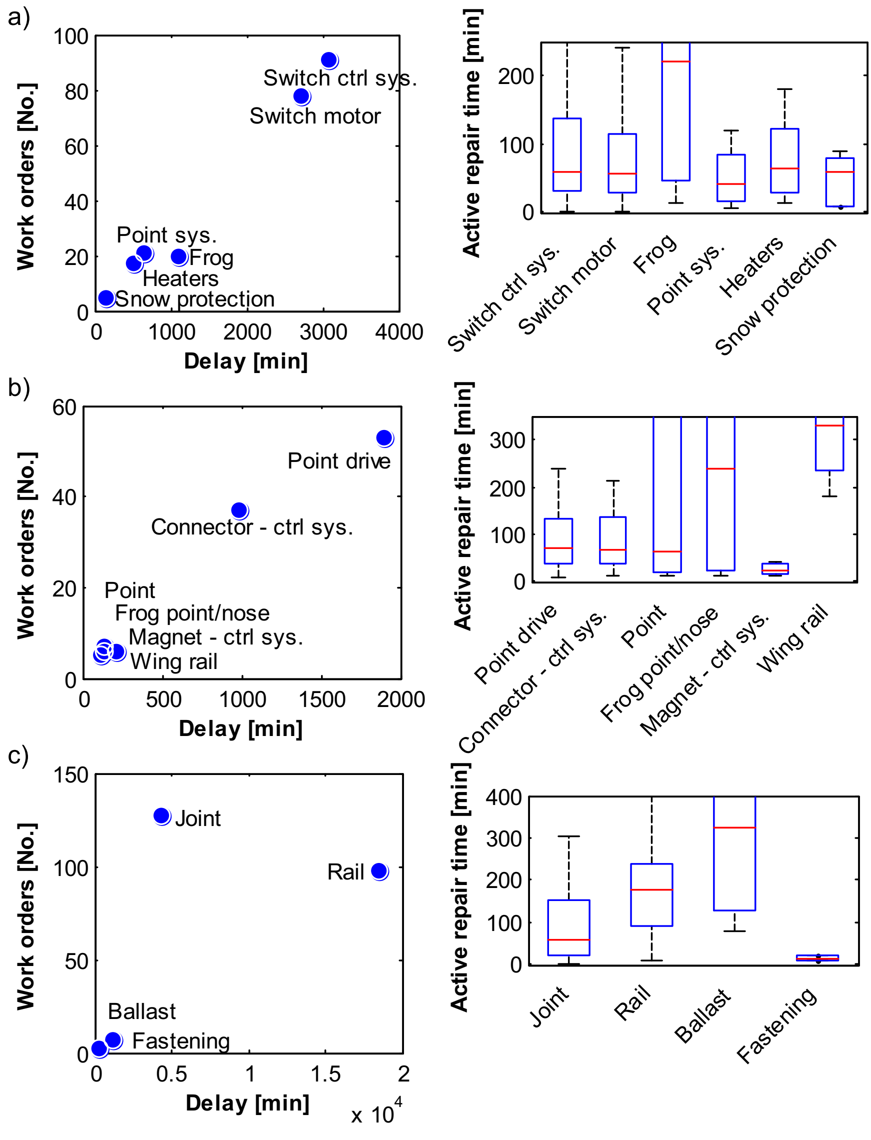
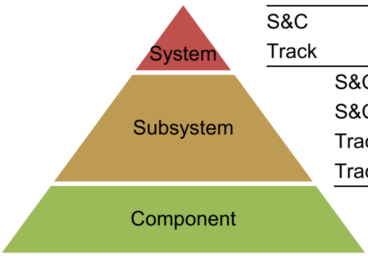


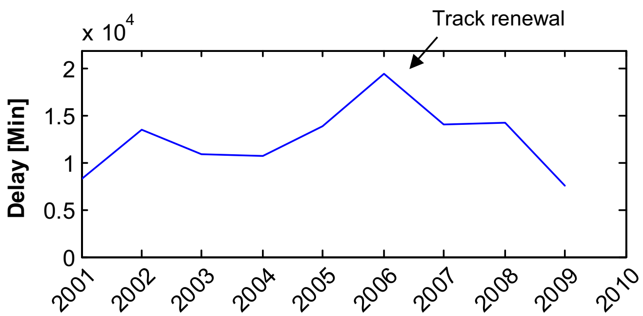

*Figure 8: Analysis of (a) the subsystems of the S&C, (b) components of the S&C and (c) subsystems of the track. Delay data up to the 98$^{th}$ percentile are used.*

Table 2 gives an indication of potential savings in WOs and train delays; however, aggregating data over 9 years does not necessarily give accurate information on the present state. Another goal of the link and effect model is to present PIs with the underlying factors, thus providing direction for improvements, rather than merely presenting an aggregated measure. The data of railway section 111 (up to the 98$^{th}$ percentile) were used to calculate a yearly risk ranking and the results are plotted in Figure 9. As in the risk matrices, the risk is given by the hypotenuse. The top three systems appear for each year. It can be seen that the track (letter B) disappears after 2006, coinciding with a major rail replacement (Figure 10).

*Table 2: The failure work orders (WOs), train delays and operational risk (R) of the performance killers.* $R = \sqrt{{v_1}^2 + (17 \times 10^{-3} v_2)^2}$




| | WOs [No.] | Delay [Min] | Risk rank |
|---|---|---|---|
| S&C | 404 (21%) | 16880 (15%) | 496 |
| Track | 308 (16%) | 28590 (25%) | 575 |
| S&C: Ctrl sys. | 91 (4,7%) | 3069 (2,7%) | 105 |
| S&C: Motor sys. | 78 (4,0%) | 2724 (2,4%) | 91 |
| Track: Joints | 127 (6,6%) | 4325 (3,8%) | 147 |
| Track: Rail | 98 (5,1%) | 18470 (16%) | 329 |
| S&C: Connector | 37 (1,9%) | 989 (0,9%) | 41 |
| S&C: Point drive | 53 (2,8%) | 1898 (1,7%) | 62 |




| 2001 | 2002 | 2003 | 2004 | 2005 | 2006 | 2007 | 2008 | 2009 |
|---|---|---|---|---|---|---|---|---|
| **A:** 35 | **B:** 96 | **B:** 68 | **A:** 38 | **D:** 59 | **D:** 150 | **D:** 102 | **D:** 64 | **A:** 42 |
| **B:** 28 | **A:** 32 | **A:** 47 | **B:** 44 | **A:** 57 | **B:** 78 | **A:** 77 | **A:** 51 | **D:** 24 |
| **C:** 21 | **C:** 30 | **C:** 46 | **C:** 29 | **C:** 43 | **A:** 63 | **C:** 29 | **C:** 40 | **C:** 20 |

A: Switches and crossings C: Positioning

B: Track D: Fault dissappeared

*Figure 9: Train delay with the three underlying systems of highest operational risk, note that the track (letter B) disappears after 2006 from the top three; see Figure 10.*

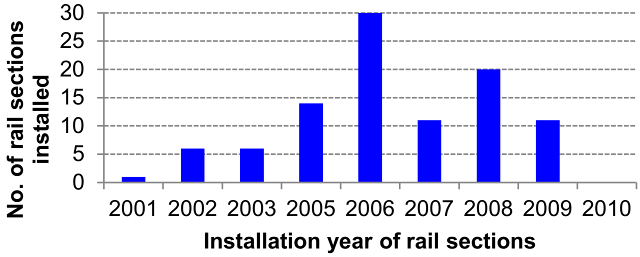



*Figure 10: Renewal of rail sections. The large number of renewals in 2006 coincides with the disappearance of the track in the top three poor performing systems in 2006; see Figure 9. A total of 99 out of 188 rail sections were replaced between 2001 and 2010.*

### 4.4 Step 4: Identification of improvements, ranking and implementation

The previous section shows how indicators can be developed. Performance killers and drivers, i.e. items of poor and good performance, are identified in Figure 8 to 10 and Table 2. By redesigning or applying preventive maintenance to the identified performance killers, the overall delay can be reduced effectively, directly impacting the indicators listed in Step 2. However, it is preferable to simulate improvements before moving into action. Figure 11 provides an example of a simulation. Figure 11(a) shows the result on the S&C system when all the WOs of the switch controller subsystem are removed from the data set, i.e. the controller subsystem is assumed to be redesigned and maintained so as to never fail. Such a change in the data set affects other factors at the system level. In Figure 11(b) all WOs of the railway section are sorted by the actual faults found by the repair team. The open circles show the result from Figure 11(a) when all the WOs of the switch controller system are removed from the data set. It can be seen that power cut faults in the railway experience the largest reduction.

## 5 Discussion and conclusions

Two key issues of PM systems are: they need to be able to handle implementation issues and business changes, and that the elements of strategic planning need to be clear as they sometimes are missing or used in different ways in organisations. The proposed link and effect model was developed with an emphasis on three components: continuous improvement; the key elements of strategic planning; and on the underlying factors responsible for the observed performance. The link and effect model differs from other PM systems in its focus on three components, in providing a break down process with description of the key elements of strategic planning, but especially, in its focus on the underlying factors of PIs. In traditional PM systems, PIs are given threshold values,

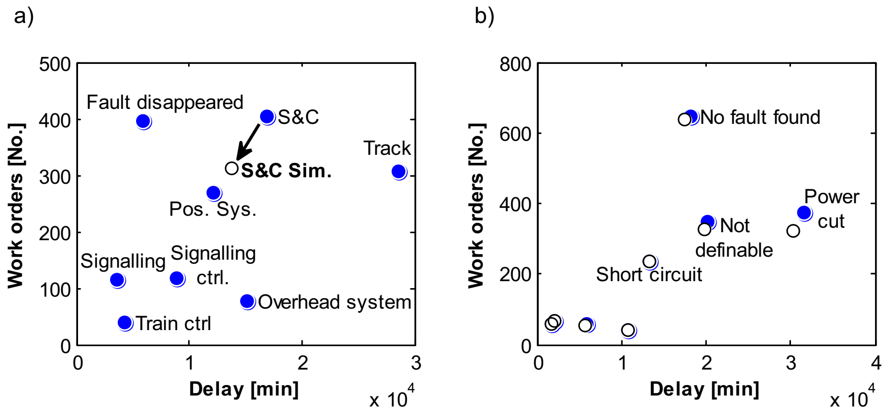



*Figure 11: Simulation at system level (a) impact on the S&C system when all the WOs of the switch controller subsystem are removed from the data set and (b) all WOs sorted on the registered actual fault. The open circles show the result when all the WOs of the switch controller subsystem are removed from the data set; power cut failures experience the largest reduction with 94 of the 1 926 WOs being removed.*

indicating when an action needs to be taken, i.e. they can make the system reactive if not appropriately used. Moreover, PIs are often aggregated individual indicators, e.g. total delay, which can make the PIs abstract and fail to provide in-depth knowledge.

The link and effect model was designed to isolate performance killers and drivers, to complement thresholds of indicators in traditional PM systems. In this approach, the problems of reactive thresholds and aggregated black box indicators are avoided, making the PM system more dynamic.

It was observed in the application of the model to the Iron Ore Line in Sweden, that the key elements of strategic planning in the railway business are used differently and to varying extents by the various stakeholders; this means that an experienced person is required to align strategic, tactical and operational planning under the same terminology and top-down basis.

Data analysis was carried out in two parts. The first part calculated performance killers of railway infrastructure systems over a 9 year period (Table 2). The second part performed a similar analysis for each of the nine individual years (Figure 9). It was found that aggregating the nine years of data does not necessarily give accurate information about the present state.

The algorithms developed in the case study take spreadsheets of raw data as inputs, which most computer software can generate. Thus, automatic analysis for specific needs can be carried out in-house, without large investment, to complement commercial CMMSs. The method is highly efficient, as the data cleaning process is simple. Therefore, detailed analysis needs to be carried out before taking specific actions. Additionally, simulations can be performed by modifying the input spreadsheets. Tests showed that modification of the data at the component level of the S&C appears on the indicators at the system level in terms of risk, failures, delays and maintenance times. In other words, it is possible to simulate the effect at the system level before carrying out improvements at the component level.

Further research could consider data quality in more detail. WOs require a number of fields to be completed before closure; therefore, detailed analysis of practice and requirements for WO closure can enhance the understanding of WO morphology and data quality. Moreover, stakeholders such as maintenance contractors and train operating companies can be considered in a mutual performance measurement system.

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# Paper B

# Performance Indicators of Railway Infrastructure

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# Performance Indicators of Railway Infrastructure

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**Abstract**

Railway traffic has increased over the last decade and it is believed to increase further with the movement of transportation from road to rail, due to the increasing energy costs and demand to reduce emissions. As a result of increasing need of railway capacity, more efficient and effective operation and maintenance is required. To manage the assets effectively within the business objectives, the results of operation and maintenance activities must be measured and monitored. Performance indicators are developed to support infrastructure managers in decision making, but they are sometimes used ad hoc and and not properly defined. In this paper, performance indicators for railway infrastructure, with primary focus on the railway track, have been mapped and compared with indicators of European Standards. The listed indicators can be applied to form a performance measurement system for railway infrastructure.

## 1 Introduction

Railway traffic has increased over the last decade and it is believed to increase further with the movement of transportation from road to rail, due to the increasing energy costs and the demand to reduce emissions. The key goals of the White Paper 2011 for the European transport system include; a 50 % shift of medium distance intercity passenger and freight journeys from road to rail and waterborne transport, and a 60 % cut in transport $CO_2$ emissions by 2050 (EC, 2011). At the same time, the crude oil output reached its all-time peak in 2006 (IEA, 2010). The available capacity of the railways has to be enhanced in order to meet these new demands in transportation.

As railway infrastructure and their components have a long life span, their management requires a long term sustainable strategy. Ongoing technical and economic assessments are necessary to optimise the performance of railway infrastructure and receive the return on investment (ROI) in a manageable timeframe. Long-term asset management objectives and strategies are developed to steer the operation and maintenance activities in the right direction. These objectives need to be broken down into quantitative operation and maintenance objectives to achieve a high level of robustness, punctuality and capacity within the operational budget, at the lowest life cycle cost, with no or an acceptable level of risk. See work by Espling and Kumar (2004), for further discussion on developing maintenance strategies for railway infrastructure.

To manage assets effectively within the agreed objectives, the effect of maintenance activities must be measured and monitored. Performance indicators (PIs) for RAMS (Reliability, availability, maintainability and maintenance supportability), capacity, punctuality, etc., are continuously developed to support infrastructure managers (IMs) to identify performance killers (items that performs poorly or hinders performance) and in making more efficient and effective decisions, but they are sometimes used ad hoc and and not properly defined. Measuring entails data collection, but since raw data does not give any information by itself, these must be analysed, validated and converted to information in the right format for decision making. This consumes resources, especially, if wrong parameters are measured. However, a good performance measurement system does not necessarily require a high level of precision (Kaydos, 1991). It is more important to know whether the trend is up or down and how the current value compares to historical measures. Consistency is therefore especially important in order to capture long term trends, predict future development and take the appropriate corrective actions at an early stage. Thus, if the methods for measuring or analysing are changed, the old information or analysis method should be kept for some time to safeguard the trend tracking. Moreover, performance measurement is also important for feasibility of railway certifications (Faria et al., 2012). It is crucial to thoroughly analyse what to measure, as large costs and equally large savings are associated with measuring. Thus, there exists a need to study the railway PIs used by different IMs, to find out which ones are the most important, which are required and which are not required.

A study was undertaken to review the maintenance PIs used by researchers in the field of railway maintenance, as well as reviewing project reports, policy documents, handbooks, etc. of European IMs. Interviews were also carried out. About 60 managerial maintenance PIs and about 70 infrastructure condition parameters have been identified in the study. Similar indicators have been considered as one in order to limit the total number of indicators.

Increased interoperability and building of a trans-European railway network is another goal of the European Union. The required harmonisation and standardisation of the management of railways have led to increased use of European standards. The identified PIs have therefore been compared to the European Standards; Maintenance Key Performance Indicators (KPIs), EN 15341, in order to find indicators in common (CEN, 2007).

Several projects on indicators and benchmarks for railway transport operations have been carried out, see reviews by EQUIP (2000), IMPROVERAIL (2001) and UTBI (2004). However, similar works on the maintenance aspect are few, which can be seen in Åhrén and Kumar (2004) and Åhrén (2008).

In this study, maintenance performance indicators for railway infrastructure have been mapped and compared with indicators of EN 15341 (CEN, 2007). The listed indicators form a basis for constructing a performance measurement system (PM-system) for railway infrastructure.

This paper is based upon Stenström et al. (2012), but the current paper includes the following additional research: grouping of indicators revised, revised text and figures, besides extended literature review.

# 2 Performance measurement

Measuring is a management tool which facilitates and supports efficient and effective decision making. In and of itself, it does not determine performance, but it can facilitate good management. What gets measured gets managed is not a promise (Emiliani, 2000).

Organisations use indicators in some form or another to measure their performance. The most common indicators are financial; many of these are mandatory by law. Other indicators are technical, organisational, HSE (health safety and environment), etc. There are few agreements on how to categorise indicators. It is up to each organisation to decide which standards or frameworks to use. Well known standards for maintenance KPIs are the European Standards EN 15341 and SMRP Best practice metrics (CEN, 2007, SMRP, 2011). Use of standardised indicators or metrics, such as the indicators from the standard EN 15341 or the SMRP metrics, has the following advantages (Kahn et al., 2011):

- Maintenance managers can rely on a single set of standardised indicators supported by a glossary of terms and definitions
- The use of standardised indicators makes it easier to compare maintenance and reliability performance across borders
- When a company wants to construct a set of company indicators or scorecard, the development process based on standardised indicators is simplified
- The standardised indicators can be incorporated in various enterprise resource planning (ERP) systems and reports
- The standardised indicators can be adopted and/or modified to fit specific requirements
- The need for discussion and debate on indicator definitions is not required and uncertainties are thus eliminated

Organisations' performance measurement system often grows from the need to measure different processes, thus, the number of databases and indicators grows over time. Some indicators stay while others become obsolete or disappear, but at some point, the amount of information is too large and becomes uncontrollable. The performance measurement system needs to be organised or reorganised, databases and indicators must be documented, regulations set, gaps must be identified, the performance measurement system must be aligned to the business goals and the owners of databases and indicators must be clear. See Figure 1, for high level requirements (HLRs) for organising a measurement system. Supportive guidelines for asset management in railways can be found in a work by International Union of Railways (UIC, 2010), as a seven-step procedure based on the following standards and manuals: PAS 55, the asset management standard by British Standards Institute (BSI, 2008a,b); the International Infrastructure Management Manual (IIMM) by New Zealand Asset Management Steering (NAMS) Group (INGENIUM

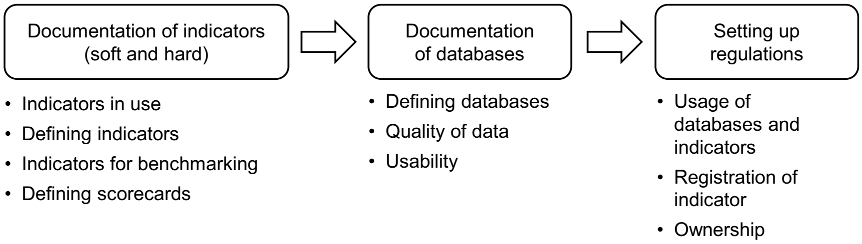


*Figure 1: High level requirements for organising or reorganising a performance measurement system (PM-system).*

and NAMS, 2006); and the Asset Management Overview by the US Highway Agency (FHWA, 2007).

According to Gillet, Woodhouse found that a human cannot control and monitor more than four to eight indicators at the same time (Gillett, 2001). Data aggregation is therefore necessary (Parida and Chattopadhyay, 2007); see Figure 2. As an example in railways, capacity and availability goals can be broken down to system and component performance requirements at the infrastructure level. The result is then aggregated and compared to the set objectives by use of indicators.

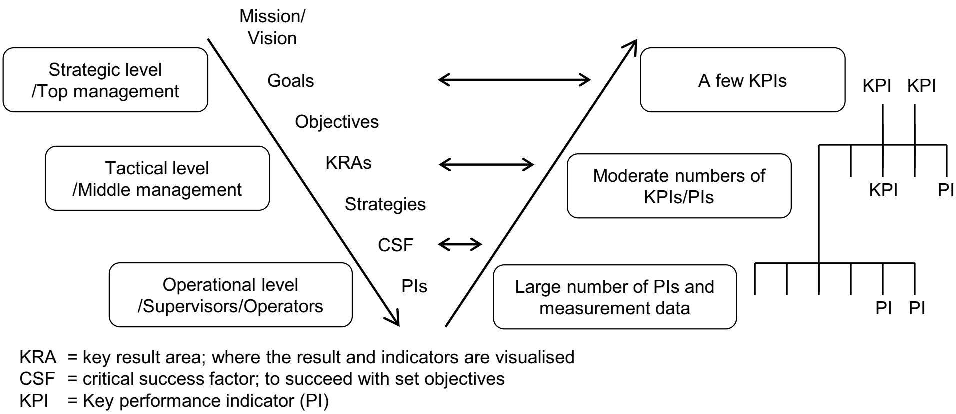


*Figure 2: Breakdown of goals and objectives and aggregation of data.*

It is not possible to measure everything with only quantitative or only qualitative methods. Rather a combination of both methods must be used to create a measurement system that is as complete as possible. Qualitative measurement methods are good for measuring soft values like employee satisfaction and for checking conformity with quantitative indicators. Galar et al. (2010, 2011) have merged qualitative measures with quantitative ones and developed an audit that shows the relation between trends in questionnaires and indicators, validating the correlation or highlighting the divergence.

As this paper focuses on quantitative indicators, there are few qualitative indicators which are presented.

## 2.1 Railway infrastructure performance indicators

A study was undertaken to review the railway infrastructure PIs used by researchers and professionals in the field of railway infrastructure, as well as reviewing project reports, policy documents, handbooks, etc., of European IMs. Interviews of the Swedish IM were also carried out. In order to manage the large number of indicators, they have been grouped into two overall groups; managerial and infrastructure condition indicators. The managerial indicators are extracted from different computer systems, e.g. enterprise resource planning (ERP), computerised maintenance management system (CMMS), etc., excluding condition monitoring data. Condition monitoring indicators are all the indicators and parameters extracted by sensors and by various inspection methods in the railway network. Managerial indicators are more at an overall system level compared to condition monitoring data that are at a subsystem or component level. See work by Stenström et al. (2011) for further discussion on terminology of performance indicators.

The PIs of EN 15341 are grouped into three categories; economic, technical and organisational. Health, safety and environment (HSE) indicators are part of the technical indicators. The railway managerial indicators are grouped accordingly, but the HSE indicators have been considered to have such importance that they have been put into a separate group. Condition monitoring data have been divided into six groups, see Figure 3. The groups can also be called key result areas; the few areas where the result and indicators are visualised (Leidecker and Bruno, 1984).

The following subsections present the four groups of managerial indicators and the six groups of the condition monitoring indicators.

### Managerial indicators

The managerial indicators are put into system and subsystem levels. System is considered as the whole railway network supervised by an IM. Subsystems are railway lines, classes, specific assets and items. Some indicators are found at both levels, while others are only found at one level. Each indicator has been given an identification number (#) similar to the system used in EN 15341 (CEN, 2007), i.e. starting with E, T, O, and for the fourth group, it starts with H.

Technical indicators are closely related to reliability, availability and maintainability (RAM); see Tables A.1 and A.2. The research is extensive: for work on failure frequencies and delays, see Nyström and Kumar (2003), Granström and Söderholm (2005), Granström (2008) and VTI (2011); for maintainability, see Nyström and Kumar (2003) and INNOTRACK (2009); for capacity, see UIC (2004) and Åhrén and Kumar (2004);

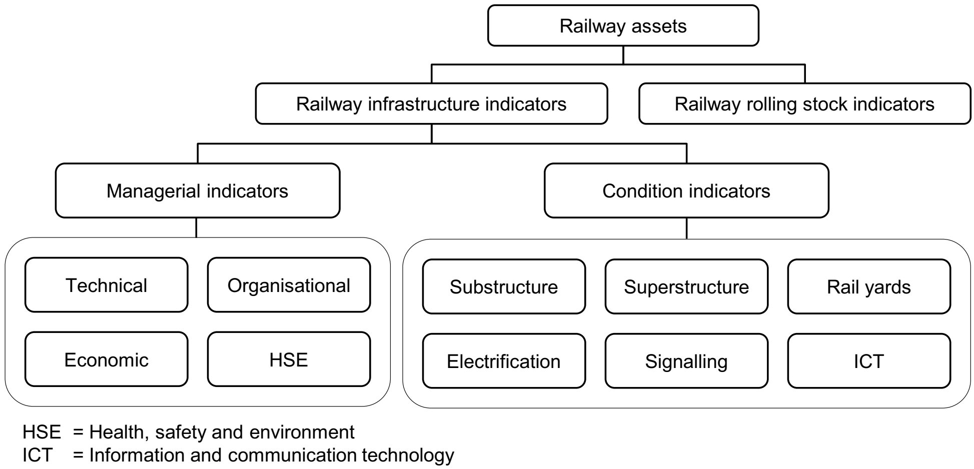


*Figure 3: Structure of railway infrastructure performance indicators.*

and for overall equipment effectiveness (OEE) and data envelopment analysis (DEA), see George and Rangaraj (2008), Åhrén and Parida (2009) and Malhotra et al. (2009).

Quantitative indicators should always be complemented with qualitative indicators, like questionnaires. This has special importance in the organisational perspective due to strong human interactions. See Table A.3, for quantitative organisational indicators.

Many overall financial indicators are regulated by the ministry of the IM and are therefore easy to find; see Table A.4. Besides annual reports, those indicators are also often used in high-level benchmarking, e.g. see Parida and Chattopadhyay (2007) and Galar et al. (2010). Similar cost indicators at operational level, i.e. per item, are scarcer, but research is carried out, e.g. on switches and crossings by REMAIN (1998), Nissen (2009a) and Nissen (2009b).

Maintenance staffs are exposed to hazards and suffer from bad ergonomics due to unstandardized or non-routine work, lowered barriers, leakage, pressure, electricity, etc. (Galar et al., 2011). As in all forms of rail transportation, the safety is a critical factor. Thus, HSE has a special importance in the management of railway infrastructure maintenance. General HSE indicators are easy to find and often required by law, but specific ones for maintenance are scarcer. Both types have been considered in Table A.5.

### Condition monitoring indicators

The railway condition monitoring (CdM) indicators have been divided into six groups; substructure, superstructure, rail yards, electrification, signalling, and information and communication technology (ICT), Figure 3. Condition monitoring of these assets has been mapped by studying various inspection methods, mainly from Esveld (2001), INNOTRACK (2008) and BSL (2009); see Tables A.6 and A.7. Ocular inspections and manual inspections using gauges have been left out due to their large number of routines. Bridges and tunnels condition monitoring have not been considered either; they are out of the scope of this paper. Wayside detectors are monitoring trains; only the infrastructure is considered in this paper. Nevertheless, the rolling stock is as important as the infrastructure since it will be in similar condition (Lardner, 1850). See work by Bracciali (2012) for a state-of-the-art review on wayside detectors.

## 2.2 Constructing a railway maintenance scorecard

A scorecard, scorebook or scoresheet in business is a statistical record used to measure achievement or progress towards a particular goal (Oxford Dict., 2011).

For a successful MPM-system, it needs to be able to provide the right information at the right time, to the right people, in the right quantity and format (Parida and Kumar, 2004). According to Gillett (2001), Woodhouse found that a human cannot control and monitor more than four to eight indicators at the same time. For these reasons, it is essential to find the right indicators for the different organisational levels, indicators that match the objectives and strategy of the business. With use of a scorecard the top management can oversee the indicators for each responsibility, e.g. operations, financial, HR, etc. The indicators and parameters in Tables A.1-7 have been brought together into a scorecard; see Table 1.

*Table 1: Railway infrastructure performance measurement scorecard.*

| **Perspective** | **Aspect** | **Indicators [no.]** | |
|---|---|---|---|
| **Managerial** | | **System** | **Subsystem** |
| Technical | Availability | 7 | 7 |
| | Maintainability | 1 | 1 |
| | Capacity consumption | 1 | 3 |
| | Riding comfort | - | 1 |
| | OEE and DEA | - | 2 |
| | Age | - | 1 |
| Organisational | Maintenance management | 4 | 2 |
| | Failure reporting process | 1 | 1 |
| Economic | Allocation of cost | 6 | 1 |
| HSE | Health | 3 | - |
| | Safety - General | 6 | - |
| | Safety - Maintenance | 4 | - |
| | Environment | 4 | - |
| **Condition monitoring** | | **Subsystem** | **Component** |
| Technical | Substructure | 6 | 16 |
| | Superstructure | 10 | 30 |
| | Rail yard | - | - |
| | Electrification | - | - |
| | Signalling | 1 | 4 |
| | Information communication tech. | - | - |

# 3 Linking railway indicators to EN 15341

The indicators of EN 15341 consist of 71 key performance indicators (KPIs) categorised into three groups and three levels (CEN, 2007). The groups are economic, technical and organisational indicators, and the levels are going from general indicators to more specific indicators. The KPIs have been constructed by taking the ratio of two or more factors, or PIs. The railway indicators have therefore been compared both with the factors and the KPIs of level one to three; see Tables 2 and 3. Indicators at the same row are considered to be closely related to each other.

*Table 2: Relationship between railway PIs and EN 15341 PIs.*

| **Railway PIs** | | **EN 15341 PIs** | |
|---|---|---|---|
| **#** | **Name/Description** | **#** | **Name/Description** |
| E3 = E1/T17 | Maintenance cost / Traffic volume | E3 | Total maintenance cost / Quantity of output |
| E2/E1 | Maintenance management cost / Maintenance cost | E13 | Cost for indirect maintenance personnel / Total maintenance cost |
| E4/E1 | Maintenance contractor cost / Maint. cost | E10 | Total contractor cost / Total maintenance cost |
| E1/H15 | Maintenance cost / Energy consumption per area | E14 | Total maintenance cost / Total energy used |
| E5/E1 | Corrective maintenance cost / Maintenance cost | E15 | Corrective maintenance cost / Total maintenance cost |
| E6/E1 | Preventive maintenance cost / Maint cost | E16 | Preventive maint. cost / Total maint. cost |
| H10/ Time | Maintenance accidents and incidents / Time | T5 | Injuries for people due to maintenance / Working time |
| H11/T3 | Failure accidents and incidents / Failures in total | T11 | Failures causing injury to people / Number of failures |
| | | T12 | Failures causing pot. injury to people / Number of failures |
| O2+T16 | Mean waiting time (MWT) + Mean time to repair (MTTR) | T21 | Total time to restoration / Number of failures |
| O3 | Maintenance backlog | O22 | Work orders performed as scheduled / Scheduled work orders |

*Table 3: Relationship between railway PIs and EN 15341 PIs.*

| Railway PIs | | EN 15341 PIs | |
|---|---|---|---|
| **#** | **Name/Description** | **#** | **Name/Description** |
| E1 | Maintenance cost | E1.1 | Total maintenance cost |
| T17 | Traffic volume | E3.2 | Quantity of output |
| E2 | Maintenance management cost | E13.1 | Cost for indirect maintenance personnel |
| E4 | Maintenance contractor cost | E10.1 | Total contractor cost |
| H15 | Energy consumption per area | E14.2 | Total energy used |
| E5 | Corrective maintenance cost | E15.1 | Corrective maintenance cost |
| E6 | Preventive maintenance cost | E16.1 | Preventive maintenance cost |
| H10 | Maintenance accidents and incidents | T5.1 | Injuries for people due to maintenance |
| T3 | Failures in total | T11.2 | Total number of failures |
| H11 | Failure accidents and incidents | T11.1 | Failures causing injury to people |
| | | T12.1 | Failures causing pot. injury to people |

# 4 Discussion

Maintenance performance indicators for railway infrastructure have been identified and listed in Tables A.1-7. Similar indicators have been considered as one indicator. Some indicators have been added, since they are considered as general indicators, e.g. maintenance personnel absenteeism. The listed indicators form a basis for constructing a performance measurement system for railway infrastructure. Though, the focus has been on the railway track, besides considering some parts of the overhead contact system, other systems have not been considered, e.g. bridges, tunnels, and signalling. Moreover, studies have shown that the railway infrastructure and train operating companies (TOCs) are responsible for 20-30 % and 30-40 % of the train delay, respectively (Espling and Kumar, 2004, Nyström and Kumar, 2003, Granström and Söderholm, 2005). The studies also showed that the rolling stock, vehicle failures, is responsible for 10-20 % of the delay. Performance measurement and indicators for assessing the performance of rolling stock and operations are therefore likewise important for the credibility and dependability of railways. Extensive work on indicators and benchmarking on this have been carried out in (EQUIP, 2000, IMPROVERAIL, 2001, Adeney, 2003, Anderson et al., 2003, UTBI, 2004).

The identified indicators have been compared to EN 15341 (CEN, 2007) in Tables 2 and 3. It was found that 11 PIs are similar. A number of the indicators in the European standard are general for any maintenance functions. Nevertheless, it has to be kept in mind that the standard is mainly for manufacturing businesses and not for linear assets. Thus, many railway indicators cannot be found in the standard.

The scorecard in Table 1 has two groups called availability and capacity, respectively.

Availability related indicators are considered as indicators of punctuality, regularity, failures, delay and temporary speed restrictions, while capacity related indicators are of traffic volume and capacity consumption. The latter one is according to UIC (2004). However, any general availability indicators for railways could not be found, such as uptime measures, or like indicator T1 of EN 15341: Total operating time / Total Operating time + Downtime due to maintenance. Regarding capacity, the indicator Capacity consumption by UIC (2004) is extensively used by IMs, which is a measure of how occupied an infrastructure is. Thus, the amount of output, effective capacity, or such, is not measured.

Performance measurement of railway infrastructure provides information regarding the condition of systems and components. Failure rates, failure causes and the corresponding delays can be monitored and compared to expected lifetime calculations. Thus, it provides additional inputs to lifecycle costing and cost-benefit analysis, which can be made more accurate. However, it requires a well-developed performance measurement system with consistency over time for trend tracking. For a thorough review of railway maintenance cost estimation, see work by Ling (2005).

# 5 Conclusions

A study of the performance measurement of railway infrastructure was undertaken. As a result, performance indicators of railway infrastructure have been listed in Tables A.1-7 and categorised into two groups; managerial and condition monitoring indicators. The identified indicators have been compared to EN 15341 (CEN, 2007); 11 indicators were found to be similar, which can facilitate external benchmarking.

Infrastructure managers use performance measurement to study whether results are in line with set objectives, for predicting maintenance and reinvestments, decision support and benchmarking, i.e. business safety. The listed indicators can therefore be used by infrastructure managers for reviewing and improving their performance measurement system. It also provides a background for a possible future standardisation of railway indicators. However, harmonising between infrastructure managers for benchmarking is a challenge, since the operational and geographical conditions varies extensively.

This study has been mainly focused on the railway track. Scope of future work can be on other infrastructure assets and the rolling stock.

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# A Tables

*Table A.1: Technical railway infrastructure indicators.*

| **Technical indicators** | | | |
|---|---|---|---|
| **Category** | **Indicators** (Comments) [Unit] | **Reference** | # |
| Availability | **System level** | | |
| | Arrival punctuality [no. or %, passenger or freight] | (Banverket, 2010, Söderholm and Norrbin, 2011) | T1 |
| | Train regularity [no. or %, passenger or freight] | (Banverket, 2010) | T2 |
| | Failures in total [no.] | (Nyström and Kumar, 2003, Granström and Söderholm, 2005, Granström, 2008, VTI, 2011, CEN, 1999, Banverket, 2003) | T3 |
| | Train delay [time] | | T4 |
| | Delay per owner (Operation centrals, Secondary delays, Infrastructure, Train operators, Accidents and incidents, etc.) [%/owner] | | T5 |
| | Faults interfering with traffic [no. or %] | (Banverket, 2007) | T6 |
| | Temporary speed restrictions (TSRs) [no.] | (BSL, 2009) | T7 |
| | **Subsystem level** | | |
| | Punctuality per line, line class or area [no. or %/line, class or area] | (Banverket, 2010) | T8 |
| | Regularity per line, line class or area [no. or %/line, class or area] | - | T9 |
| | Failures per item [no./item] | (Nyström and Kumar, 2003, Granström and Söderholm, 2005, Granström, 2008, VTI, 2011, Banverket, 2003) | T10 |
| | Failures per track-km, line, line class or area [no./track-km, line, class or area] | | T11 |
| | Delay per item [time/item] | | T12 |
| | Delay per line, line class or area [time/line, class or area] | | T13 |
| | Temporary speed restrictions (TSRs) per line, line class or area [no./line, class or area] | (BSL, 2009) | T14 |
| Maintainability | **System level** | | |
| | Mean time to repair (MTTR) (or Mean time to maintain (MTTM), or Maintainability) | (INNOTRACK, 2009, CEN, 1999) | T15 |
| | **Subsystem level** | | |
| | Mean time to repair (MTTR) per item (or Maintainability) | (Nyström and Kumar, 2003, INNOTRACK, 2009) | T16 |

*Table A.2: Continuation of technical railway infrastructure indicators.*

| **Technical indicators** | | | |
|---|---|---|---|
| **Category** | **Indicators** (Comments) [Unit] | **Reference** | # |
| Capacity consumption | **System level** | | |
| | Traffic volume [train-km or tonne-km] | (Åhrén and Kumar, 2004, Banverket, 2010) | T17 |
| | **Subsystem level** | | |
| | Traffic volume per line, line class or area [train-km or tonne-km/line, class or area] | (Åhrén and Kumar, 2004, Banverket, 2010) | T18 |
| | Capacity consumption (or Capacity utilisation) (24h and 2h) [%] | (Åhrén and Kumar, 2004, UIC, 2004, Banverket, 2010) | T19 |
| | Harmonised capacity consumption (double track counted twice) [train-km/track-metre] | (Stenström, 2012a) | T20 |
| Riding comfort | **Subsystem level** | | |
| | Track quality index (TQI) (e.g. K-/Q-value) [index] | (BSL, 2009) | T21 |
| OEE and DEA | **Subsystem level** | | |
| | Overall equipment effectiveness (OEE) per line, line class or area [%/line, class or area] | (Åhrén and Parida, 2009) | T22 |
| | Data envelopment analysis (DEA) [-] | (George and Rangaraj, 2008, Malhotra et al., 2009) | T23 |
| Age | **Subsystem level** | | |
| | Mean age of assets (rail, S&C, OCS, ballast, etc.) [time] | (Trafikverket, 2011) | T24 |

*Table A.3: Organisational railway infrastructure indicators.*

| **Organisational indicators** | | | |
|---|---|---|---|
| **Category** | **Indicators** (Comments) [Unit] | **Reference** | # |
| Maintenance management | **System level** | | |
| | Preventive maintenance share (or Corrective maintenance share) [%] | (Unckel, 2010) | O1 |
| | Mean waiting time (MWT) (or Maintenance supportability, or Organisational readiness, or Reaction time, or Arrival time) [time] | (INNOTRACK, 2009) | O2 |
| | Maintenance backlog [no. or time] | (BSL, 2009) | O3 |
| | Maintenance possession overrun [time or no.] | (Olsson and Espling, 2004) | O4 |
| | **Subsystem level** | | |
| | Preventive maintenance share (or Corrective maintenance share) per line, line class, area or item [%/line, class, area or item] | (Stenström, 2012a) | O5 |
| | Mean waiting time (MWT) per line, line class, area or item [time/line, class, area or Item] | | O6 |
| Failure reporting process | **System level** | | |
| | Faults in infrastructure with unknown cause [no. or %] | (Stenström, 2012a,b) | O7 |
| | **Subsystem level** | | |
| | Faults in infrastructure with unknown cause per line, line class, area or item [no. or %/line, class, area or item] | (Stenström, 2012a,b) | O8 |

*Table A.4: Economic railway infrastructure indicators.*

| **Economic indicators** | | | |
|---|---|---|---|
| **Category** | **Indicators** (Comments) [Unit] | **Reference** | # |
| | **System level** | | |
| Allocation of cost | Maintenance cost (incl. or excl. management cost) [monetary] | (BSL, 2009, Banverket, 2010, Trafikverket, 2011) | E1 |
| | Maintenance management cost (or Indirect maintenance cost) [monetary] | (Banverket, 2010, Trafikverket, 2011) | E2 |
| | Maintenance cost per train-km, track-km or gross-tonne-km [monetary/train-km, track-km or gross-tonne-km] | (BSL, 2009, Banverket, 2010, Wireman, 2003, UIC - LICB, 2008) | E3 |
| | Maintenance contractor cost [monetary] | (Trafikverket, 2011) | E4 |
| | Corrective maintenance cost [monetary] | (Stenström, 2012a) | E5 |
| | Preventive maintenance cost [monetary] | | E6 |
| | **Subsystem level** | | |
| | Maintenance cost per line, line class, area or per item [monetary/line, class, area or item] | (REMAIN, 1998, Nissen, 2009a,b) | E7 |

*Table A.5: HSE (health, safety and environment) railway infrastructure indicators.*

| **HSE indicators** | | | |
|---|---|---|---|
| **Category** | **Indicators** (Comments) [Unit] | **Reference** | # |
| Health | Maintenance personnel absenteeism [time or no.] | General | H1 |
| | Maintenance employee turnover [no.] | | H2 |
| | Maintenance employee talks [no.] | | H3 |
| Safety - General | Urgent and one-week inspection remarks [no.] | (Stenström, 2012a) | H4 |
| | Harmonised inspection remarks | | H5 |
| | Deaths and injuries (or Casualties and accidents) [no.] | (BSL, 2009, Trafikverket, 2011, Holmgren, 2005) | H6 |
| | Accidents at level crossings [no.] | (Åhrén and Kumar, 2004, BSL, 2009) | H7 |
| | Accidents involving railway vehicles [no.] | (Åhrén and Kumar, 2004) | H8 |
| | Incidents (or Mishaps, or Potential injuries) [no.] | (Trafikverket, 2011) | H9 |
| Safety - Maintenance | Maint. accidents and incidents (occurred and potential) [no.] | (Holmgren, 2005) | H10 |
| | Failure accidents and incidents (occurred and potential) [no.] | | H11 |
| | Derailments [no.] | (BSL, 2009, Trafikverket, 2011, Famurewa et al., 2011) | H12 |
| | Bucklings (or Sun kinks) [no.] | (BSL, 2009) | H13 |
| Environment | Environmental accidents and incidents due to failure [no.] | General | H14 |
| | Energy consumption per area [J/area] | (Åhrén and Kumar, 2004) | H15 |
| | Use of environmental hazardous materials [-] | | H16 |
| | Use of non-renewable materials [-] | | H17 |

*Table A.6: Condition monitoring of railway infrastructure and data extracted.*

| Features | Method | Parameters (component level) | PIs (Subsystem level) |
|---|---|---|---|
| **Substructure - Embankment** | | | |
| Ballast composition | Ground penetrating radar (automatic) | Ballast composition (layered structure) | - |
| Track stiffness (related to bearing capacity) | Hydraulic loading (automatic with stops) | Track deflection/stiffness/ strength | Deduced: Stiffness loss inspection remarks [no. or no./length] |
| | Deflectographs (continuous) | Track deflection/stiffness/ strength, Deflection speed | |
| **Substructure - Track geometry** | | | |
| Geometry | Contact axles, Optical sys., Gyroscope sys., Intertial sys. | Gauge, Cross level, Cant, Long. level, Twist, Geometry of rails, Alignment, Wheel-rail contact profile | TQI (Track quality index), based on std. dev., commonly for each 200 m.<br>Deduced: Track geometry inspection remarks [no. or no./km] |
| | Failure reporting | Bucklings (or Sun kinks) | Bucklings [no.] |
| **Substructure - Track surroundings** | | | |
| Clearance and signal visibility | Video system | Vegetation clearance, Signal visibility | Track surroundings inspection remarks [no. or no./km] |
| **Superstructure - Rail** | | | |
| Integrity | Continuous monitoring using sensors | Temperature, Stress (longitudinal) | Deduced: Potential buckling hazards [no. or no./km], Potential rail breaks [no. or no./km], Bucklings [no. or no./km], Rail breaks [no. or no./km] |
| | Ultrasonic inspection | Discontinuities in central part of head, web, foot and running side | Deduced: Ultrasonic and eddy current inspection remarks [no. or no./km] |
| | Eddy current inspection | Discontinuities in the running surface | |
| Rail profile, Rail surface, Fasteners | Optical profile and surface sys., LVDT corrugation sys., Axle box accelerometers | Profile, Gauge wear, Running surface wear, Rail inclination, Rail type, Corrugation (amp. and $\lambda$) | Deduced: Inspection remarks requiring grinding, rail replacement or component replacement [no. or no./km], Rail breaks [No.] |
| | Video system | Rail breaks, Rail joints, Burns/patches, Corrugation, Fastenings | |

*Table A.7: Continuation of condition monitoring of railway infrastructure and data extracted.*

| Features | Method | Parameters (component level) | PIs (Subsystem level) |
|---|---|---|---|
| **Superstructure - Switches and crossings (S&C)** | | | |
| Geometry and integrity | Geometry car | Track deflection at S&Cs | Deduced: S&C deflection inspection remarks [No. or No./S&C] |
| | Continuous monitoring using sensors | Contact area between blade and rail, Switch flangeway (open distance), Operational force, Power and current usage, Residual stress (retaining force), Detector rods pos. | Deduced: Malfunctions per switch type [No. or %] (in open, in closed, residual stress, detector rods, power or current consumption) |
| | | Impacts on frog (wear) | Deduced: Axis passing [No.] |
| | | Rail temp, Stress (longitudinal) | |
| | Mechatronic system | Gauge, Switch blades groove width, Cross level, Twist | Switch total deviation |
| | Ultrasonic Testing | Discontinuities at critical spots | Deduced: Ultrasonic testing remarks [No. or No./switches] |
| **Superstructure - Overhead contact system (OCS)** | | | |
| Position and Condition | Optical system (laser) | Vertical and lateral (stagger) position of contact wire, Contact wire thickness, Abrasion patches at contact wire | Deduced: Inspection remarks requiring adjustment or replacements of OCS components [No. or No./km] |
| | Video system | Condition of catenary wire, droppers, clamps and contact wire | |

# Paper C

# Measuring and Monitoring Operational Availability of Rail Infrastructure

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# Measuring and Monitoring Operational Availability of Rail Infrastructure

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**Abstract**

In reliability and maintenance engineering, availability can be described as the ability of an item to be in a state to perform a required function at a given instant of time. Availability is commonly given as a measure between zero and one, where one is meaning that the probability of an item to be available for use at a given time is 100 %. The practice of measuring availability can be found in many areas, such as electronics, information technologies, military equipment, electrical grids and the industry, however, such a measure has not been scientifically integrated in railways. Therefore, a method for measuring availability in railways has been developed in this study, and verified through a case study with comparison of results using various approaches.

## 1 Introduction

Railway traffic has increased over the last decade and it is believed to grow further as passenger and freight transportation shift from road to rail, due to rising energy costs, congestion of roads and sky, and the demand to reduce emissions (EC, 2001, 2011). As for the European transport system, the White Paper 2011 include a 50 % shift of medium distance intercity passenger and freight journeys from road to rail and waterborne transport, and a 60 % cut in transport $CO_2$ emissions by 2050 (EC, 2011). Thus, the capacity of railways needs to be enhanced with preserved or increased availability to meet these new demands in the transport sector.

As railways are capital intensive and have a long life span, their operation and maintenance requires a long term and sustainable strategy. Strategic planning involves collecting information, setting of goals, translation of goals to specific objectives and setting up activities for achieving the objectives. Following the formulation of the strategy, objectives are broken down to tactical and operational plans. The outcomes of the strategy are continuously assessed by collecting data, aggregating the data into information and report back the information to the strategic, tactical and operational planning, often in the form of scorecards (Marsden and Snell, 2009, Stenström et al., 2013). The information commonly consists of indicators of both technical and organisational perspectives. Technical indicators in railways are for example failures, train delay, punctuality and track geometry (Stenström et al., 2012).

As humans have a limited perception and limited capability to process information, the number of indicators that one person can monitor is limited, and thus, the number of strategic-level indicators depends on the number of senior managers. Consequently, identification of the most important indicators and data aggregation is needed, since there can be several hundreds of indicators or parameters at the operational level of railways (Stenström et al., 2012). Availability is a function of reliability, maintainability and maintenance supportability, i.e. it depends on how often an item fails, the time it takes to restore the function by carry out maintenance, and the time it takes for the supporting organisation to react on failures. Therefore, availability measures include critical aspects of both technical and organisational perspectives in a single measure. Availability measures are used in various fields of design, operation and maintenance for measuring and monitoring performance, such as electronics (U.S. Dept of Defense, 1995), electricity generation (IEEE, 2007), mining (Kumar and Klefsjö, 1992) and maintenance (Jardine and Tsang, 2013). It is often considered as a key performance indicator (KPI) (CEN, 2007, SMRP, 2011), and is also used in calculation of overall equipment effectiveness (OEE).

In railways, the European Standards EN 50126 (CEN, 1999) gives guidelines to RAMS (reliability, availability, maintainability and safety) specification. The standard defines availability in accordance to other standards. However, as the standard is concerning RAMS specification, monitoring of performance during operation and maintenance is only mentioned briefly. Furthermore, Patra and Kumar (2010) developed a Petri net model that can be used for RAMS specification. The model takes failure rates and down times as inputs and gives the availability as an output. Besides, utilising increased availability is a main goal of timetabling, punctuality and delay time modelling (Huisman et al., 2005, Vromans et al., 2006, Wang et al., 2011). Similarly, reliability modelling (Carretero et al., 2003, MacChi et al., 2012) and maintenance management (Zoeteman, 2001, 2006) also aim at increased availability.

For monitoring of availability during the operation and maintenance, Mahmood et al. (2013) studied reliability, availability and maintainability of frequency converters in railways using the IEEE Std 762 (IEEE, 2007). The data stretched over four years and 46 frequency converter stations.

When it comes to availability of rail infrastructure and train operation, Nyström (2009) reviewed indicators related to availability. Examples of indicators reviewed are measures of punctuality, track condition and disabled state (down state). Nyström further constructed two measures to be used as measures of availability in rail infrastructure, namely: obtained capacity / planned capacity, and 1 - slack time / total travel time. Availability of rail infrastructure has also been studied in the INNOTRACK project; a project part of EU's Sixth Framework Programme. Indicators related to the availability of rail infrastructure were found to be: train delay, obtained capacity divided by the planned capacity, up time and down time, and arrival punctuality (INNOTRACK, 2009, 2010). It is further found that the definition of availability in railways needs to be sorted out if it a function of capacity utilisation, what data is required for it and how it is related to train delays (INNOTRACK, 2009). It is also found that availability is defined differently between infrastructure managers. For RAMS analysis, it is suggested that availability should be studied for the system/track to understand the extent to which it is available for operation. This for example can give a guarantee of track availability without traffic interruptions (INNOTRACK, 2010). For this, Söderholm and Norrbin (2014) used the share of successful train passages as a measure of availability.

In view of the studies above, monitoring of availability in the operation and maintenance phase of railways needs to be studied further to comply with common practice. Thus, the aim of this study is to apply and measure availability in the operation and maintenance phase of railways using common definitions. A short review of availability is given in the next section, followed by the methodology. A case study is carried out thereafter to verify and demonstrate the methodology. The findings are thereafter concluded in the last section.

# 2 Availability

Qualitatively, availability can be described as the ability of an item 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 (IEC, 1990, CEN, 2010). Quantitatively, availability can be calculated as instantaneous availability, mean availability and asymptotic availability (CEN, 1999, IEC, 1990, U.S. Dept. of Defense, 1998). Instantaneous availability is the probability that an item is in a state to perform a required function under given conditions at a given instant of time, assuming that the required external resources are provided (IEC, 1990), or the probability that a system will be available for use at any random time $t$ after the start of operation (U.S. Dept. of Defense, 1998). Mean availability is then the mean of the instantaneous availability over a given time interval, and the asymptotic is the limit of the instantaneous availability when the time approaches infinity.

Availability depends on the combined aspects of reliability, maintainability and maintenance supportability (IEC, 1990, CEN, 2010); see Figure 1.

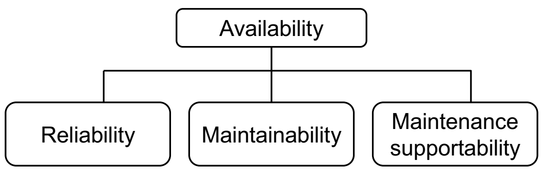


*Figure 1: Reliability, availability, maintainability and maintenance supportability.*

Similarly to availability, reliability and maintainability can be described both qualitatively and quantitatively. Quantitatively, reliability can be defined as the probability that an item can perform a required function under given conditions for a given time interval (IEC, 1990), and maintainability as the 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 (IEC, 1990). In this context, active maintenance time is the time during which a maintenance action is performed on an item, excluding logistic delays (IEC, 1990, CEN, 2010). Maintainability is a design parameter, where mean time to repair (MTTR) is the primary parameter (U.S. Dept. of Defense, 1997, O'Connor and Kleyner, 2012). However, maintenance support parameters can be included depending on the method used for calculating maintainability (O'Connor and Kleyner, 2012). Maintenance supportability is described as the ability of a maintenance organisation, under given conditions, to provide upon demand, the resources required to maintain an item, under a given maintenance policy (IEC, 1990, CEN, 2010). Maintenance support issues can for example be measured in administrative delay and logistic delay (IEC, 1990).

An informative explanation of what availability measures are about, is given by U.S. Dept of Defense (2005): availability, as measured by the user, is a function of how often failures occur and corrective maintenance is required, how often preventative maintenance is performed, how quickly indicated failures can be isolated and repaired, how quickly preventive maintenance tasks can be performed, and how long logistics support delays contribute to down time.

Availability and non-availability can be measured with respect to various parameters. Nevertheless, there are three common measures that can be found in both standards and books (CEN, 2007, 1999, U.S. Dept. of Defense, 1998, O'Connor and Kleyner, 2012):

**Inherent availability ($A_I$)**, also known as intrinsic availability, includes the corrective maintenance time and omits the preventive maintenance and maintenance support. The inherent availability is a common measure given by original equipment manufacturers under ideal operational conditions. The AI is calculated as:

$$A_I = \frac{MTBF}{MTBF + MTTR} \tag{1}$$

where MTBF is the mean operating time between failures, and MTTR is the mean time to repair. MTTR is a part of active corrective maintenance time during which repair actions are performed on an item (IEC, 1990, CEN, 2010).

**Achieved availability ($A_A$)** includes the corrective and preventive maintenance time and omits the maintenance support:

$$A_A = \frac{MTBM}{MTBM + MAMT} \tag{2}$$

where MTBM is the mean operating time between maintenance, and MAMT is the mean active maintenance time. The active maintenance time is the part of the maintenance time during which a maintenance action is performed on an item, excluding logistic delays (IEC, 1990, CEN, 2010). A maintenance action may be carried out while the item is performing a required function, but these actions are excluded in the calculation of $A_A$.

**Operational availability** ($A_O$) includes the corrective maintenance time, preventive maintenance time and maintenance support. $A_O$ is the real availability under given operating environment and maintenance support:

$$A_O = \frac{MTBM}{MTBM + MMDT} = \frac{Up\,time}{Up\,time + Down\,time} \tag{3}$$

where MMDT is the mean maintenance down time.

The listed availability measures are used to calculate the mean availability over a period of time. It should also be noted that availability measures may vary between organisations and engineering fields, depending on the operating environment, and especially on what data is collected.

# 3 Methodology

To calculate availability, it requires that the down time is known, which includes failure rates, corrective maintenance times, preventive maintenance time, maintainability and maintenance support. Railways are utilised or occupied by trains according to a predefined time table, i.e. railways can be seen as a semi-continuous process, and thus, preventive maintenance is carried out between trains or at planned shutdowns. As the issue of measuring availability is concerning railways during operation and the preventive maintenance does not affect the operation as the corrective maintenance, the preventive maintenance is not included in the study.

Corrective maintenance is carried out after a fault is recognised. In railways, faults are commonly recognised by train drivers and dispatchers. When a fault has been recognised, the maintenance support is contacted and a work order is set up. The work order is followed up during the maintenance process and closed after the failure has been rectified and approved. Nowadays, most maintenance management systems include various data fields for administrative delay, logistic delay and repair time. However, since the maintenance times are typed in by train dispatchers and by the maintenance support, it is only approximate values of the times taken. Therefore, the registered times or averages can be used for calculation of availability. Maintenance times often have a log-normal distribution (U.S. Dept. of Defense, 1997, O'Connor and Kleyner, 2012), thus, the log-normal mean or median can be applied. However, care should be taken when the log-normal mean is used as it is sensitive to outliers. As an example, Figure 2 shows the time to restoration (TTR) using the data collected in the next section. The TTR includes the logistic time and repair time. The figure includes maintenance work order data up to the 95$^{th}$ percentile with reference to the TTR. It gives a log-normal mean of 410 minutes and a median of 171 minutes. Alternatively, instead of discarding data according to a percentage, limits can be set. By limiting the logistic time (LT) and active repair time (RT) to $5 < LT < 240$ minutes and $10 < RT < 600$ minutes, the log-normal mean is 204 minutes and the median is 147 minutes, i.e. less difference.

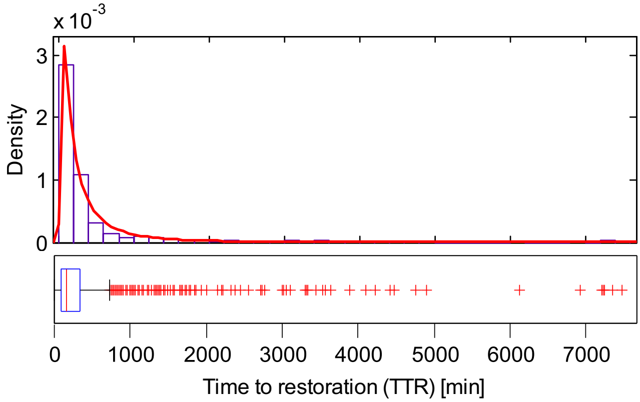


*Figure 2: Probability density function of the time to restoration (TTR) of the Swedish Iron Ore Line.*

Depending on the length of the railway section and if the whole infrastructure is included or only specific systems, there is a probability that more than one failure takes place at the same time. Consequently, the resulting availability will differ depending on how concurrent faults are considered in the work order data. See Figure 3. $\Delta t$ can be the registered time, the log-normal or the median of the time to restoration, logistic delay or repair time.

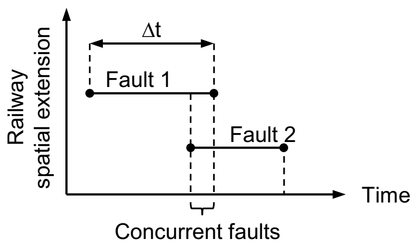


*Figure 3: Sketch of concurrent faults.*

As railways are operated semi-continuously, it is not all failures that will affect the trains and result in train delays. The aim of operational availability is to have a measure of the real experienced availability. If all failure work orders are included in the calculation of availability, the resulting measure will be the availability experienced by the infrastructure manager, and if only the train affecting failure work orders are included, the measure will be the availability experienced by the train operators and passengers in case of passenger trains. Henceforth, the availability based on train-delaying failures is called service affecting availability ($A_{SA}$).

Concluding, the following options are open in the conduct of availability measures in the operation and maintenance phase of railways:

- Selection of the maintenance data processing procedure, i.e. decide if the registered maintenance times, the log-normal mean or the median is to be used, as well as decide upon outliers and limiting ranges

- Incorporate concurrent faults, i.e. adjust to count concurrent faults only once

- Include all failures to measure the availability experienced by the infrastructure manager or only include the train-delaying failures to measure the availability experienced by the train operators

# 4 Data collection

Rail infrastructure related corrective maintenance data has been collected from the Swedish infrastruture manager (IM) Trafikverket (the Swedish Transport Administration) to verify the method and to study the effect of the different options the method comprises. The corrective maintenance data consist of urgent inspection remarks (requireing immediate repair) reported by the maintenance contractor, as well as failure events and failure symptoms identified outside the inspections, commonly reported by the train driver, but occasionally reported by the public. The collected data comes from seven railway lines in Sweden (Figure 4), and include 65 sections (Table 1).

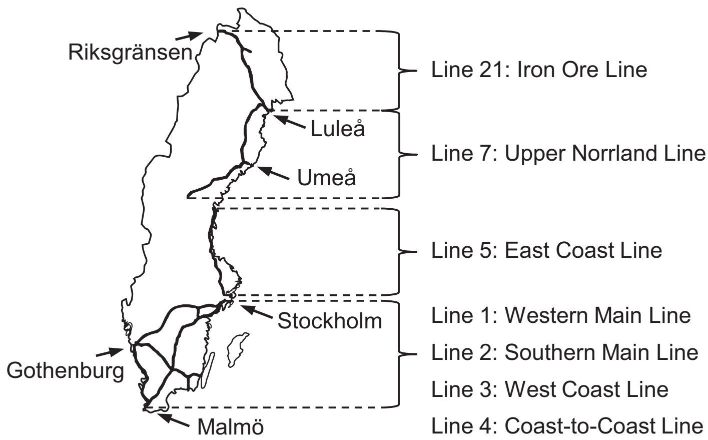


*Figure 4: Railway lines 1-5, 7 and 21 of the Swedish network.*

*Table 1: Sections of the railway lines for analysis.*

| Line | Section labels | No. of sections | Track length [km] | No. of S&Cs | Main track type |
|---|---|---|---|---|---|
| 1 | 410, 412, 414, 416, 418, 419, 420, 511, 512, 611, 612 | 11 | 979 | 792 | Double |
| 2 | 421*, 422, 502, 504, 505, 810, 811, 813, 814, 815, 817, 909, 910, 912 | 14 | 1117 | 947 | Double |
| 3 | 626, 627, 628, 630, 904*, 920*, 938, 940 | 8 | 531 | 393 | Double |
| 4 | 641, 655, 720, 721, 821, 822, 823, 824, 827 | 9 | 413 | 305 | Single |
| 5 | 234, 235, 303, 429, 430**, 433**, 243** | 7 | 629 | 634 | Single |
| 7 | 119, 120, 122, 124, 126, 129, 130, 138, 146, 211 | 10 | 723 | 701 | Single |
| 21 | 111, 112, 113, 114, 116, 118 | 6 | 467 | 248 | Single |
| Sum: | | 65 | 4859 | 4020 | |

*Single track, **Double track (counted twice in the track length column)

The lines connect the three largest cities of Sweden; Stockholm, Gothenburg and Malmö, as well as the heavy haul line in the north part of Sweden. The failure data are between 2013.01.01 - 2013.12.31, i.e. 1 year. Reported number of failures is 24 816, with 25 % of the failures resulting in train delays, i.e 6 131 train-delaying failures. Figure 5 shows the main types of train delaying failures. Train delay is the delay in minutes caused by failures, which in turn is recorded through the signalling system.

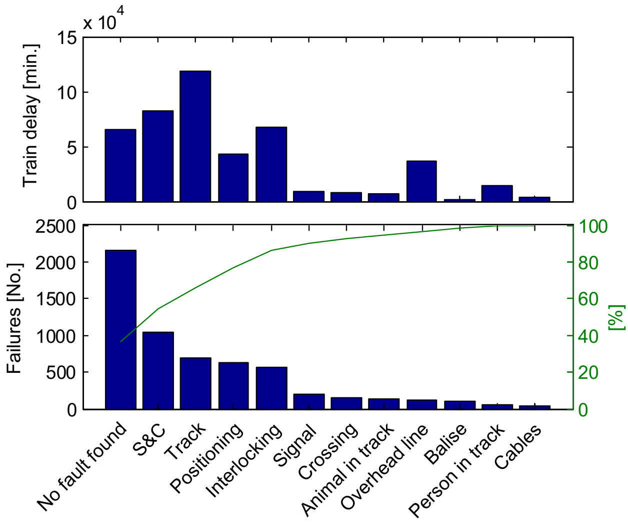


*Figure 5: Train delaying failures of the 65 railway sections.*

Availability at different technical levels will also be studied, and for that purpose a part of the rail asset register is included in Figure 6.

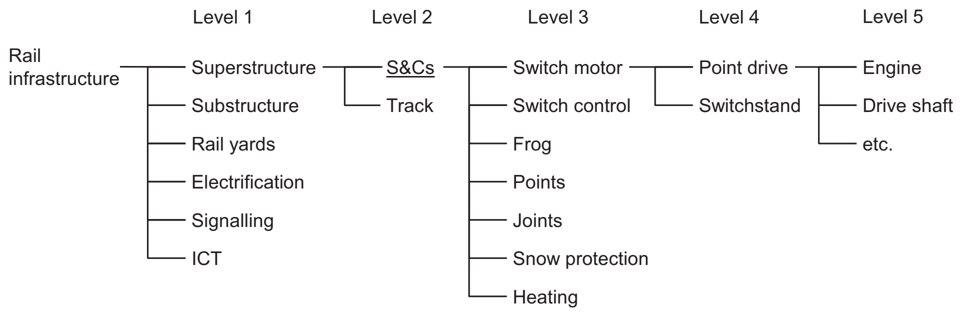


*Figure 6: A portion of the rail asset register of Trafikverket specifying the different levels of the switches and crossings (S&Cs).*

# 5 Results and discussion

Results are achieved by recalling Equation 3 and apply it on the collected data according to the considerations in Section 3. The service affecting availability ($A_{SA}$) at asset level 2 is shown in Figure 7, with comparison of the median time to restoration (TTR) and the log-normal mean TTR. The resulting availability may seem low; however, since 65 railway sections are included, the probability that there will be a failure in about 5 000 km of track is high. Due to some critical failures, such as tear down of the overhead contact wire, some of the failures have extraordinary long TTR, and therefore the availability is based on failures with TTR up to the $95^{\text{th}}$ percentile for the log-normal mean. It can be seen that the availability based on the log-normal mean (Figure 7b) is lower than for the availability based on the median (Figure 7a), which is in accordance with the discussion on Figure 2. It can further be seen that the traction substation system has a considerable lower availability when it is based on the log-normal mean in comparison to the median. This is due to few failures (21 failures) and the log-normal mean's sensitivity to outliers. This fallacy can be avoided by changing the percentile for outliers, i.e. set it lower than $95^{\text{th}}$ percentile, or by putting a range of which the failures' TTR must be within.

Credibility of indicators is critical for acceptance, implementation and use. An indicator that can show its usefulness will reduce discussion and uncertainties regarding its definition and application. Therefore, the availability measure is tested for correlation with train delays, with comparison to the correlation between failures and train delays; see Figure 8. The 14 data points in each of the two plots correspond to the 14 systems in Figure 7. Train delays and train-delaying failures are correlated with a $R^2$ of 0,73, while

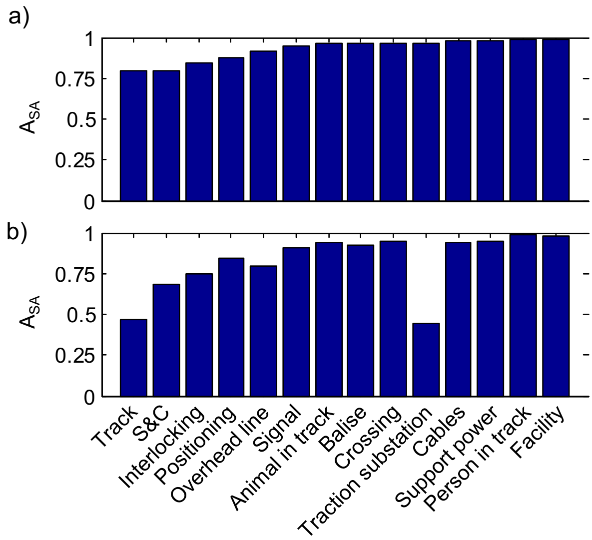


*Figure 7: Service affecting availability ($A_{SA}$) at asset level 2, based on the median time to restoration (TTR) in (a) and on the lognormal mean TTR in (b).*

the $R^2$ of train-delays and the service affecting availability ($A_{SA}$) is 0,94. Train delay data up the 98$^{\text{th}}$ percentile and TTR up to the 95$^{\text{th}}$ percentile are included. The $A_{SA}$ is based on the log-normal mean of the TTR.

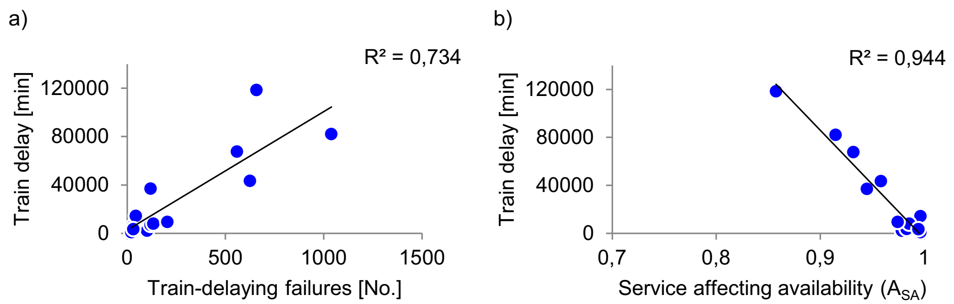


*Figure 8: Comparison of correlation of failures and availability with train delays.*

Comparison of log-normal mean TTR, median TTR and registered TTR is shown in Figure 9. It can be seen that the correlation is similar for the log-normal mean and the median. When the real registered TTR is used the correlation is considerably lower. Figure 9 also shows the operational availability ($A_O$), which includes both train-delaying failures and non-train-delaying failures. Since the $A_O$ measures the availability experienced by the infrastructure manager, it gives a lower correlation.

The availability measures calculated in the above figures are adjusted for concurrent faults, i.e. concurrent faults are counted only once. In Table 2, the effect of concurrent faults can be seen. The calculated availability measures are of railway Section 111. The availability may seem low, but in this case it is the total/overall availability of the whole section, i.e. it is calculated at the infrastructure level including all systems.

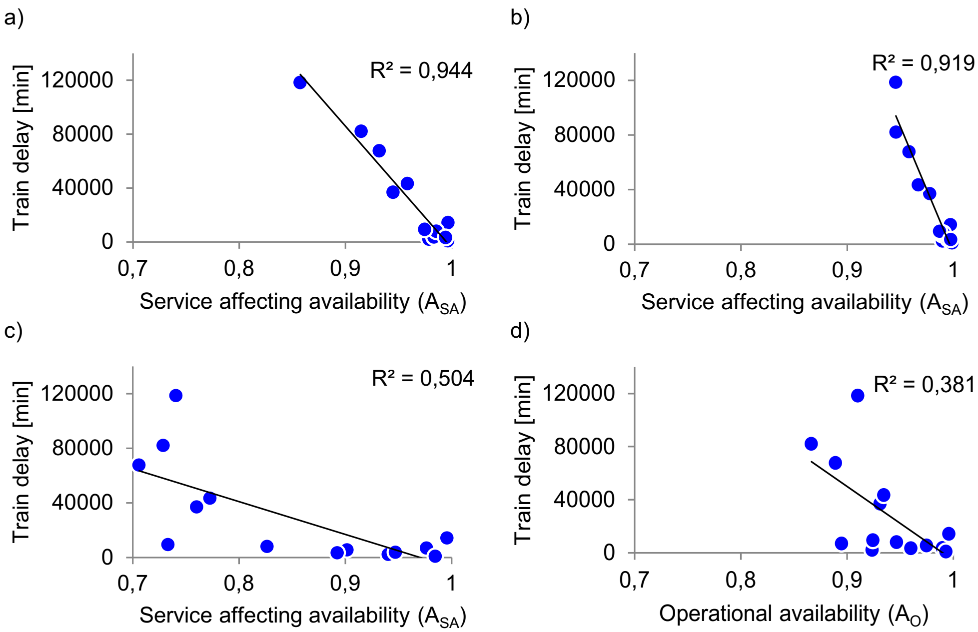


*Figure 9: Comparison of availability measures. The service affecting availability ($A_{SA}$) is shown in: a) using the log-normal of the TTR, b) using the median of the TTR, and in c) using the registered TTR. The operational availability (Ao) is shown in d) using the median of the TTR.*

If we study the availability at lower asset levels, it is seen that the availability approaches unity. Figure 10 shows the availability of levels 3, 4 and 5 of the switches and crossings, of the 65 railway sections.

Availability can be used to study trends and for prognostics. Figure 11 shows the availability of switches and crossings in railway Section 111 from year 2001-2014, using the log-normal mean TTR as input. The maintenance work order process and maintenance management system were replaced in the end of 2009, making it difficult to do comparison before and after 2009 year end. A piecewise linear fit is added for trending.

*Table 2: Availability of railway Section 111 (line 21) based on failures' median time to restoration (TTR).*

| | Including all failures | Including train-delaying failures |
|---|---|---|
| Availability not adjusted for concurrent faults | 0,70 | 0,91 |
| Availability adjusted for concurrent faults | 0,79 | 0,94 |
| Concurrent faults down time | 21 % | 5 % |

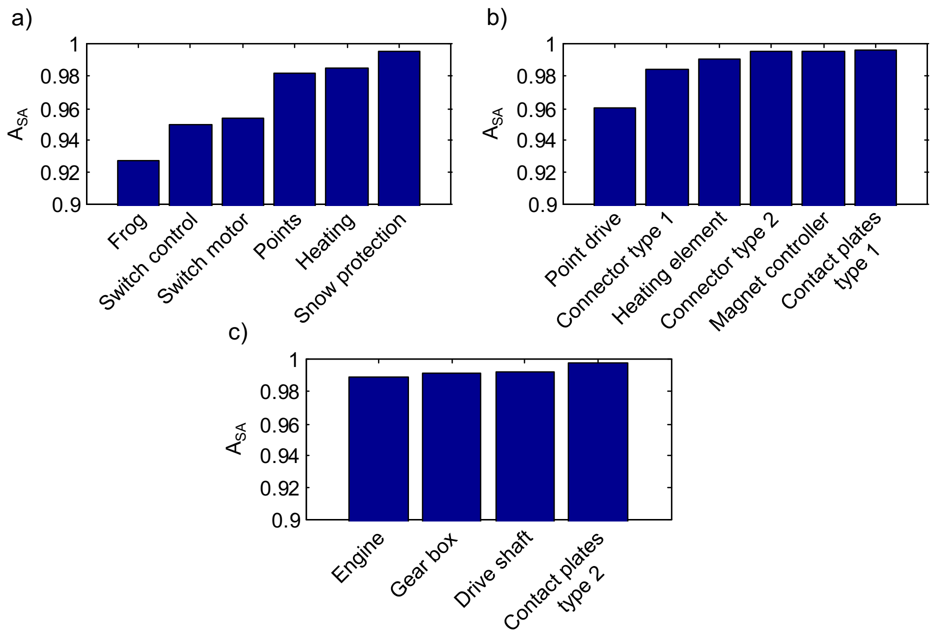


*Figure 10: Availability at asset levels 3 (a), 4 (b) and 5 (c) of the switches and crossings, based on failures' median TTR.*

Lastly, sensitivity analysis is carried out on the percentile of the TTR data. The percentile is set to range from the 90$^{th}$ to the 100$^{th}$ percentile, e.g. 90$^{th}$ percentile excludes the 10 % of the failures with the longest TTR. Figure 12 shows the resulting $A_{SA}$ using log-normal mean and median of railway Section 111. Both availability measures are adjusted to count concurrent faults only once. However, the share of concurrent faults is also shown. It is seen that the median based availability is insensitive to outliers; ranging from 94,2 % (equals value of Table 2) at the 100$^{th}$ percentile to 95,1 % at the 90$^{th}$ percentile. On the other hand, the log-normal mean ranges from 59 to 91 %. The

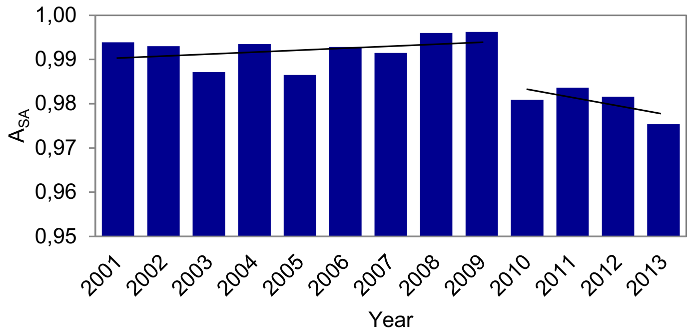


*Figure 11: Service affecting availability ($A_{SA}$) of the switches and crossings of railway Section 111 (Line 21).*

median's insensitivity to outliers is an advantages considering ease of use. However, for studying the effect on rail infrastructure availability from failures causing long TTR, the log-normal mean's sensitivity to outliers is an advantage. Moreover, it is seen that the log-normal mean based availability do not increase very fast, which indicates that there is not a very large distance between the outer most outliers and the rest of the data set. Nevertheless, from the 100$^{\text{th}}$ percentile to the 99$^{\text{th}}$ percentile, the availability increases with eight percentage points, i.e. from 59 to 67 %.

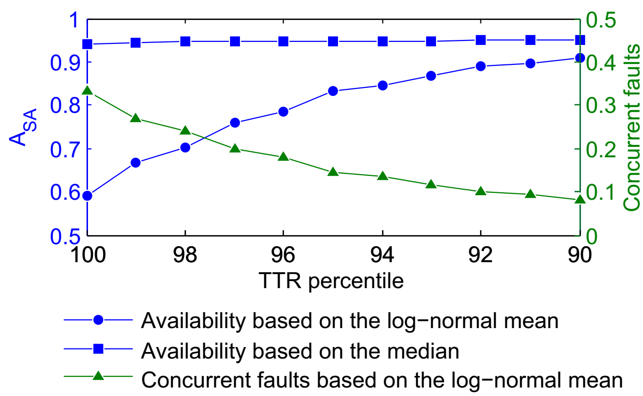


*Figure 12: Service affecting availability ($A_{SA}$) as a function of TTR percentile of railway Section 111 (Line 21).*

# 6 Conclusions

Operational availability has been studied in the operation and maintenance phase of railways using common definitions. The resulting availability measures give a higher correlation with train delays ($R^2$ = 0,94) than what failures gives with train delays ($R^2$ = 0,73). The result is reasonable since availability is a function of reliability, maintainability and maintenance support, i.e. it includes failures, repair time and logistic delay. Furthermore, the case study showed that it is preferred to use the median or log-normal of the maintenance time data for calculation of availability, as it yields better results than using the registered maintenance times. High quality of the data adds on to the data analysis and appropriate decision making.

Future research could be to apply availability measures for comparing performance of different railway sections, with normalisation according to track lengths and the number of switches and crossings.

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# Paper D

# Development of an Integrity Index for Monitoring Rail Infrastructure

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International Journal of Rail Transportation

# Development of an Integrity Index for Monitoring Rail Infrastructure

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**Abstract**

Railways are large, geographically dispersed assets, consisting of numerous systems, subsystems and components, for which considerable amounts of data and numerous indicators are generated for monitoring their operation and maintenance. Proper assessment of operation and maintenance performance is essential for sustainable and competitive rail transportation. Composite indicators, or indices, can simplify the performance measurement by summarising the overall performance of a complex asset into a single figure, making it easier to interpret than multiple indicators and plots. In this article, a composite indicator termed as rail infrastructure integrity index is developed and verified in a case study. The results show that composite indicators can be used for benchmarking and assessing the overall performance of railway sections in a single figure, indicating which sections need further study. Their implementation should allow data users to do sensitivity analysis and decomposition for traceability.

## 1 Introduction

Rail transportation is comparatively safe, environment friendly and comfortable, yet, it is capital intensive and has limited accessibility, i.e. it requires the use of a track, making effective maintenance and performance measurement critical to remain competitive. However, since railways are linear assets, i.e. geographically spread out and operated semi-continuously, proactive management is challenging, as the measurement of dependability and RAMS (reliability, availability, maintainability and support/safety) parameters are complex. In addition, rail traffic has grown over the last decade (EC, 2001), leading to high infrastructure demands and capacity utilisation and shortening the window for maintenance.

Benchmarking, i.e. comparing for best practice, is a tool that supports organisations in the pursuit of continuous improvement of their business processes. Benchmarking helps in developing realistic goals, strategic targets and facilitates the achievement of excellence in operation and maintenance (Almdal, 1994). For a review of benchmarking, see Dattakumar and Jagadeesh (2003); as this work also studies previous reviews in detail and refers to introductory publications. Briefly stated, benchmarking is the measurement and analysis of an organisation's operations against those of the best-performing organisations in an industry (Fuld, 1989, Camp, 1989), but looking for innovation rather than imitation (Thompson and Cox, 1997). Nevertheless, benchmarking can be internal as well (Zairi and Leonard, 1994).

Benchmarking of individual indicators in rail transport is common (UIC, 2012, Åhrén and Parida, 2009a, IMPROVERAIL, 2001, SuperGreen, 2010, UTBI, 2004). As an example, UIC railway statistics (UIC, 2012) give indicators of train-km, passenger-km, tonnes-km, punctuality, cost, energy, etc., for various countries. An important benchmarking project undertaken for railways is the Lasting Infrastructure Cost Benchmarking (LICB) carried out by UIC with 14 European IMs participating (UIC - LICB, 2008). This project harmonises maintenance and renewal costs per track-km for single track/double tracks, switches and crossings, etc., but details are not given due to confidentiality. At a railway line level, Åhrén and Parida (2009b) have done benchmarking for the Narvik-Kiruna railway line crossing the Norwegian-Swedish boarder, using operation, maintenance and reinvestments costs. Composite indicators (CIs), often called indices, are not extensively used; see Section 2. But there are many decision support models for railways, often based on deterioration rates and costs. A review of models for railway track maintenance developed by academia and industry is given by Guler (2013). In a study of rail infrastructure condition, the U.S. Army Construction Engineering Research Laboratories (Uzarski et al., 1993) suggested condition indices for: rail, joints and fastenings; ties; and ballast, subgrade and sideway components. These indices are primarily based on visual inspection condition surveys through score-sheets. The study includes a composite index for the track as a whole.

Rail transport requires comprehensive monitoring due to its complexity. For rail infrastructure, Stenström et al. (2012) identified over 100 indicators used by infrastructure managers (IMs) and researchers, and developed a method for improved performance measurement (Stenström et al., 2013). For assisting railway operators, Nathanail (2008) studied the quality of service for passengers and identified 22 indicators for its assessment. Composite indicators (CIs) can simplify the performance measurement by summarising the overall performance of a complex asset into a single number; which is easier for decision-makers to interpret than multiple indicators and plots (Saisana and Tarantola, 2002).

In this study, CIs are applied as a method for monitoring and benchmarking rail infrastructure performance. It includes a case study, where a composite indicator is developed, called rail infrastructure integrity index, based on the concept of structural integrity; the state of being unified or sound in construction.

# 2 Composite indicators

Composite indicators (CIs) can be described as: a mathematical combination (or aggregation) of a set of individual indicators with no common meaningful unit of measurement and no obvious way of weighting them (Saisana and Tarantola, 2002). CIs have the following advantages (Saisana et al., 2005):

- Summarise complex or multi-dimensional issues to support decision-makers

- Provide the big picture and can be easier to interpret than trying to find a trend in many separate indicators
- Help to reduce the size of a list of indicators or include more information within the existing visible size limit

and disadvantages:

- Construction involves stages requiring judgement: the selection of individual indicators, choice of model, weighting indicators and treatment of missing values, etc. These judgements should be transparent and based on sound statistical principles, e.g. wrong or poor input data and weighting will produce poor outcomes
- May send misleading, non-robust policy messages if poorly constructed or misinterpreted. Sensitivity analysis can be used to test for robustness
- May invite decision makers to draw simplistic policy conclusions. Composite indicators should be used in combination with individual indicators for correct policy/strategic conclusions

The advantages and disadvantages of these indicators have triggered much discussion about their use (Saisana et al., 2005, Sharpe, 2004). However, the justification and acceptance of a composite indicator requires negotiation, peer acceptance and fitness for use (Saltelli, 2007, Funtowicz and Ravetz, 1990).

After reviewing some well-known composite indicators, Bandura (2008) found 178 CIs, e.g. by the World Bank, European Commission, UNESCO and OECD, measuring, for example, education, science, technology, economy, sustainability and peace.

A common indicator practiced in industry is overall equipment effectiveness (OEE), set as a product of availability (up time), performance (production speed), and quality (product quality). Another such indicator is the overall factory vibration level (Galar et al., 2012). In the railway industry, Åhrén and Parida (2009b) proposed overall rail infrastructure effectiveness (ORIE), a CI that resembles OEE. Another common indicator used in railways is indices of track geometry, e.g. the track quality index (TQI) (Esveld, 2001, BSL, 2009). However, classifying these indicators as CIs depends on how a CI is defined. Saisana and Tarantola (2002) describe a CI as: a mathematical combination (or aggregation) of a set of individual indicators with no common meaningful unit of measurement and no obvious way of weighting them. OEE and vibration based indices would then be more of aggregated data.

Another method for benchmarking, besides CIs, is data envelopment analysis (DEA), a non-parametric statistical method for evaluating the productive efficiency of a set of peer entities called decision-making units (DMUs), which convert multiple inputs into multiple outputs (Cooper et al., 2011, Seiford, 1990). A major difference of DEA from other benchmarking techniques is that relative weights are used in this method; thus, the most favourable weights for each unit subject to other units are calculated, making benchmarking possible. George and Rangaraj (2008) apply DEA to Indian railway zones to benchmark their performance, using the following inputs: operating expenses, tractive effort (total horse powers consumed by locomotives), equated track kilometres (total km of track), number of employees, number of passenger carriages and number of wagons. Passenger kilometres and ton kilometres are used as outputs. Similar studies have been carried out on the North American freight railroads (Malhotra et al., 2009), on the London Underground (Costa and Markellos, 1997) and on data from the Urban Public Transport Statistics (Graham, 2008).

# 3 Methodology

Several steps are required for constructing composite indicators (Freudenberg, 2003, Jacobs et al., 2004, OECD & JRC - EC, 2008). In terms of steps, OECD & JRC - EC (2008) break the process down in the furthermost detail, including the ten steps listed below. Broadly speaking, the method applied here follows OECD's approach:

1. Theoretical framework
2. Data selection
3. Imputation of missing data
4. Multivariate analysis
5. Normalisation
6. Weighting and aggregation
7. Uncertainty and sensitivity analysis
8. Back to data
9. Links to other indicators
10. Visualisation of results

## 3.1 Theoretical framework

The objective of constructing a rail infrastructure integrity index is to measure the performance of railways in a single figure; easy to interpret and useful for comparative purposes. The first step in the development of such an index is to suggest suitable underlying indicators for the CI.

A central concept in system engineering and maintenance is dependability, a collective term used to describe availability and its influencing factors: reliability, maintainability and maintenance supportability (IEC, 1990); see Figure 1. Reliability is the ability of an item to perform a required function, while maintainability is the ability of an item to be restored to perform a required function, and maintenance supportability is the ability of a maintenance organisation to provide required resources to maintain an item. Availability, in turn, is the ability of an item to be in a state to perform a required function. Availability can be measured quantitatively, while dependability is only used as a qualitative description. For details on terminology, see IEC 60050-191 and EN 13306 (IEC, 1990, CEN, 2010).

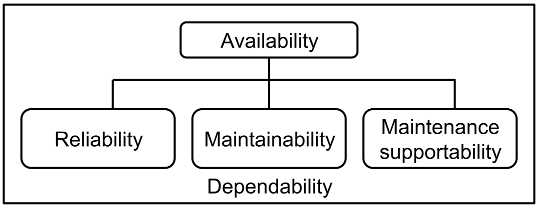


*Figure 1: Dependability and RAMS (reliability, availability, maintainability and maintenance supportability) as described by IEC (1990).*

By applying the influencing factors of availability as inputs to the rail infrastructure performance, we can link output measures; see Figure 2. These factors, reliability, maintainability and supportability, are considered as inputs since reliability and maintainability are design parameters, and the supportability depends on how the maintenance organisation has been set up or designed reacting upon failures. Preventive maintenance (PM) and the train time table (TTT) are added as inputs, as frequency of failure is a dependent variable of the PM programme and the TTT, i.e. capacity utilisation.

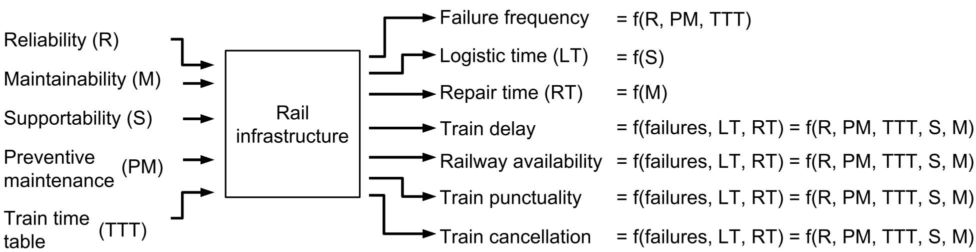


*Figure 2: Input and output factors of rail infrastructure performance.*

Since the objective of constructing a rail infrastructure integrity index is to measure performance, only output measures should be included in the index. According to Figure 2, there are seven possible output measures to consider as individual indicators for an integrity index. All seven could be included in an initial set-up, with additional factors added or removed in a later stage in the construction of the integrity index. However, the outputs, train delay, railway availability, train punctuality and train cancellations are more or less dependent on failures, logistic time and repair time. Therefore, only one is considered, namely, train delay. Consequently, for an initial set-up, four individual indicators are considered for the integrity index:

- Failure frequency (number of failures)
- Train delays (due to failures) [minutes]
- Logistic time (LT) [minutes]
- Repair time (RT) [minutes]

## 3.2 Data selection

Failure data have been collected from the Swedish infrastructure manager (IM) Trafikverket (Swedish Transport Administration) and constitute of infrastructure related corrective maintenance work, i.e. functional failures. Rail infrastructure failure data consist of urgent inspection remarks (requiring immediate repair) reported by the maintenance contractor, as well as failure events and failure symptoms identified outside the inspections, commonly reported by the train driver, but occasionally reported by the public. The collected data come from seven railway lines in Sweden (Figure 3), which together include 65 sections (Table 1).

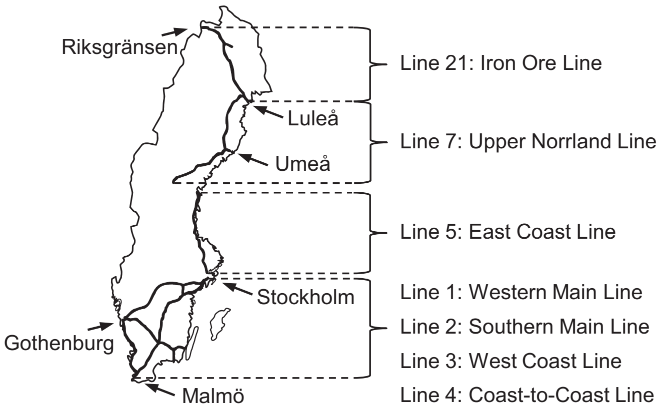


*Figure 3: Railway lines 1-5, 7 and 21 of the Swedish network.*

The lines connect the three largest cities of Sweden, Stockholm, Gothenburg and Malmö, as well as the Iron Ore Line in the north of the country. The failure data are

*Table 1: Sections of the railway lines for analysis.*

| Line | Section labels | No. of sections | Track length [km] | No. of S&Cs | Main track type |
|---|---|---|---|---|---|
| 1 | 410, 412, 414, 416, 418, 419, 420, 511, 512, 611, 612 | 11 | 979 | 792 | Double |
| 2 | 421*, 422, 502, 504, 505, 810, 811, 813, 814, 815, 817, 909, 910, 912 | 14 | 1117 | 947 | Double |
| 3 | 626, 627, 628, 630, 904*, 920*, 938, 940 | 8 | 531 | 393 | Double |
| 4 | 641, 655, 720, 721, 821, 822, 823, 824, 827 | 9 | 413 | 305 | Single |
| 5 | 234, 235, 303, 429, 430**, 433**, 243** | 7 | 629 | 634 | Single |
| 7 | 119, 120, 122, 124, 126, 129, 130, 138, 146, 211 | 10 | 723 | 701 | Single |
| 21 | 111, 112, 113, 114, 116, 118 | 6 | 467 | 248 | Single |
| Sum: | | 65 | 4859 | 4020 | |

*Single track, **Double track (counted twice in the track length column)

between 2010.01.01 - 2013.12.31, i.e. 4 years. Reported number of failures is 97 105, with 22 % of the failures resulting in train delays. The main types of train delaying corrective maintenance failures are shown in Figure 4.

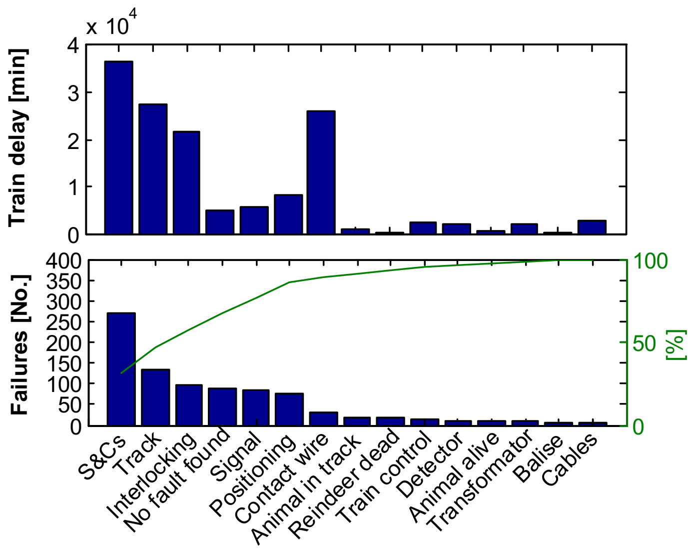


*Figure 4: Typical train delaying failures, based on section 111 (Line 21).*

Railways consist of both linear and point assets. Examples of sub-systems that can be treated as linear are rails, sleepers, fasteners, ballast and the catenary system. On the other hand, sub-systems difficult to consider as linear are S&Cs and various types of stations, as examples. Since S&Cs stand for a major part of all failures and train delay (Figure 4), normalisation have been carried out according to the number of S&Cs and the track length. Thus, the two individual indicators failure frequency and train delay becomes:

- S&Cs failures per S&C
- Linear assets failures per track-km [$km^{-1}$]
- S&Cs train delay per S&C [minutes]
- Linear assets train delay per track-km [minutes/km]

Further normalisation is possible, e.g. for various signalling and power stations, but this represents a separate study and is beyond the scope of this article.

The selected indicators have a number of features requiring consideration. Failures are registered by train dispatchers in consultation with the person (commonly the train driver) experiencing a failure in the rail infrastructure or when a detector signals a failure. A registered failure is at times found to be false or impossible to identify. Even if the time to restoration and/or train delay is near to zero or zero, there is a cost, as a work order is set up. Therefore, all registered rail infrastructure failures are considered failures in the analysis.

## 3.3 Data quality, outliers and imputation of missing data

Regarding the time to restoration (TTR), i.e. the logistic and repair time (LT and RT), a possible issue is missing data which may require imputation and outliers, i.e. high and low extreme values. Furthermore, registration of maintenance times, i.e. logistic time and repair time, is carried out by the maintenance contractor or train dispatchers. Therefore, the precision are somewhat unknown; expert opinion could, to some extent, fill in this gap. However, not all failures cause train delays; in overall, 22 % of the failures cause train delays. Consequently, the TTR can vary since it can be assumed that the maintenance personnel travel to the failure location as soon as possible and carry out repair more efficiently, if there are train delays. Therefore, the LT and RT in this study are based on train delaying failures to reduce variability in the data.

For the LT and RT, the data turn out to be highly skewed. The time to restoration (TTR), i.e. LT + RT, gives a log-normal mean of 410 minutes and a median of 171 minutes, when data up to the $95^{th}$ percentile are considered of train-delaying failures (Figure 5). Alternatively, limits can be set by discard data according to a percentage. By limiting the LT and RT to $5 < LT < 240$ minutes and $10 < RT < 600$ minutes, the log-normal mean is 204 minutes and the median is 147 minutes; i.e. there is less difference. Either the median or log-normal mean can be used. However, care should be taken if the log-normal mean is used, as it is sensitive to outliers. In this study we use the log-normal mean of train-delaying failures that meet 5 < LT < 240 minutes and 10 < RT < 600 minutes.

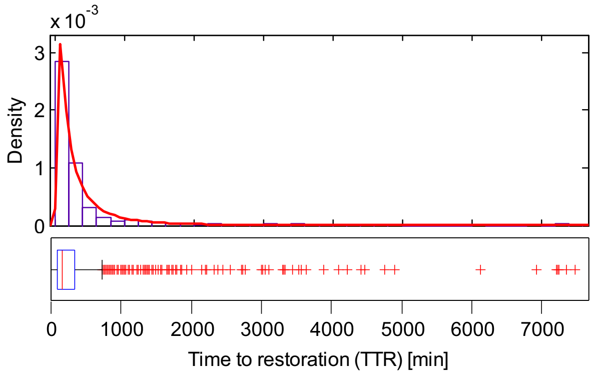


*Figure 5: Distribution of TTR up to 95th percentile of railway section 111, with a log-normal fit. Based on train-delaying failures.*

About 6 % of the failures are missing the time when repair was finished, with some variations between the railway sections. Mean imputation can be used for the missing TTR data; this is done by filling the median/log-normal mean of each railway section in question into the missing TTRs.

Train delay data are registered by the signalling system; therefore, the precision is assumed to be satisfactory. However, some failures cause long delays due to some extraordinary failures, e.g. tear down of the overhead contact wire by locomotive pantographs or derailments. Therefore, the 2 % of the failures with the longest delays are considered as outliers and not included in the study. Nevertheless, outliers should be included in a separate analysis as they can represent a major cost, but this is beyond the scope of this study.

## 3.4 Correlation and multivariate analysis

Correlation analysis is done to decide which indicators to include or to assign weights to avoid double counting highly correlated variables. Correlation is studied by means of a correlation matrix, whose entries note the dependence between the individual indicators; in this case, we use Pearson's linear correlation coefficient; see Table 2. As the table shows, failures and train delays are positively correlated, i.e. more failures cause more delays. Thus, one of the variables could be discarded or corresponding weighting could be applied to avoid double counting. Other correlations are below |0.5|, i.e. are not high.

Multivariate analysis studies the interrelationship of the individual indicators. Factor

*Table 2: : Correlation matrix (CM) of the 65 railway sections.*

| | S&C failures per S&C | Linear assets failures [km$^{-1}$] | S&C delay per S&C [min] | Linear assets delay [min/km] | Logistic time (LT) [min] | Repair time (RT) [min] |
|---|---|---|---|---|---|---|
| S&C failures per S&C | 1.00 | 0.10 | 0.87 | 0.25 | 0.09 | -0.12 |
| Linear assets failures [km$^{-1}$] | | 1.00 | -0.08 | 0.87 | -0.39 | -0.12 |
| S&C delay per S&C [min] | | | 1.00 | 0.07 | 0.14 | -0.01 |
| Linear assets delay [min/km] | | | | 1.00 | -0.34 | -0.16 |
| Logisitic time (LT) [min] | | | | | 1.00 | 0.36 |
| Repair time (RT) [min] | | | | | | 1.00 |

analysis (FA) is used in the construction of composite indicators; it gives measures of how much variables vary between items (OECD & JRC - EC, 2008). In this case, the studied items are railway sections. Variables showing little variation between the railway sections will not explain the variation in performance between the railway sections; to solve this problem, higher weights can be put on the variables that vary the most. FA gives factor loadings which, in turn, can be used to calculate weights. From Table 3 we see that all six variables receive about the same weights; thus, the four factors vary equally.

The weights are calculated as the following example on the first weight ($w_1$) for the first variable (S&Cs failures):

$$w_1 = \frac{\beta_{12} \sum_{i=1}^{6} \alpha_{i2}^2}{\sum_{j=1}^{4} \sum_{i=1}^{6} \alpha_{ij}^2} = \frac{\alpha_{12}^2}{\sum_{j=1}^{4} \sum_{i=1}^{6} \alpha_{ij}^2} = \frac{0.957^2}{5.79} = 0.16 \quad (1)$$

where:

$\alpha_{ij}$ = Rotated factor loadings

$\beta_{ij}$ = Squared scaled factor loadings

## 3.5 Normalisation

In Section 3.2, normalisation was carried to minimise the effect of railway sections' various number of S&Cs and track length. However, another normalisation is required since

*Table 3: Rotated factor loadings and calculation of weights.*

Rotated factor loadings (Varimax)

| Variable | Factor 1 | Factor 2 | Factor 3 | Factor 4 | Sum |
|---|---|---|---|---|---|
| S&C failures per S&C | 0.142 | -0.957 | 0.086 | 0.073 | |
| Linear assets failures [km$^{-1}$] | 0.955 | 0.033 | 0.026 | -0.174 | |
| S&C delay per S&C [min] | -0.048 | -0.975 | -0.029 | 0.029 | |
| Linear assets delay [min/km] | 0.953 | -0.125 | 0.076 | -0.113 | |
| Logisitic time (LT) [min] | -0.229 | -0.085 | -0.187 | 0.951 | |
| Repair time (RT) [min] | -0.066 | 0.042 | -0.982 | 0.17 | |
| Variance | 1.899 | 1.893 | 1.015 | 0.983 | 5.789 |
| % Var | 0.317 | 0.315 | 0.169 | 0.164 | 0.965 |

Squared scaled factor loadings

| Variable | Factor 1 | Factor 2 | Factor 3 | Factor 4 | Weights |
|---|---|---|---|---|---|
| S&C failures per S&C | 0.01 | 0.48 | 0.01 | 0.01 | 16 % |
| Linear assets failures [km$^{-1}$] | 0.48 | 0.00 | 0.00 | 0.03 | 16 % |
| S&C delay per S&C [min] | 0.00 | 0.50 | 0.00 | 0.00 | 17 % |
| Linear assets delay [min/km] | 0.48 | 0.01 | 0.01 | 0.01 | 16 % |
| Logisitic time (LT) [min] | 0.03 | 0.00 | 0.03 | 0.92 | 16 % |
| Repair time (RT) [min] | 0.00 | 0.00 | 0.95 | 0.03 | 17 % |
| Sum | 1.00 | 1.00 | 1.00 | 1.00 | 1.00 |

the individual indicators have different ranges and measurement units. Common normalisation methods are ranking, standardisation (Z-score), Min-Max, distance to reference and categorical scales (Jacobs et al., 2004). Ranking is simply ordering the raw values. It is not sensitive to outliers but its drawback is the loss of absolute levels of the raw data. The Z-score normalises the data to have a mean of zero and a standard deviation of one. The Min-Max method normalises the data to have a range of zero to one. Both the Z-score and Min-Max are sensitive to outliers, something requiring consideration. For the rail infrastructure integrity index, this is addressed by excluding outliers in the train delay and limiting the logistic and repair times. Comparing Min-Max and Z-score normalisation, the former can widen the range of values confined in a small range. Rank, Z-score and Min-Max normalisations are applied and calculated according to:

$$I^t_{qi} = Rank(x^t_{qi}) \tag{2}$$

$$I^t_{qi} = \frac{x^t_{qi} - \mu^t_{qi=\bar{i}}}{\sigma^t_{qi=\bar{i}}} \tag{3}$$

$$I^t_{qi} = \frac{x^t_{qi} - min(x^t_q)}{max(x^t_q) - min(x^t_q)} \tag{4}$$

where:

$x^t_{qi}$ = Raw value of individual indicator $q$ for item (railway section) $i$ at time $t$, with $q = 1, \ldots, Q$ and $i = 1, \ldots, M$

$I^t_{qi}$ = Normalised value

$\mu^t_{qi=\bar{i}}$ = Average across items

$\sigma^t_{qi=\bar{i}}$ = Standard deviation across items

Thus, $Q$ and $M$ equal 6 and 65, respectively; six individual indicators and 65 railway sections. In our case, $t$ is a constant, as we study performance over four years.

## 3.6 Weighting

From the correlation matrix (CM), we found failures and train delays to be highly correlated (0.87); therefore, one of these variables can be discarded or half the weight can be put on each. Factor analysis (FA) provides no further insight, as it gives the same weights as equal weighting. Another weighting method is the analytical hierarchy process (AHP), a qualitative and non-statistical method for decision-making. In this method, a group of decision-makers will put a rating on each individual indicator and calculate the weights accordingly. In this study, four railway researchers carried out pairwise comparison with consensus between the group members. The group members' research experience in railway specific projects is two, four, six and ten years. One group member has also worked as a railway track engineer at an infrastructure manager (IM) for about three years. For implementation within an IM, the expert group is preferably larger, more heterogeneous and with longer practical experience. The pairwise comparison is shown in Table 4. Failures and delay are for both the S&C and linear asset failures. For further applications of pairwise comparisons in railways, see Lundberg (2000) or Nyström and Söderholm (2010).

*Table 4: Expert opinion weighting using pairwise comparison method.*

| | Failures | Delay | LT | RT | Sum | Weight | |
|---|---|---|---|---|---|---|---|
| Failures | 1 | 0 | 0 | 0 | 1 | 1/16 | 0.06 |
| Delay | 2 | 1 | 2 | 2 | 7 | 7/16 | 0.44 |
| LT | 2 | 0 | 1 | 1 | 4 | 4/16 | 0.25 |
| RT | 2 | 0 | 1 | 1 | 4 | 4/16 | 0.25 |
| Sum | | | | | $16 = 4^2$ | 1 | 1.00 |

CM shows failures and delays to be highly correlated, and AHP finds train delays are more important than failures. It is, therefore, reasonable to disregard the failures in the CI calculation. This is done by introducing another weighting procedure, which we call the reduced composite indicator (RCI). As a result, we end up with weights from four methods, i.e. equal weighting (EW), CM, AHP and RCI. Table 5 shows that the weights vary extensively between the methods. Weights of the EW, with respect to failures, train delay, logistic time and repair time, are divided in four equal parts, i.e. [.25 .25 .25. 25]. However, when distinguishing between S&Cs and linear assets, the first two weights are divided and the weights become [.125 .125 .125 .125 .25. 25]. In CM weighting, to avoid double counting, the weights are divided into three parts, i.e. [0.33 0.33 0.33]. But when distinguishing between S&Cs and linear assets, the first is divided into four [.08 .08 .08 .08 .33 .33]. For the AHP weight, the first two weights of [.06 .44 .25 .25] are divided and the weights become [.03 .03 .22 .22 .25 .25]. For the RCI, the weight is set to zero for failures and 0.5 for train delays, i.e. [.0 .0 .25 .25 .25 .25].

*Table 5: Comparison of different weighting methods.*

| | S&C failures per S&C | Linear assets failures [km$^{-1}$] | S&C delay per S&C [min] | Linear assets delay [min/km] | Logistic time (LT) [min] | Repair time (RT) [min] |
|---|---|---|---|---|---|---|
| EW | 0.125 | 0.125 | 0.125 | 0.125 | 0.250 | 0.250 |
| CM | 0.083 | 0.083 | 0.083 | 0.083 | 0.333 | 0.333 |
| AHP | 0.030 | 0.030 | 0.220 | 0.220 | 0.250 | 0.250 |
| RCI | 0.000 | 0.000 | 0.250 | 0.250 | 0.250 | 0.250 |

## 3.7 Aggregation

Aggregation can be divided into additive and geometric methods. The commonly used additive method is the summation of weighted and normalised indicators, e.g. see Pahl et al. (2007):

$$CI_i = \sum_{q=1}^{Q} w_q I_{qi} \tag{5}$$

A drawback of additive aggregation is full compensability; i.e. low indicator values can be compensated by one sufficiently high value in another indicator. As an example, the sum of 1-1-1-17 equals the sum of 5-5-5-5. This feature is avoided in geometric aggregation, but the relative contribution by each individual indicator to the composite is not visualised as in additive aggregation. Common geometric aggregation is given by:

$$CI_i = \prod_{q=1}^{Q} I_{qi}^{w_q} \tag{6}$$

### 3.8 Sensitivity analysis

Sensitivity analysis studies how CIs are affected by different sources of uncertainties in their inputs and construction, e.g. selection of individual indicators, data quality, normalisation, weighting and aggregation. Uncertainties can be assessed by: including/excluding individual indicators; considering various data quality conditions; and applying alternative normalisations, weighting and aggregation techniques. In an ideal case, all uncertainties should be considered; as this is normally not practical, the following factors are studied:

- Including/excluding individual indicators (applied in the RCI weights)
- Applying three different normalisation techniques: Rank, Z-score and Min-Max
- Applying three different aggregation techniques: equal weighting, correlation matrix and analytical hierarchical process
- Applying different aggregation techniques: additive and geometric aggregation

### 3.9 Back to the data and linkage

After sensitivity analysis, the CI is decomposed to study the contribution of each individual indicator to the total, giving a preliminary picture of where to make improvements and verifying what can be seen in the raw data. CI results should be linked to other indicators, if possible, to discover the reason for a certain performance. However, in this study, CI results are discussed with reference to the raw data and the background context of the railway sections.

### 3.10 Assumptions

The following assumptions have been made within the study:

- Through normalisation to track length and counting double track twice, it is assumed that single track and double track railway sections can be analysed together and compared. Moreover, normalisation according to track length and number of S&Cs is assumed to improve results of railway section for comparison purpose
- Probability distributions are assumed to be similar for all railway sections. Thus, the same limits and mean values can be used for all railway sections. Also, the data quality is assumed to be similar for all railway sections

# 4 Results and discussion

Table 6 shows a comparison of the three normalisation techniques. It gives ranked CI results for the top ten railway sections, using equal weighting (Table 5) and additive aggregation (Eq. 5). The best performing section has a CI result of one, and the worst performing one has a result of 65. Min-Max and Z-score have similar results in comparison ranking. Henceforth, we apply Min-Max [0,1] to preserve the relative raw values of the individual indicators.

*Table 6: Composite indicator result using different normalisation methods, together with equal weighting and additive aggregation. The top ten railway sections are shown.*

| | | Composite indicator result | | |
|---|---|---|---|---|
| Line | Section | Min-Max | Z-score | Rank |
| 4 | 655 | 1 | 1 | 3 |
| 3 | 630 | 2 | 3 | 4 |
| 1 | 412 | 3 | 2 | 5 |
| 1 | 419 | 4 | 5 | 15 |
| 1 | 420 | 5 | 4 | 8 |
| 1 | 410 | 6 | 6 | 12 |
| 3 | 920 | 7 | 8 | 11 |
| 7 | 146 | 8 | 9 | 7 |
| 3 | 626 | 9 | 10 | 10 |
| 3 | 938 | 10 | 7 | 1 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |

As an example for clarifying the procedure, CI results using additive aggregation and Min-Max normalisation are given by:

$$Rank\left(CI_i\right) = Rank\left(\sum_{q=1}^{Q=6} w_q I_{qi}\right) = Rank\left(\sum_{q=1}^{Q=6} w_q \frac{x_{qi} - min(x_q)}{max(x_q) - min(x_q)}\right) \tag{7}$$

With the weights of Table 5 and values of Table 7, Rank($CI_1^{(655)}$) equals 1 and Rank($CI_2^{(111)}$) equals 65. The values 655 and 111 within parenthesis mean that $i = 1$ and $i = 2$ correspond to railway sections 655 and 111. These two results are also seen in Tables 6 and 8.

Recalling Eq. 5 and 6, we can study the effect of additive and geometric aggregation (Table 8). Sensitivity for compensability is especially clear in the railway sections that do not perform as well as others. According to additive aggregation, section 823 is the third poorest performing section, but according to geometric aggregation, it comes seventh.

*Table 7: Example values of $x_{qi}$ for railway sections 655 and 111.*

| | S&C failures per S&C | Linear assets failures [km$^{-1}$] | S&C delay per S&C [min] | Linear assets delay [min/km] | Logistic time (LT) [min] | Repair time (RT) [min] |
|---|---|---|---|---|---|---|
| $x_{q1}^{(655)}$ | 0.9 | 58 | 1.4 | 225 | 29 | 105 |
| $x_{q2}^{(111)}$ | 13 | 22 | 555 | 615 | 62 | 121 |

Section 823 has a very good result in the individual indicator of train delay per length; thus, multiplying with a value near zero gives a low CI. Note that a poor CI result does not mean poor productivity.

*Table 8: Comparison of additive and geometric aggregation, together with Min-Max [0,1] normalisation and equal weighting.*

| | | Composite indicator result | |
|---|---|---|---|
| Line | Section | Additive | Geometric |
| 21 | 111 | 65 | 64 |
| 21 | 118 | 64 | 62 |
| 4 | 823 | 63 | 7 |
| 21 | 113 | 62 | 60 |
| 21 | 112 | 61 | 63 |
| 2 | 910 | 60 | 56 |
| 21 | 116 | 59 | 22 |
| 2 | 422 | 58 | 21 |
| 4 | 824 | 57 | 37 |
| 4 | 827 | 56 | 33 |
| ⋮ | ⋮ | ⋮ | ⋮ |

The intention of building a rail infrastructure integrity index is not only to have a single figure of performance; the contribution of each individual indicator is also important. Therefore, we apply additive aggregation hereafter to allow study of compensability later on.

Table 9 gives the results for equal weighting (EW), correlation matrix (CM), analytical hierarchy process (AHP) and for the reduced composite indicator (RCI), using Min-Max normalisation and additive aggregation. The results are sorted according to EW. The RCI results are similar to those for EW and AHP. However, railway section 817 differs a bit between its EW and RCI; more specifically, it has many failures, but less train delay.

Finally, by decomposing the CI, we can study the contribution of each individual

*Table 9: Rankings of different weighting methods; equal weighting (EW), correlation matrix (CM), analytical hierarchy process (AHP) and reduced composite indicator (RCI).*

| | | Composite indicator result | | | |
|---|---|---|---|---|---|
| Line | Section | EW | CM | AHP | RCI |
| 4 | 655 | 1 | 2 | 2 | 3 |
| 3 | 630 | 2 | 3 | 1 | 1 |
| 1 | 412 | 3 | 4 | 3 | 2 |
| 1 | 419 | 4 | 1 | 4 | 4 |
| 1 | 420 | 5 | 6 | 5 | 5 |
| 1 | 410 | 6 | 5 | 6 | 6 |
| 3 | 920 | 7 | 7 | 7 | 7 |
| 7 | 146 | 8 | 8 | 8 | 9 |
| 3 | 626 | 9 | 9 | 10 | 10 |
| 3 | 938 | 10 | 16 | 12 | 12 |
| 3 | 627 | 11 | 15 | 11 | 11 |
| 2 | 817 | 12 | 11 | 9 | 8 |
| ⋮ | ⋮ | ⋮ | ⋮ | ⋮ | ⋮ |
| 4 | 827 | 56 | 57 | 55 | 54 |
| 4 | 824 | 57 | 59 | 58 | 58 |
| 2 | 422 | 58 | 60 | 59 | 59 |
| 21 | 116 | 59 | 61 | 57 | 56 |
| 2 | 910 | 60 | 55 | 61 | 61 |
| 21 | 112 | 61 | 42 | 60 | 60 |
| 21 | 113 | 62 | 64 | 63 | 63 |
| 4 | 823 | 63 | 65 | 64 | 64 |
| 21 | 118 | 64 | 63 | 62 | 62 |
| 21 | 111 | 65 | 62 | 65 | 65 |

indicator. Figure 6 shows the decomposed CI using RCI weighting, Min-Max normalisation and additive aggregation. As an example, section 655 (Borås city track) has a very low number of train delays and less logistic time but the mean repair time is quite long. Meanwhile, section 112 (Kiruna city track) has a large delay for linear assets, which can be explained by its 2 km length and technical density. The mean length of the 65 sections is 74 km. Additionally, the logistic time of section 112 is low which makes sense as it is a city track, like the Borås city track.

The results also give information on how the railway lines perform at an overall level. From Table 9 and Figure 6, we see railway lines 1 and 3 are performing well, as many of their sections have good CI results. The CI results for line 21 (Iron Ore Line) are not as good, but this line is a 30 tonne axle load track in an arctic climate, transporting large amounts of iron ore to the harbours in Narvik and Luleå cities. In addition, lines 1 and 3 have a higher safety inspection classification as they have higher train speed limits than line 21. Besides, lines 1 and 3 are double track railways, making them less sensitive to failures than line 21 which is a single track line.

According to the theoretical framework (Figure 2), train delays are a function of the logistic and repair time. Hence, a data envelopment analysis (DEA) model can be

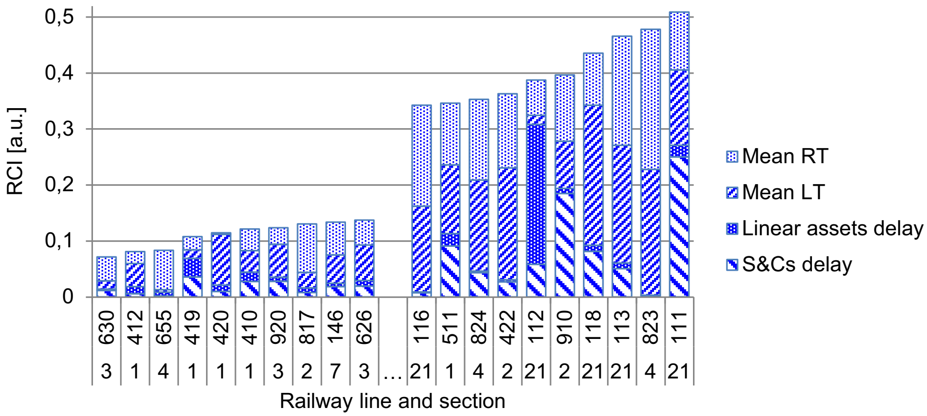


*Figure 6: Indicators' relative contribution using RCI weighting, Min-Max normalisation and additive aggregation.*

set up using LT and RT as inputs, and train delay per S&C and per track length as outputs. Efficiency is defined as the output divided by the input. Less time to repair, i.e. less effort, with as little train delay as possible, gives higher efficiency. DEA is another approach to measure performance and could yield interesting comparative results. Therefore, we construct a DEA model, using MaxDEA software, with the 65 railway sections as decision-making units (DMUs), LT and RT as inputs, and train delays as outputs. In other words, they are the same data as in the RCI result. The result of DEA efficiency ranking compared to RCI performance ranking is shown in Figure 7. These are two different benchmarking techniques, or decision support tools, so the correlation of 0.80 does, to some extent, further verify the work carried out. A thorough study of DEA using railway operation and maintenance data would be interesting. However, the present study is confined to the application of CIs in railways, with DEA included for purposes of comparison.

# 5 Conclusions

A composite indicator (CI) for assessing rail infrastructure integrity is developed based on rail infrastructure failures, train delays, logistic time and repair time.

Depending on the normalisation, weighting and aggregation techniques chosen, the resulting CI will change, often slightly but sometimes extensively. Therefore, when CIs are being implemented into an infrastructure manager's computerised maintenance management system (CMMS), it is useful to let data users study sensitivity by choosing factors within the graphical user interface (GUI). The same is true for decomposing a CI the GUI of a CMMS implementation should let data users decompose the indicator for root cause analysis.

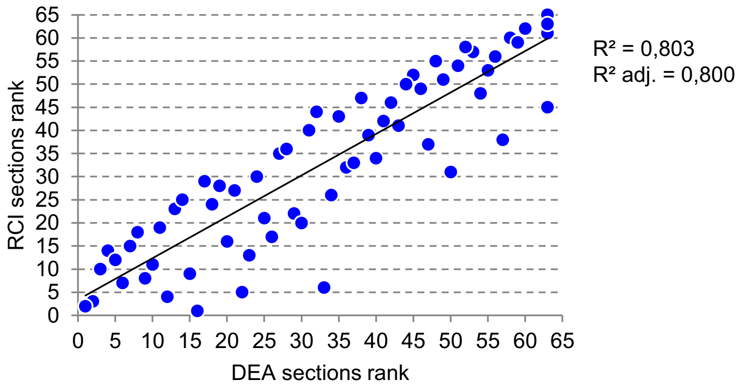


*Figure 7: Comparison of RCI and DEA results.*

The correlation matrix (Table 2) shows a high correlation between failures and train delay (0.87). Pairwise comparison following expert opinion leads to a low weight on failures and a higher weight on train delays, suggesting that the individual indicator of failures can be neglected in the construction of a rail infrastructure integrity index.

In the case study results, railway lines 1 and 3 have the best CI result, while line 21 lags behind the other lines. This is not surprising, given the Arctic climate and higher axle load of line 21 (Iron Ore Line). In addition, lines 1 and 3 have a higher safety inspection classification, as they have higher train speed limits. Also, lines 1 and 3 are double track railways, making them less sensitive to failures than line 21 which is a single track line.

# Acknowledgements

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# Paper E

# Preventive and Corrective Maintenance: Cost Comparison and Cost-benefit Analysis

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Structure and Infrastructure Engineering: Maintenance, Management, Life-Cycle Design and Performance

# Preventive and Corrective Maintenance: Cost Comparison and Cost-benefit Analysis

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**Abstract**

Maintenance can represent a significant portion of the cost in asset intensive organisations, as breakdowns have an impact on the capacity, quality and cost of operation. However, the formulation of a maintenance strategy depends on a number of factors, including the cost of down time, reliability characteristics and redundancy of assets. Consequently, the balance between preventive maintenance (PM) and corrective maintenance (CM) for minimising costs varies between organisations and assets. Nevertheless, there are some rules of thumb on the balance between PM and CM, such as the 80/20 rule. Studies on the relationship between PM and CM in practice are rare. Therefore, PM and CM costs are studied in this paper by analysing historical maintenance data. A case study of rail infrastructure historical data is carried out to determine the shares of PM and CM, together with a cost-benefit analysis (CBA) to assess the value of PM. Results indicate that railway sections with the lowest total maintenance cost have a higher share of PM than sections with the highest maintenance cost. The CBA shows the benefit of PM is positive, but the result depends on the inclusion/exclusion of down time cost in addition to individual organisational parameters.

## 1 Introduction

Asset intensive industries require long-term and sustainable maintenance strategies to stay competitive, whether they produce goods or services. Strategic planning involves collecting information, setting goals, translating goals to specific objectives and setting up activities to achieve the objectives (Armstrong, 1982, Boston and Pallot, 1997, Parida and Chattopadhyay, 2007). As unavailability of assets has an impact on production cost, quality and capacity, maintenance often represent a significant portion of the business cost in asset intensive organisations (Dekker, 1996, Salonen and Deleryd, 2011).

Maintenance can be divided into corrective and preventive maintenance. Corrective maintenance (CM) is carried out after a fault has been recognised; it is intended to put the failed item back into a state in which it can perform its required function. Preventive maintenance (PM) is carried out at predetermined intervals or according to prescribed criteria and is intended to reduce the probability of failure or the degradation of items (CEN, 2010, IEC, 1990). The aim of PM is to provide maximum system reliability and safety with a minimum of maintenance resources (Huang and Dismukes, 2003). However, PM requires that the items in question have an expected life span or a measurable degradation rate. Selection of a maintenance strategy depends on a number of factors, including cost of down time, redundancy and items' reliability characteristics. Consequently, the balance between PM and CM for minimising costs varies between organisations and assets. Further discussion of maintenance strategies can be found in Swanson (2001), Parida and Chattopadhyay (2007), Bontempi et al. (2008), and Frangopol (2011).

Finding the ratio of PM to CM in an organisation or system is complicated, as there are numerous influencing factors. Firstly, it needs to be clear which activities belong to PM or CM, and this classification can vary from organisation to organisation. Secondly, the resources spent on each activity must be registered. Such registration is carried out in enterprise resource planning (ERP) systems or computerised maintenance management systems (CMMS). However, data quality and analysis are a concern as data largely depend on human inputs. In their interviews of 20 companies, Davenport et al. (2001) found a major concern was the inability to turn data into information and knowledge. Karim et al. (2009) made similar observations in maintenance data processing, highlighting that the gap between data processing and knowledge management is too large. Thirdly, some costs can be hard to estimate, especially indirect costs and costs of outsourcing.

While studies on PM to CM costs are lacking, a common rule of thumb for evaluating performance says we should aim for a PM to CM share of 80/20 in general (Wireman, 2003), i.e. following the Pareto principle. However, such rules of thumb may not be useful if proposed by a person outside the organisation in question.

Some literature has considered the total cost of maintenance. For example, OECD (2006) estimated road infrastructure will need a global investment of USD 220-290 billion/year from 2010-30 (maintenance and net additions). For rail infrastructure, the estimate is USD 49-58 billion/year. Annual investment for road, rail, telecoms, electricity (transmission and distribution) and water is estimated to account, on average, for about 2.5 % of world gross domestic product (GDP); it sum up to USD 37 trillion from 2010-30. In the US, ASCE (2011) found that to resolve existing deficiencies in highways, bridges and transit, USD 74 billion was needed in 2010. If present trends continue, the funding gap will be USD 3.6 trillion (55 % unfunded) in 2040. To reach minimum tolerable conditions, USD 220 billion will be required annually from 2010 to 2040. Deteriorating conditions are estimated likely to impose cumulative costs on American households and businesses of USD 2.9 trillion by 2040.

There are numerous studies of maintenance optimisation models and maintenance cost models; see reviews by Dekker (1996), Garg and Deshmukh (2006), and Sinkkonen et al. (2013). Dekker (1996) noted a gap between theory and practice in maintenance optimisation modelling, likely because of the mathematical purpose and stochastic nature of many models, and the traditional focus on deterministic approaches in mechanical engineering. In addition, few companies are interested in publishing. Garg and Deshmukh (2006) and Sinkkonen et al. (2013) made similar observations; maintenance optimisation models and cost models applications are limited.

Some studies on industrial equipment have presented case studies with the aim of optimising PM and CM costs (Charles et al., 2003, Khalil et al., 2009). These considered single machineries and details were left out for demonstration purposes. As for infrastructure concerns, extensive work has been done on life cycle costing (LCC) and life cycle cost benefit (LCCB) analysis, including costs and benefits to society, owners, users and the environment (Thoft-Christensen, 2012). Studies have considered investments, reinvestments, related induced user costs, and maintenance work. Many models take a stochastic approach, with some practical applications available (Thoft-Christensen, 2012). In this study, we focus solely on comparing PM and CM, taking a deterministic approach and using historical maintenance data. A similar approach to the analysis of historical maintenance data was used by Nissen (2009). Nissen constructed a LCC model for switches and crossings (turnouts) and provided a case study. The LCC model includes cost of acquisition, PM, CM and reinvestments, but details on the respective shares of PM and CM are not provided.

In the present study, PM and CM costs are assessed through the analysis of historical data, with the aim of finding the shares of PM and CM; in addition, the study conducts a cost-benefit analysis (CBA) to assess the value of PM. The method is described in the next section, followed by a case study carried out on rail infrastructure. Infrastructure, such as roads, bridges, railways, electrical grids and pipelines, differ from other assets as they stretch over large geographical areas; consequently, the logistic/travel time can be significant. Following the case study, the last two sections give the discussion and conclusions respectively.

It should be noted that the work is related to maintenance performance measurement; e.g. see maintenance classification by Garg and Deshmukh (2006) and reviews by Kumar et al. (2013) and Simões et al. (2011).

# 2 Methodology

Preventive and corrective maintenance data are associated with both direct and indirect costs. Direct costs are those for materials and labour, and indirect costs are everything else. Common operation and maintenance data are: maintenance times (administrative, logistic and active repair times), down time, delays, failures, remedies, causes and item information. The recorded maintenance data vary between preventive and corrective maintenance, however, as well as between organisations.

To calculate the cost of corrective maintenance, important data on costs are considered to be: service/production loss, logistic time, repair time and materials. Thus, corrective maintenance cost of a system over a given time interval is the sum of four objects:

$$C_{CM} = \sum_{i=1}^{n} \left( n_{P,i} C_P \left\{ 2t_{LT,i} + t_{RT,i} \right\} + C_{M,i} + t_{DT,i} C_{DT} \right) \tag{1}$$

where:

$n$ = Number of functional failures

$n_P$ = Number of personnel on the maintenance team

$t_{LT}$ = Logistic time (LT) for travelling one way, i.e. travel time [t]

$t_{RT}$ = Repair time (RT), i.e. active repair [t]

$t_{DT}$ = Service/production loss time [t]

$C_P$ = Monetary cost per personnel and unit of time [$t^{-1}$]

$C_M$ = Monetary cost of materials (spare parts, tools and machinery)

$C_{DT}$ = Monetary cost of service/production loss [$t^{-1}$]

Similarly, the cost of preventive maintenance (PM) of a system over a given time interval is as follows:

$$C_{PM} = C_P \left( \sum_{i=1}^{m} n_{P,i} t_{PM,i} + \sum_{j=1}^{k} n_{P,j} \left\{ t_{AT,j} + 2t_{LT,j} \right\} \right) + C_{PMM} + C_{PMDT} \qquad (2)$$

where:

$m$ = Number of inspections executed or potential failures (inspection remarks) repaired

$k$ = Number of trips from workshop to item locations

$t_{PM}$ = Active PM time [t]

$t_{AT}$ = Administrative/preparation time [t]

$C_{PMM}$ = Monetary cost of materials for PM (spare parts, tools and machinery)

$C_{PMDT}$ = Monetary cost of service/production loss due to PM shutdown [$t^{-1}$]

Eq. 2 can be applied to inspections and the repair of potential failures, i.e. inspection remarks. A potential failure can be described as an identifiable condition that indicates a functional failure is either about to occur or is in the process of occurring (Moubray, 1997), a concept also used in delay-time analysis (Christer and Waller, 1984). $C_{PMM}$ is put separately in Eq. 2, as it can be treated as a lump sum or per $m$ and/or $k$ depending on inclusion/exclusion of spare parts, tools and machinery costs. $C_{PMDT}$ is also put separately, as down time (DT) for PM is commonly due to extraordinary events.

If cost comparison is to be carried out for internal or external benchmarking, it may be necessary to normalise costs according to the asset types and quantities, or in the case of infrastructure, it may be required to normalise to the assets' linear length.

## 2.1 Cost-benefit analysis

Cost-benefit analysis (CBA) is a decision-making procedure for comparing costs and benefits of activities, like projects and policies. The objective of CBA is to support decision-making and make it more rational and, thus, to have more efficient allocation of resources (Boardman et al., 2013, Thoft-Christensen, 2012). In CBA, a monetary value is assigned to both costs and benefits to determine if a project is worth doing (Pearce et al., 2006). Common decision rules for accepting projects include calculation of net benefits, benefit-cost ratios and internal rate of returns. Through benefit-cost ratios, the value of PM can be assessed as the benefit from unity investment, i.e. intuitive to human perception. However, the benefit-cost ratio has limitations: it cannot be singlehandedly used as a decision rule in mutually exclusive projects and it is sensitive to negative values subtracted from benefits or added to costs; e.g. user costs can be set as negative benefits. Nevertheless, these limitations are not a concern in assessing the value of PM, as mutually exclusive only applies when several alternatives are ranked, and negative values are not included in the formulation set-up. The benefit-cost ratio (B/C), or return of maintenance investment (ROMI), for assessing the value of PM is defined in this study as:

$$B/C = \frac{B_{PM}}{C_{PM}} = \frac{\alpha\beta\overline{C}_F}{\overline{C}_I + \alpha\overline{C}_R} \tag{3}$$

where:

$B_{PM}$ = Benefit of preventive maintenance

$C_{PM}$ = Cost of preventive maintenance

$\overline{C}_F$ = Mean cost of functional failure (including or excluding cost of production/service losses)

$\overline{C}_I$ = Mean cost of inspection

$\overline{C}_R$ = Mean cost of potential failure repair

$\alpha$ = Probability of detection (POD) of potential failure, $\alpha \in [0, 1]$

$\beta$ = Potential to functional failure likelihood, $\beta \in [0, 1]$

The cost ($C_{PM}$) is set as the monetary value invested in PM; it is the inspections cost ($\overline{C}_I$) and the repair cost of the potential failures ($\overline{C}_R$) identified from the inspections. As each inspection is related to a probability of detection (POD), a fraction $\alpha$ is introduced. The benefit ($B_{PM}$) from the PM is the cost saved by avoiding functional failures ($\overline{C}_F$) and corrective maintenance (CM). However, it is not certain that all potential failures identified by PM will deteriorate to functional failures. Accordingly, another fraction $\beta$ is introduced. Quantitatively, the mean costs are estimated as follows:

$$\overline{C}_I = \frac{1}{m_I}\sum_{i=1}^{m_I} c_{I,i} = \frac{1}{m_I} C_{PMI} \tag{4}$$

$$\overline{C}_R = \frac{1}{m_R}\sum_{i=1}^{m_R} c_{R,i} = \frac{1}{m_R} C_{PMR} \tag{5}$$

$$\overline{C}_F = \frac{1}{n}\sum_{i=1}^{n} c_{F,i} = \frac{1}{n} C_{CM} \tag{6}$$

where:

$c_I$ = Monetary cost of inspecting item

$c_R$ = Monetary cost of potential failure repair of item

$c_F$ = Monetary cost of functional failure repair of item

$m_I$ = Number of inspections

$m_R$ = Number of potential failures

The probability of detection is given by:

$$\alpha = \frac{m_R}{m_I} \tag{7}$$

Note: probability of detection is a term used in non-destructive testing (NDT); within inspections, NDT is commonly applied in the form of visual inspections. In the above formulation, $\alpha$ is the fraction of inspected items that does not meet the functional level requirements. In this sense, it does not mean that $1-\alpha$ of the items passed with undetected failures. Rather, $1-\alpha$ is the fraction of items that do meet the functional requirements.

Considering the potential to functional failure likelihood, $\beta$ depends on the criticality of potential failures and the time frame considered. However, there is no obvious way of calculating $\beta$. It would be possible if all potential failures were left unattended, and their condition was monitored instead. We would then be able to see how many potential failures have deteriorated to functional failures, requiring corrective maintenance, at a specific time. Unfortunately, this may not be feasible in practice. Nevertheless, potential failures are commonly assigned a priority with respect to criticality and time frame for rectification; a high priority indicates a high $\beta$. Thus, the assigned priorities can be used as an indicator for setting $\beta$, which is used in Section 4.2-3.

# 3 Case study

We used a rail infrastructure case study to examine the relationship between PM and CM in practice. Similar analysis of other assets, such as bridges, will not yield the same result, though the method for assessing maintenance costs is similar in terms of maintenance requirements.

## 3.1 Data collection

Maintenance data have been collected from the Swedish infrastructure manager (IM) Trafikverket (Swedish Transport Administration). Data comprise both infrastructure related corrective maintenance (CM) activities, i.e. functional failure data, and preventive maintenance (PM) data from inspections and rectification of potential failures. The CM data consist of urgent potential failures (classified as functional failures) reported by the maintenance contractor during inspections, as well as functional failures identified outside the inspections, commonly reported by the train driver, but occasionally reported by the public. The PM data include visual inspections and manual measurements using gauges and non-destructive testing. The collected data come from seven railway lines in Sweden, which include 65 sections; see Figure 1. The lines connect the three largest cities of Sweden, Stockholm, Gothenburg and Malmö, as well as the heavy haul line in the north of Sweden. The maintenance data are between 2013.01.01 - 2013.12.31, i.e. 1 year. Reported number of functional failures is 24 816, with 25 % of those failures resulting in train delays, i.e. 6 131 train-delaying functional failures. Performed inspections number 352 679, potential failures equal 52 854, and rectified potential failures equal 28 704. See Appendix A for summary statistics of the collected data.

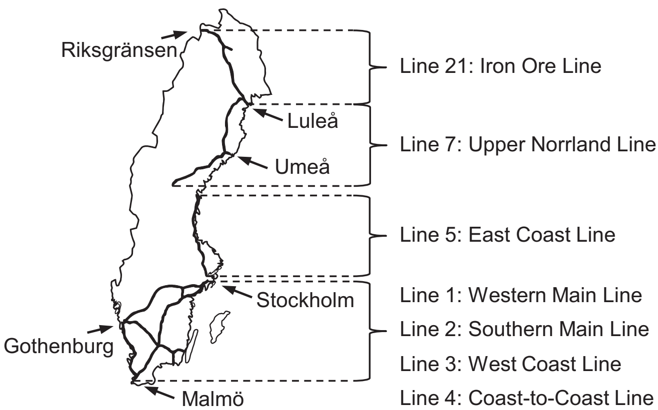


*Figure 1: Railway lines 1-5, 7 and 21 of the Swedish network.*

## 3.2 Data quality and outliers

### Functional failures data (corrective maintenance)

Depending on the collected data, the method may need to be specified further. In the case study's data, the maintenance times of rail infrastructure functional failures are registered by maintenance personnel and train dispatchers. This means the precision in the data can vary; therefore, using the mean logistic and repair times instead of the actual values may be preferable. Thus, recalling Eq. 1, corrective maintenance cost of a rail infrastructure item (line, section, system or component) over a given time interval is given by:

$$C_{CM} = n\left(\overline{n}_P C_P \left\{2m_{LT} + m_{RT}\right\} + \overline{C}_M\right) + C_{DT}\sum_{i=1}^{n} t_{DT,i} \tag{8}$$

where:

$\overline{n}_P$ = Mean number of personnel in the maintenance team

$m_{LT}$ = Mean logistic time (LT)

$m_{RT}$ = Mean repair time (RT)

$\overline{C}_M$ = Mean monetary cost of materials

Studying Line 21, the time to restoration (TTR), i.e. LT + RT, gives a log-normal mean of 401 minutes and a median of 139 minutes, when data up to the 95$^{th}$ percentile are considered. Alternatively, limits can be set by discarding data according to a percentage. By limiting the logistic time (LT) and active repair time (RT) to 5 < LT < 240 minutes and 10 < RT < 600 minutes, the log-normal mean is 156 minutes and the median is 130 minutes; i.e. there is less difference (Figure 2). Either the median or log-normal mean can be used. However, care should be taken if the log-normal mean is used, as it is sensitive to outliers. Moreover, because CM consists of immediate and deferred maintenance (CEN, 2010), some functional failures require a few days for correction, affecting the recorded LT and RT. In addition, not all functional failures lead to train delays, and, consequently, the LT and RT vary.

For train-delaying functional failures, it is assumed the maintenance team travels to the failure location as soon as possible and carries out repair efficiently. Thus, the LT and RT of train-delaying functional failures should represent the real time taken to perform maintenance better than non-delaying functional failures. Therefore, in this study, $m_{LT}$ and $m_{RT}$ are estimated using the log-normal mean of train-delaying functional failures that fulfils: 5 < LT < 240 minutes and 10 < RT < 600 minutes. $m_{LT}$ and $m_{RT}$ are then applied to all functional failures, with the exception of some failures that have been excluded because they caused extraordinarily long train delays.

Train delays are recorded through the signalling system and can therefore be considered to be of high precision. The train-delaying functional failures have some outliers;

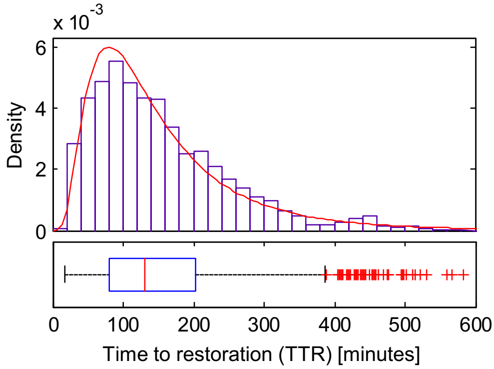


*Figure 2: Distribution of the time to restoration (TTR) of functional failures of Line 21.*

i.e. some functional failures result in disturbance up to several days, e.g. derailments. Consequently, the 2 % with the longest delays are considered outliers and excluded from the analysis. Outliers should be included in a separate analysis, as they can represent a major cost, but this is beyond the scope of the present study.

The collected data do not cover the tools/machinery cost and have been left out in $\overline{C}_M$ of Eq. 8. Similarly, the spare parts cost and number of personnel are unknown, for which a mean spare parts cost $\overline{C}_M$ and mean number of personnel $\overline{n}_P$ are used, respectively.

**Inspections and potential failures (preventive maintenance)**

Eq. 2 is applied for inspections $C_{PMI}$ and repair of potential failures $C_{PMR}$, of a rail infrastructure item over a given time interval as:

$$C_{PMI} = C_P \overline{n}_{PI} \left( m_I \overline{t}_{PMI} + k_I \overline{t}_{ATI} + 2 \sum_{j=1}^{k_I} t_{LTI,j} \right) \tag{9}$$

$$C_{PMR} = C_P \overline{n}_{PR} \left( m_R \overline{t}_{PMR} + k_R \overline{t}_{ATR} + 2 \sum_{j=1}^{k_R} t_{LTR,j} \right) + \overline{C}_{PMMR} \tag{10}$$

where:

$\overline{n}_{PI}$ = Mean number of personnel in the inspection team

$m_I$ = Number of inspections

$k_I$ = Number of trips for inspections

$\overline{t}_{PMI}$ = Active inspection time [t]

$\bar{t}_{ATI}$ = Administrative/preparation time for inspections [t]

$t_{LTI}$ = Logistic time (LT), i.e. travel time, for inspections [t]

$\bar{n}_{PR}$ = Mean number of personnel in the potential failures repair team

$m_R$ = Number of potential failures

$k_R$ = Number of trips for potential failures repair

$\bar{t}_{PMR}$ = Active potential failures repair time [t]

$\bar{t}_{ATR}$ = Administrative/preparation time for potential failures repair [t]

$t_{LTR}$ = Logistic time (LT), i.e. travel time, for potential failures repair [t]

$\overline{C}_{PMMR}$ = Monetary cost of materials for potential failures repair (spare parts, tools and machinery)

$C_{PMMI}$ and $C_{PMDT}$ are left out due to missing data. The logistic time ($t_{LTI}$ and $t_{LTR}$) is calculated as the mean travel distance by the mean travel speed; i.e. $\bar{l}/\bar{v}$. $\bar{l}$ depends on the railway section in question; i.e. $t_{LTI,j} = \bar{l}_j/\bar{v}$.

## 3.3 Normalisation

Railways consist of both linear and point subsystems. Examples of subsystems that can be treated as linear are rails, sleepers, fasteners, ballast and the catenary system. Sub-systems difficult to consider as linear are switches and crossings (S&Cs) and various types of stations. Since S&Cs stand for a major part of all failures and train delay (Appendix A), for this study, normalisation has been carried out according to the number of S&Cs and the track length. More specifically, maintenance data of S&Cs are normalised according to the number of S&Cs, and maintenance data of other sub-systems are normalised according to the track length, with double track counted twice; i.e. the resulting costs are divided by the number of S&Cs and track length. That is, for each one of the 65 railway sections, the normalised cost is given by:

$$C = \frac{1}{N}\left(C_{CM}^{S\&Cs} + C_{PMI}^{S\&Cs} + C_{PMR}^{S\&Cs}\right) + \frac{1}{M}\left(C_{CM}^{Track} + C_{PMI}^{Track} + C_{PMR}^{Track}\right) \tag{11}$$

where $N$ and $M$ are the total number of S&Cs and track length in kilometres respectively, of a particular railway section.

## 3.4 Assumptions

The study made the following assumptions:

- By normalising track length and counting double track twice, it is assumed single track and double track railway sections can be analysed together. Moreover, normalisation according to track length and number of switches and crossings is assumed to improve results of a railway section for comparison purposes.

- Probability distributions are assumed to be similar for all railway sections. Thus, the same limits and mean values can be used for all railway sections. In addition, the data quality is assumed to be similar for all railway sections.

- Cost of man-hours, train delays, spare parts and required number of personnel for maintenance are assumed to be the same for all railway sections. Time of inspections, rectification of potential failures and preparations are also assumed to be the same for all railway sections.

- Travelling speed for preventive maintenance is assumed to be the same for all railway sections; thus, the logistic time depends on the section's geographical length. For corrective maintenance, the logistic time comes from the maintenance data.

# 4 Results

The results are calculated treating the time period of the collected data as one element; i.e. results cover one year. Each of the 65 railway sections is calculated separately using Eq. 11. The constants are set as follows:

$\overline{n}_P = 2$

$\overline{n}_{PI} = 1$

$\overline{n}_{PR} = 2$

$C_P =$ €100 /h

$C_{DT} =$ €53 /minute (Nissen, 2009)

$\overline{C}_M =$ €100 (per functional failure)

$\bar{t}_{PMI} = 5$ minutes

$\bar{t}_{ATI} = \bar{t}_{PMR} = \bar{t}_{ATR} = 30$ minutes

$\overline{v} = 80$ km/h

$\overline{C}_{PMMR} =$ €100 (per potential failures)

We assume the following remain constant. When a functional failure takes place, two persons travel by car to the failed item's location to carry out maintenance. The travel time ($m_{LT}$) and repair time ($m_{RT}$) are estimated from the log-normal mean of the train-delaying functional failures of the particular railway section in question. In the presence of any train delay ($t_{DT,i}$), a cost of €53 /minute is added. A mean spare parts cost of €100 is added. Inspections are carried out by one person who prepares his/her work for 30 minutes, travels the mean distance to the railway section in question, and performs $x$

number of inspections taking five minutes each. The number of inspections and trips are given in the inspections data. Similarly, potential failures are repaired, on average, by two persons; each repair takes 30 minutes and costs € 100 per repair. Each person costs € 100 /h. Although mean figures are applied, in reality, they may vary between railways and sections.

Recalling Eq. 8-10, for all 65 railway sections, the cost proportion of functional failures ($C_{CM}$), inspections ($C_{PMI}$) and potential failures repairs ($C_{PMR}$) are shown in Figure 3. The figure shows that the cost of train delay represents 61 % of the CM cost, and the inspections and repair of potential failures represent ∼80 % of the PM cost.

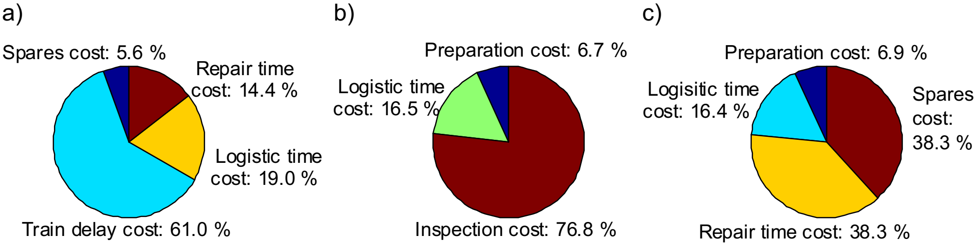


*Figure 3: Cost proportions of a) functional failures, i.e. corrective maintenance, b) inspections and c) potential failures repair, of the 65 railway sections.*

## 4.1 Normalised cost for comparing railway sections

Recalling Eq. 11, Figure 4 shows the normalised cost as a function of the railway sections, sorted from the lowest to the highest total normalised maintenance cost, i.e. PM and CM added together. It can be seen that the railway sections with the lowest maintenance cost have ∼30 % PM, while the railway sections with the highest maintenance cost have ∼10 % PM. A linear fit gives an $R^2$ of 0.38, not very high, but there are numerous factors influence the performance of a railway section; see the discussion section of this paper.

It can also be seen from Figure 4 that a few railway sections have very high total maintenance cost relative to the other railway sections. Plotting the normalised cost as a function of track length reveals some dependence between the costs and track length, even after normalisation (Figure 5). Studying the eight outliers, indicated with crosses in Figure 5 right hand side, we found these are city tracks, which have high technical density and short track lengths. The eight outliers have a mean track length of 7.8 km, while the mean length of the 65 sections is 69 km.

The normalised cost can be plotted as a function of the PM to CM ratio, as shown in Figure 6. The logarithmic fit does not include the outliers marked with crosses. A PM to CM of 0.1 gives a normalised cost of 21 356, while a PM to CM of 0.2 gives a normalised cost of 14 638, i.e. 31 % less. However, increasing the PM will not definitely lower the total maintenance cost, as the $R^2$ of 0.40 is quite low.

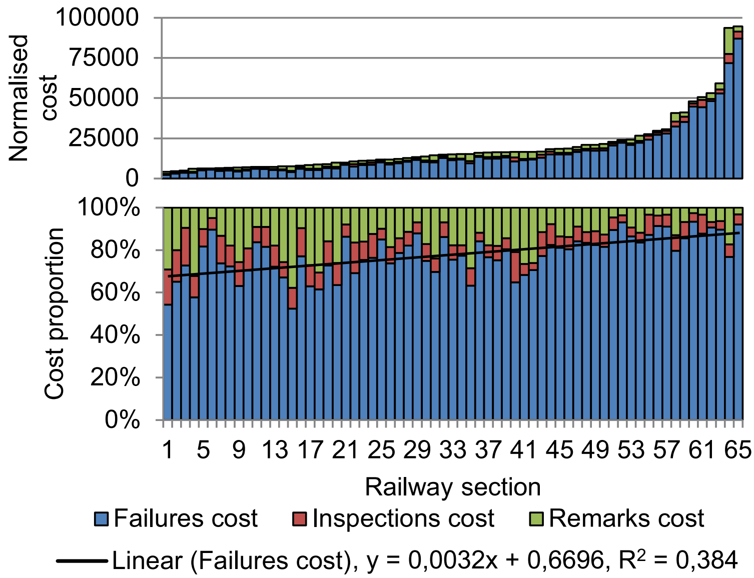


*Figure 4: Normalised maintenance cost and cost proportion of the 65 railway sections.*

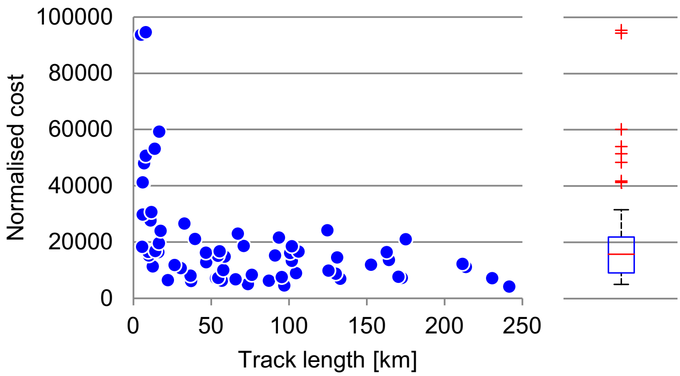


*Figure 5: Normalised cost as a function of track length with box-plot.*

Comparing the ten railway sections with the lowest cost to the ten sections with the highest cost, we found the sections with the highest costs to have twice the number of trains and three times the tonnage; see Table 1. Mean tonnage and number of trains are given in arbitrary units (a.u.) in this table due to confidentiality and are available for five

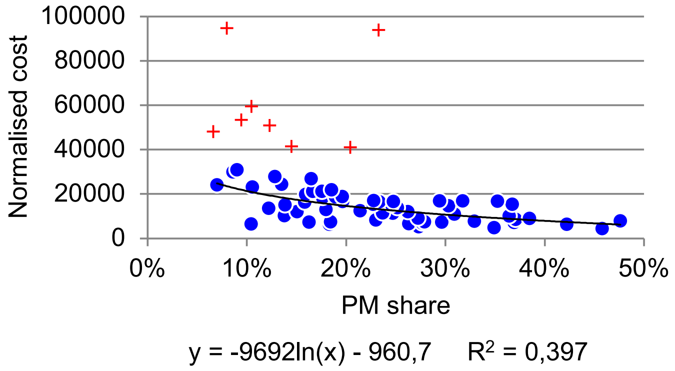


*Figure 6: Normalised cost as a function of the PM/(PM + CM). Outliers, marked with crosses, are not included in the logarithmic fit.*

of the high cost sections and five of the low cost sections. The costlier sections also have 4.5 times more track functional failures (rails, joints, fastenings, sleepers and ballast), 6.7 times more joint functional failures and 3.2 times more frog/crossing functional failures.

*Table 1: Comparison of the ten sections with the lowest cost with the ten sections bearing the highest costs.*

| | Lowest cost sections | Highest cost sections | Ratio |
|---|---|---|---|
| Normalised cost | 59489 | 249125 | 4,2 |
| S&Cs mean installation year | 1995 | 1998 | |
| Rail mean installation year | 1997 | 1994 | |
| Mean tonnage [a.u.] | 1 | 3 | 3 |
| Mean trains [a.u.] | 1 | 2 | 2 |
| Inspections per track-km | 48,4 | 110 | 2,3 |
| S&Cs inspections per S&Cs | 5,0 | 5,4 | 1,1 |
| Track failures per track-km | 0,18 | 0,80 | 4,5 |
| S&Cs failures per S&Cs | 0,56 | 1,12 | 2,0 |
| Rail joints failures per track-km | 0,04 | 0,26 | 6,7 |
| Frog failures per S&Cs | 0,009 | 0,029 | 3,2 |

## 4.2 Cost-benefit analysis

For the CBA, normalisation is not applicable. Recalling Eq. 3, the benefit-cost ratio (B/C) of PM is given by:

$$B/C = \frac{\alpha\beta\overline{C}_F}{\overline{C}_I + \alpha\overline{C}_R} = \frac{\alpha\beta\frac{1}{n}C_{CM}}{\frac{1}{m_I}C_{PMI} + \alpha\frac{1}{m_R}C_{PMR}} = \frac{\alpha\beta\frac{1}{n}(Eq.\ 8)}{\frac{1}{m_I}(Eq.\ 9) + \alpha\frac{1}{m_R}(Eq.\ 10)} \tag{12}$$

The B/C-ratio can be used for a system, component, or a whole railway. In this study, we calculated the B/C-ratio for the whole data set, i.e. 24 816 functional failures, 352 679 inspections and 28 704 rectified potential failures. The $\overline{C}_F$, $\overline{C}_I$ and $\overline{C}_R$ were calculated for each of the 65 railway sections, followed by taking the mean of the 65 sections. The mean functional failure cost $\overline{C}_F$ is found to be €1 806, the mean inspection cost $\overline{C}_I$ is €11.2 and the mean repair of potential failures cost $\overline{C}_R$ is €273. The probability of detection (POD) of potential failure $\alpha$ is found recalling Eq. 7. Number of inspections carried out is 352 679, potential failures are 52 855 and rectified potential failures are 28 704. To avoid overestimating the benefit, we only considered the more critical potential failures, i.e. those that were rectified. This came to 28 704 potential failures. The value of $\alpha$ is then 28 704 / 352 679 = 0.08. Out of the 28 704 rectified potential failures, 72 % had the priority 'month' assigned and 20 % had the priority 'week'; see Figure A.4. In other words, inspection personnel had estimated that, if not rectified, the potential failures would deteriorate to a functional failure or be a safety risk in the near future. Using the priority 'month' as an example, rectification is required within three months according to regulations of Trafikverket, and, thus, the near future is three months. Following inspection personnel's estimation and the maintenance policy, the potential to functional failure likelihood $\beta$ would then be set to unity. Of course, not all potential failures would deteriorate to functional failures in practice if PM was omitted. Therefore, we set the potential to functional failure likelihood $\beta$ at 0.75. The benefit-cost ratio (B/C) then turns out to be 3.3.

## 4.3 Sensitivity analysis

We performed sensitivity analysis for the B/C-ratio, as both the fractions $\alpha$ and $\beta$ introduce uncertainty into the B/C calculation. The probability of detection, i.e. $\alpha$, was set as the rectified potential failures per inspections (28 704 / 352 679 = 0.08). An inspection, therefore, has 8 % probability to lead to a repair. This number depends on how effective the inspections are. An organisation with little PM that introduces a basic PM program known to be effective might obtain an $\alpha > 0.08$, while an organisation with an extensive PM program who extends the PM program even further may lower its $\alpha$. The potential to functional failure likelihood, i.e. $\beta$, can be settled by an expert group and priorities can be assigned to the potential failures. A large share of potential failures with high priority indicates a high $\beta$. The effect of $\alpha$ and $\beta$ on the B/C-ratio is shown in Figure 7. The B/C-ratio initially increases quickly for $\alpha$ to approach a horizontal asymptote. For $\beta$, the B/C-ratio increases linearly. Note: there is an interdependency between $\alpha$ and $\beta$; if maintenance limits for potential failures are made more strict, $\alpha$ will increase and $\beta$ will decrease. Moreover, user costs in the form of train delays have a large impact on the B/C-ratio. According to Figure 3, 61 % of the corrective maintenance cost ($C_{CM}$) comes from train delays. Discounting the train delay cost gives a B/C-ratio of $0.39 \times 3.3 = 1.29$.

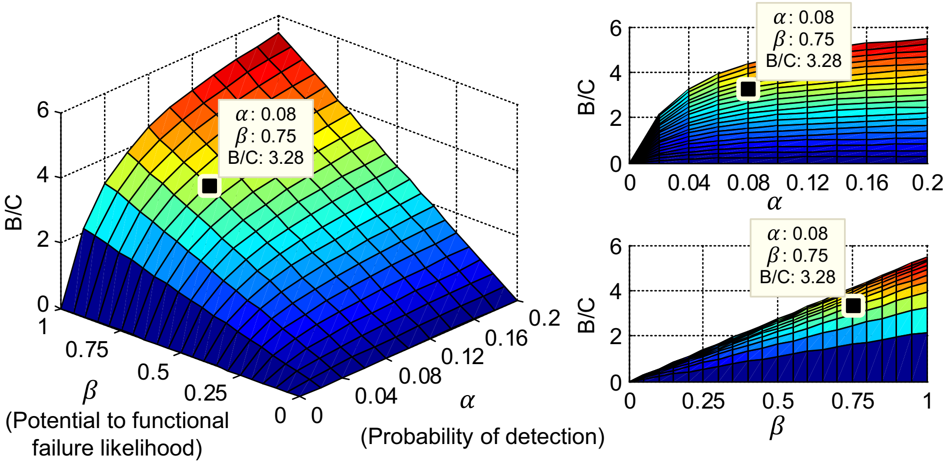


*Figure 7: Benefit-cost ratio (B/C) of the railway lines as a function of $\alpha$ and $\beta$.*

# 5 Discussion

From the case study, we determine that 70-90 % of the maintenance cost comes from corrective maintenance (CM) which, in turn, constitutes 61 % of down time/delay cost (Figures 3 and 4). Consequently, the results depend on the cost of down time; if the down time cost is disregarded in the case study, CM stands for 50-70 % of the maintenance cost. In addition, the travel speed for preventive maintenance (PM) was set rather high; if it were lower, this would affect the results by a few percentage points. The size of the logistic time is shown in Figure 3.

We also find the railway sections with the lowest total maintenance cost have the largest share of PM; 30 % PM compared to ~10 % PM for the costliest sections. This does not mean the railway sections with the lowest total maintenance cost invest more resources in PM in monetary terms; rather, as Figure 4 indicates, the railway sections with the lowest cost have both lower PM and CM costs. Those sections with the highest maintenance cost transport three times the tonnage of the sections with the lowest costs; thus, inspections are carried out more frequently due to higher track classification (Appendix A). As an example, inspections of S&Cs are carried out 1-6 times per year depending on the track classification. The difference in the PM to CM ratios may be explained by that the higher classification does not increase the inspections and PM program as actually required. There may also be different maintenance policies between the railway sections and lines, even though they are covered by the same infrastructure manager.

The linear fit of Figure 4 does not show a high coefficient of determination ($R^2$ equals 0.38), but as numerous factors affect rail infrastructure performance and only a few are considered in the model, it may not be possible to expect a high $R^2$. Examples of factors influencing the performance of a railway section are: geographical location; climate; weather; component models, manufacturer and condition/age; freight and passenger heterogeneity; rolling stock condition/age, types, speed and tonnage; wheel and rail profiles; and maintenance policy. However, the normalisation procedure could be made more sophisticated, e.g. normalising according to the number of power converter and signalling stations.

The CBA strongly depends on the probability of detection $\alpha$ and potential to functional failure likelihood $\beta$. $\alpha$ is found in maintenance data, but $\beta$ needs to be set by decision-making, e.g. through field experts. In the case study, CBA is calculated for a group of seven railway lines, but it could as well be calculated for a specific system or component to assess the feasibility of a redesign. In any case, it requires that the data quality is satisfactory to allow linkage of datasets on inspections, potential failures and functional failures. As an example, the case study's seven railway lines include 4020 switches and crossings (S&Cs); where one of the subsystems is the switch motor, which includes a connector (transducer) for control of point blades position. Depending on the S&C's specifications, like allowable train speed, the S&C includes such a connector. For the sake of expediency, in the following example, we assume 4020 connectors. The functional failure data reveal 153 connector functional failures, each costing €1 806 when train delay cost is included. Disregarding train delay cost, each functional failure costs €703. Replacing the 4020 connectors with a redesigned connector, which fails half as often, costs €1 097 460, assuming each connector costs €100 and has a replacement cost equal to the potential failures repair cost, i.e. €273-100 = €173. In short, 76.5 functional failures per year are avoided by an investment of about a million euro. Applying a discount rate of 4 %, as used by the infrastructure manager, gives a positive net present value (NPV) after nine years. Disregarding the discount rate gives a positive difference after seven years. However, the investment is only feasible if the cost of train delays is included, which in this study is set at €53 /minute; see Figure 8.

Data on transported tonnage were collected in 21 of the 65 railway sections. Plotting the normalised cost as a function of the mean working day (business day) tonnage gives Figure 9. The linear fit does not give such a high $R^2$, but comparing it with functional failures versus tonnage gives similar results. Once again, as mentioned above, there are numerous factors to consider; this is an area requiring more research.

The Swedish National Road and Transport Research Institute (VTI) estimates the maintenance cost per S&C in Sweden to be €1 822 (EUR/SEK 9.0) per year (Hedström,

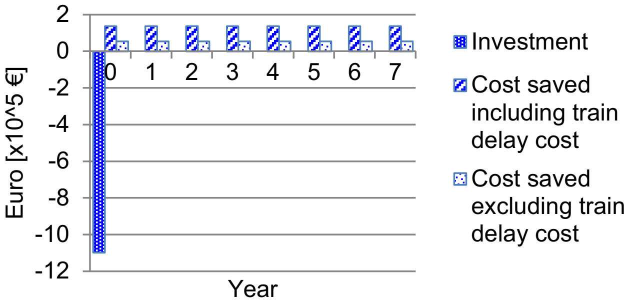


*Figure 8: Cash flows of connector investment.*

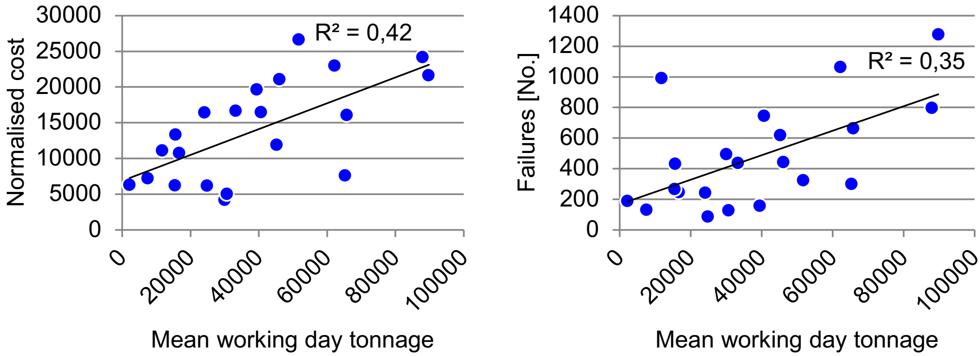


*Figure 9: Normalised cost and functional failures as functions of mean working day tonnage.*

2001). By way of comparison, our case study results suggest €1 980 per switches and crossings when train delay costs are disregarded. When train delay costs are included, we get €2 882 per S&Cs. VTI's result is based on an accounting system which includes costs that the presented method does not, such as the replacement cost of switches and crossings. Similar comparison with the accounting system of year 2013 is complicated, as maintenance is now outsourced.

Note also that the presented method does not include all costs related to maintenance, such as procurement, planning, administrative and readiness costs. Logically, planning costs should be higher for preventive maintenance than corrective maintenance, while readiness costs should be higher for corrective maintenance.

# 6 Conclusions

In this work, the respective shares of PM and CM performed on rail infrastructure are studied, together with a cost-benefit analysis to assess the value of PM. In the case study, PM represents ~10-30 % of the total maintenance cost when user costs, i.e. train delays, are included as a CM cost. The case study indicates that the railway sections with the lowest total maintenance cost have the highest share of PM. In the case study, the benefit-cost ratio of PM is estimated at 3.3, but this figure is highly dependent on the input data, especially the user costs.

The applied method takes advantage of maintenance data for estimating maintenance costs; this can be convenient when accounting systems do not allow detailed information on maintenance actions, as in the case of outsourced maintenance.

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# A Summary statistics

This appendix summarises the collected data of the case study. Maintenance data has been collected from the Swedish infrastructure manager (IM) Trafikverket (Swedish Transport Administration) and constitute of infrastructure related corrective maintenance, i.e. functional failure data, maintenance inspections and rectification of potential failures. Concerned databases of Trafikverket are Ofelia, LUPP, BESSY and BIS. The collected data includes seven railway lines that together consist of 65 railway sections; see Figure A.1 and Table A.1.

*Table A.1: The collected data.*

| | |
|---|---|
| Time period | 2013.01.01 - 2013.12.31, i.e. 1 year |
| Failures [No.] | 24 816, 25 % (6 131) train-delaying |
| Inspections [No.] | 352 679 |
| Potential failures [No.] | 52 854, 54 % (28 704) rectified |

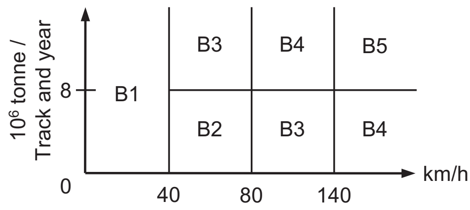



*Figure A.1: Inspection classes.*

## A.1 System description and maintenance limits

Description of the railway sections are given in Table A.2. The frequency of maintenance inspections of the Swedish railway network depends on track speed limits and tonnage transported; see Figure A.1 and Table A.3. Besides these general limits, specific limits are set per failure type, e.g. material crack sizes. Description of the railway sections is shown in Tables A.4 and A.5. Max axle loads are according to Trafikverket (2013). Transport volumes are not given due to confidentiality.

*Table A.2: Sections of the railway lines for analysis. The track length column is equated for multiple tracks, e.g. double track counted twice.*

| Line | Section labels | No. of sections | Track length [km] | No. of S&Cs | Main track type |
|---|---|---|---|---|---|
| 1 | 410, 412, 414, 416, 418, 419***, 420, 511, 512, 611, 612 | 11 | 979 | 792 | Double |
| 2 | 421*, 422, 502, 504, 505, 810, 811, 813, 814, 815, 817, 909, 910, 912 | 14 | 1117 | 947 | Double |
| 3 | 626, 627, 628, 630, 904*, 920*, 938, 940 | 8 | 531 | 393 | Double |
| 4 | 641, 655, 720, 721, 821, 822, 823, 824, 827 | 9 | 413 | 305 | Single |
| 5 | 234, 235, 303, 429, 430**, 433****, 243** | 7 | 629 | 634 | Single |
| 7 | 119, 120, 122, 124, 126, 129, 130, 138, 146, 211 | 10 | 723 | 701 | Single |
| 21 | 111, 112, 113, 114, 116, 118 | 6 | 467 | 248 | Single |
| Sum: | | 65 | 4859 | 4020 | |

*Single track, **Double track, ***Mixed (half single and half double), ****Double track or more

*Table A.3: Excerpt of inspections per system, class and year.*

| | Inspections per class and year | | | | |
|---|---|---|---|---|---|
| System | B1 | B2 | B3 | B4 | B5 |
| Catenary system | 1 | 1 | 1 | 1 | 1 |
| Crossing | 2 | 2 | 3 | 3 | 3 |
| Rail and S&Cs NDT | 1/4 | 1/3 | 1/2 | 1 | 1 |
| S&Cs | 1 | 3 | 4 | 6 | 6 |
| Signal | 2 | 3 | 3 | 3 | 3 |
| Signalling | 1 | 1 | 1 | 1 | 1 |
| Track | 1 | 2 | 3 | 3 | 3 |
| Track geometry | 1 | 3 | 4 | 6 | 6 |

S&Cs = switches and crossings

NDT = Non-destructive testing

*Table A.4: Description of the railway sections. Performed inspections per inspection class are based on the collected data of year 2013.*

| Line label | Section label | Length [km] | S&Cs [No.] | Track type | Max axle load [Tonne] | Max speed [km/h] | Performed inspections per inspection class [%] | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | B1 | B2 | B3 | B4 | B5 | Main class |
| 1 | 410 | 67 | 137 | Double | 22.5 | 130 | 7 | 0 | 82 | 5 | 6 | B3 |
| 1 | 412 | 37 | 45 | Double | 22.5 | 200 | 1 | 3 | 66 | 10 | 20 | B3 |
| 1 | 414 | 164 | 73 | Double | 22.5 | 200 | 2 | 4 | 2 | 93 | 0 | B4 |
| 1 | 416 | 125 | 38 | Double | 22.5 | 200 | 1 | 2 | 0 | 97 | 0 | B4 |
| 1 | 418 | 59 | 32 | Double | 22.5 | 250 | 3 | 2 | 0 | 20 | 76 | B5 |
| 1 | 419 | 40 | 98 | Mixed | 22.5 | - | 7 | 6 | 41 | 7 | 40 | B3/B5 |
| 1 | 420 | 14 | 44 | Double | 22.5 | 200 | 6 | 11 | 82 | 1 | 0 | B3 |
| 1 | 511 | 47 | 38 | Double | 22.5 | 200 | 2 | 3 | 14 | 0 | 80 | B5 |
| 1 | 512 | 231 | 172 | Double | 22.5 | 200 | 9 | 10 | 4 | 77 | 0 | B4 |
| 1 | 611 | 133 | 66 | Double | 22.5 | 200 | 3 | 7 | 5 | 85 | 0 | B4 |
| 1 | 612 | 71 | 49 | Double | 22.5 | 180 | 6 | 0 | 0 | 94 | 0 | B4 |
| 2 | 421 | 105 | 55 | Single | 22.5 | 160 | 1 | 10 | 50 | 39 | 0 | B3/B4 |
| 2 | 422 | 76 | 15 | Double | 22.5 | 200 | 1 | 2 | 0 | 96 | 0 | B4 |
| 2 | 502 | 11 | 57 | Double | 22.5 | 200 | 8 | 47 | 29 | 16 | 0 | B2/B3 |
| 2 | 504 | 10 | 55 | Double | 22.5 | 180 | 9 | 40 | 51 | 0 | 0 | B2/B3 |
| 2 | 505 | 153 | 85 | Double | 22.5 | 200 | 4 | 5 | 42 | 49 | 0 | B3/B4 |
| 2 | 810 | 12 | 60 | Double | 22.5 | 140 | 9 | 9 | 39 | 43 | 0 | B3/B4 |
| 2 | 811 | 173 | 88 | Double | 22.5 | 200 | 2 | 5 | 0 | 0 | 93 | B5 |
| 2 | 813 | 170 | 70 | Double | 22.5 | 200 | 1 | 4 | 0 | 0 | 95 | B5 |
| 2 | 814 | 101 | 136 | Double | 22.5 | 200 | 10 | 7 | 20 | 0 | 62 | B5 |
| 2 | 815 | 95 | 29 | Double | 22.5 | 200 | 1 | 4 | 0 | 0 | 95 | B5 |
| 2 | 817 | 13 | 80 | Double | 22.5 | 200 | 9 | 36 | 49 | 0 | 6 | B2/B3 |
| 2 | 909 | 6 | 85 | Double | 22.5 | - | 16 | 22 | 53 | 0 | 9 | B3 |
| 2 | 910 | 56 | 12 | Double | 22.5 | 200 | 0 | 3 | 0 | 0 | 97 | B5 |
| 2 | 912 | 102 | 120 | Double | 22.5 | 200 | 4 | 3 | 9 | 0 | 84 | B5 |
| 3 | 626 | 47 | 49 | Double | 22.5 | 180 | 6 | 4 | 0 | 90 | 0 | B4 |
| 3 | 627 | 242 | 122 | Double | 22.5 | 200 | 7 | 3 | 2 | 89 | 0 | B4 |
| 3 | 628 | 87 | 88 | Double | 22.5 | 200 | 6 | 2 | 11 | 81 | 0 | B4 |
| 3 | 630 | 16 | 44 | Double | 22.5 | 200 | 12 | 11 | 3 | 74 | 0 | B4 |
| 3 | 904 | 7 | 37 | Single | 22.5 | - | 7 | 0 | 89 | 4 | 1 | B3 |
| 3 | 920 | 27 | 15 | Single | 22.5 | 180 | 0 | 20 | 7 | 72 | 0 | B4 |
| 3 | 938 | 74 | 14 | Double | 22.5 | 200 | 0 | 0 | 2 | 31 | 67 | B5 |
| 3 | 940 | 22 | 24 | Double | 22.5 | 200 | 2 | 0 | 20 | 34 | 44 | B4/B5 |
| 4 | 641 | 66 | 18 | Single | 22.5 | 140 | 8 | 0 | 92 | 0 | 0 | B3 |
| 4 | 655 | 6 | 58 | Single | 22.5 | 100 | 24 | 22 | 55 | 0 | 0 | B3 |
| 4 | 720 | 55 | 65 | Single | 22.5 | 160 | 5 | 8 | 26 | 61 | 0 | B4 |
| 4 | 721 | 97 | 33 | Single | 22.5 | 160 | 8 | 7 | 86 | 0 | 0 | B3 |
| 4 | 821 | 18 | 13 | Single | 22.5 | 160 | 0 | 6 | 30 | 64 | 0 | B3/B4 |
| 4 | 822 | 58 | 30 | Single | 22.5 | 160 | 3 | 8 | 20 | 70 | 0 | B4 |
| 4 | 823 | 57 | 19 | Single | 25.0 | 130 | 1 | 12 | 86 | 1 | 0 | B3 |
| 4 | 824 | 53 | 11 | Single | 22.5 | 200 | 2 | 3 | 18 | 77 | 0 | B4 |
| 4 | 827 | 6 | 58 | Single | 22.5 | 140 | 30 | 15 | 54 | 0 | 0 | B1/B3 |
| 5 | 234 | 10 | 44 | Single | 22.5 | 130 | 13 | 19 | 69 | 0 | 0 | B3 |
| 5 | 235 | 214 | 147 | Single | 22.5 | 200 | 6 | 5 | 2 | 35 | 52 | B5 |

*Table A.5: Continuation of the description of the railway sections.*

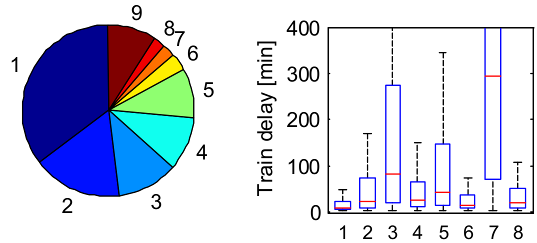
| Line label | Section label | Length [km] | S&Cs [No.] | Track type | Max axle load [Tonne] | Max speed [km/h] | Performed inspections per inspection class [%] | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | B1 | B2 | B3 | B4 | B5 | Main class |
| 5 | 303 | 14 | 128 | Single | 22.5 | 140 | 27 | 39 | 34 | 0 | 0 | B1/B2 /B3 |
| 5 | 429 | 8 | 68 | Single | 22.5 | 160 | 10 | 2 | 87 | 0 | 0 | B3 |
| 5 | 430 | 55 | 23 | Double | 22.5 | 200 | 1 | 0 | 0 | 99 | 0 | B4 |
| 5 | 433 | 94 | 126 | Two or more | 22.5 | 200 | 4 | 3 | 6 | 86 | 1 | B4 |
| 5 | 434 | 212 | 98 | Double | 22.5 | 200 | 3 | 2 | 1 | 94 | 0 | B4 |
| 7 | 119 | 33 | 35 | Single | 30.0 | 140 | 21 | 10 | 0 | 69 | 0 | B4 |
| 7 | 120 | 17 | 130 | Single | 22.5 | 120 | 48 | 20 | 0 | 32 | 0 | B1 |
| 7 | 122 | 5 | 124 | Single | 22.5 | - | 67 | 33 | 0 | 0 | 0 | B1 |
| 7 | 124 | 175 | 91 | Single | 22.5 | 160 | 11 | 0 | 3 | 82 | 4 | B4 |
| 7 | 126 | 106 | 36 | Single | 25.0 | 140 | 10 | 1 | 0 | 89 | 0 | B4 |
| 7 | 129 | 130 | 41 | Single | 25.0 | 160 | 6 | 0 | 3 | 86 | 5 | B4 |
| 7 | 130 | 91 | 55 | Single | 25.0 | 130 | 10 | 2 | 0 | 88 | 0 | B4 |
| 7 | 138 | 6 | 51 | Single | 22.5 | - | 47 | 0 | 43 | 9 | 0 | B1/B3 |
| 7 | 146 | 31 | 68 | Single | 22.5 | 135 | 29 | 0 | 71 | 0 | 0 | B3 |
| 7 | 211 | 131 | 70 | Single | 22.5 | 120 | 1 | 9 | 9 | 82 | 0 | B4 |
| 21 | 111 | 125 | 55 | Single | 30.0 | 130 | 4 | 4 | 5 | 88 | 0 | B4 |
| 21 | 112 | 8 | 34 | Single | 30.0 | 100 | 16 | 8 | 55 | 22 | 0 | B3 |
| 21 | 113 | 102 | 53 | Single | 30.0 | 160 | 9 | 6 | 73 | 12 | 0 | B3 |
| 21 | 114 | 17 | 38 | Single | 22.5 | 100 | 35 | 4 | 60 | 0 | 0 | B3 |
| 21 | 116 | 37 | 4 | Single | 30.0 | 80 | 3 | 3 | 94 | 0 | 0 | B3 |
| 21 | 118 | 163 | 64 | Single | 22.5 | 135 | 16 | 0 | 1 | 83 | 0 | B4 |

## A.2 Corrective and preventive maintenance data

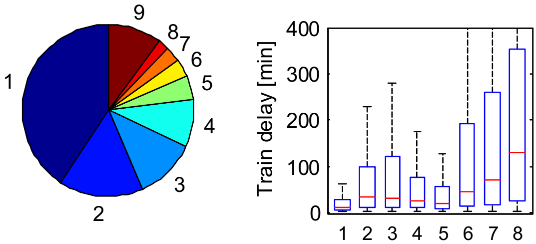
Summary statistics of train-delaying failures, performed inspections and rectified potential failures are shown in Figures A.2-4. Regarding the box plots on train-delays of Figure A.2, on each box, the central mark is the median, the edges of the box are the $25^{th}$ and $75^{th}$ percentiles, and the whiskers extend to 1.5 IQR (interquartile range). Outliers are left out. Considering Figure A.4, potential failures have various priorities depending on the severity of the potential failures. Common used priorities are immediate/urgent (A), week (W), month (M) and before next inspection (B). A remarks require immediate repair; W-remarks require rectification within two weeks; M-remarks require rectification within three months; and B-remarks require rectification before next inspection.

Examples of outliers are shown in Table A.6. The table gives short descriptions of the five failures with the longest total train delay, the five failures with the longest logistic time and the five failures with the longest repair time. Only train delaying failures are included, which means that each failure has resulted in a total of five minutes or more train delay. Train delay of a failure can come from multiple trains.

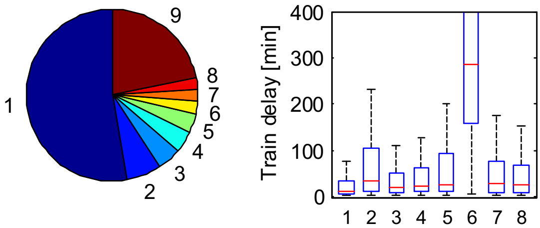
| System | Failures | [%] |
|---|---|---|
| 1. No fault found | 2154 | 35.1 |
| 2. S&C | 1045 | 17.0 |
| 3. Track | 686 | 11.2 |
| 4. Positioning | 627 | 10.2 |
| 5. Interlocking | 573 | 9.3 |
| 6. Signal | 205 | 3.3 |
| 7. Catenary system | 147 | 2.4 |
| 8. Crossing | 134 | 2.2 |
| 9. Other | 560 | 9.1 |
| Total | 6131 | 100 |




| Failure type | Failures | [%] |
|---|---|---|
| 1. No failure | 2498 | 40.7 |
| 2. Cannot define | 967 | 15.8 |
| 3. Interruption | 718 | 11.7 |
| 4. Short circuit | 546 | 8.9 |
| 5. Poor contact | 275 | 4.5 |
| 6. Material failure | 203 | 3.3 |
| 7. Poor track geometry | 178 | 2.9 |
| 8. Deformation | 127 | 2.1 |
| 9. Other | 619 | 10.1 |
| Total | 6131 | 100 |




| Failure cause | Failures | [%] |
|---|---|---|
| 1. Cause unknown | 3242 | 52.9 |
| 2. Fatigue | 396 | 6.5 |
| 3. Short circuit - rail joint | 271 | 4.4 |
| 4. Snow or ice | 259 | 4.2 |
| 5. Component broken | 213 | 3.5 |
| 6. Wheel impact | 155 | 2.5 |
| 7. Animal in track | 132 | 2.2 |
| 8. Component loose | 127 | 2.1 |
| 9. Other | 1336 | 21.8 |
| Total | 6131 | 100 |




| Action taken | Failures | [%] |
|---|---|---|
| 1. No action | 2256 | 36.8 |
| 2. Replacement | 926 | 15.1 |
| 3. Control | 764 | 12.5 |
| 4. Repair | 511 | 8.3 |
| 5. Removal | 397 | 6.5 |
| 6. Adjustment | 310 | 5.1 |
| 7. Restoration | 236 | 3.8 |
| 8. Cleaning | 173 | 2.8 |
| 9. Other | 558 | 9.1 |
| Total | 6131 | 100 |

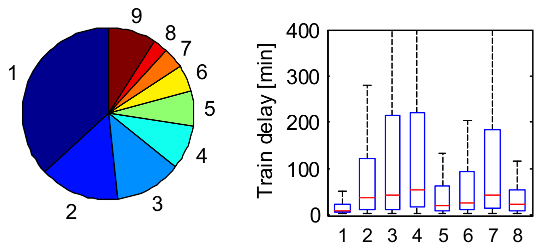



*Figure A.2: Summary statistics of train-delaying failures.*

| Track class | Inspections | [%] |
|---|---|---|
| 1. B4 | 177292 | 50.3 |
| 2. B3 | 71914 | 20.4 |
| 3. B5 | 55768 | 15.8 |
| 4. B1 | 27365 | 7.8 |
| 5. B2 | 20339 | 5.8 |
| Total | 352678 | 100 |

| Inspection type | Inspections | [%] |
|---|---|---|
| 1. Safety | 276649 | 78.4 |
| 2. Maintenance | 70532 | 20.0 |
| 3. NDT | 4388 | 1.2 |
| 4. Other | 1109 | 0.3 |
| Total | 352678 | 100 |

| System | Inspections | [%] |
|---|---|---|
| 1. Signal | 68487 | 19.4 |
| 2. Rail joint | 42097 | 11.9 |
| 3. Signal | 40492 | 11.5 |
| 4. Drainage | 26915 | 7.6 |
| 5. Balise | 24204 | 6.9 |
| 6. Culvert | 21182 | 6.0 |
| 7. S&C | 19157 | 5.4 |
| 8. Rail | 11787 | 3.3 |
| 9. Structure | 11676 | 3.3 |
| 10. Sleeper | 9870 | 2.8 |
| 11. Rail fastening | 9867 | 2.8 |
| 12. Ballast | 9679 | 2.7 |
| 13. Sub-ballast | 9670 | 2.7 |
| 14. Slope | 7890 | 2.2 |
| 15. Fence | 5235 | 1.5 |
| 16. Other | 34470 | 9.8 |
| Total | 352678 | 100 |

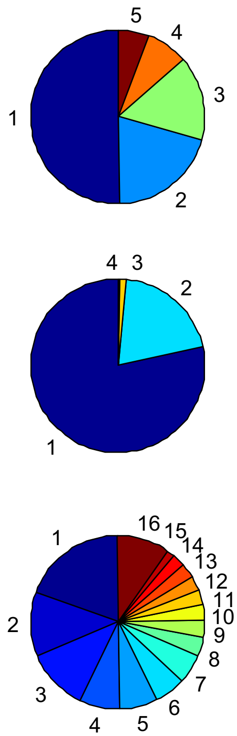


*Figure A.3: Summary statistics of performed inspections.*

| Priority | Remarks | [%] |
|---|---|---|
| 1. Month | 20527 | 71.5 |
| 2. Week | 5787 | 20.2 |
| 3. Next insp. | 1018 | 3.5 |
| 4. Immediate | 869 | 3.0 |
| 5. Year | 469 | 1.6 |
| 6. Other | 34 | 0.1 |
| Total | 28704 | 100 |

| System | Remarks | [%] |
|---|---|---|
| 1. S&C | 18227 | 63.5 |
| 2. Catenary sys. | 2100 | 7.3 |
| 3. Rail | 1493 | 5.2 |
| 4. Crossing | 1144 | 4.0 |
| 5. Rail fastening | 977 | 3.4 |
| 6. Ballast | 597 | 2.1 |
| 7. Signal | 513 | 1.8 |
| 8. Rail joint | 484 | 1.7 |
| 9. Sign | 431 | 1.5 |
| 10. Other | 2738 | 9.5 |
| Total | 28704 | 100 |

| Remark | Remarks | [%] |
|---|---|---|
| 1. See note | 3994 | 13.9 |
| 2. Out of limit | 3503 | 12.2 |
| 3. Item missing | 1725 | 6.0 |
| 4. Nut and bolt | 1424 | 5.0 |
| 5. Wear | 1418 | 4.9 |
| 6. 10 mm limit | 1350 | 4.7 |
| 7. 5 mm limit | 1258 | 4.4 |
| 8. Rolling | 951 | 3.3 |
| 9. Loose | 834 | 2.9 |
| 10. Other | 12247 | 42.7 |
| Total | 28704 | 100 |

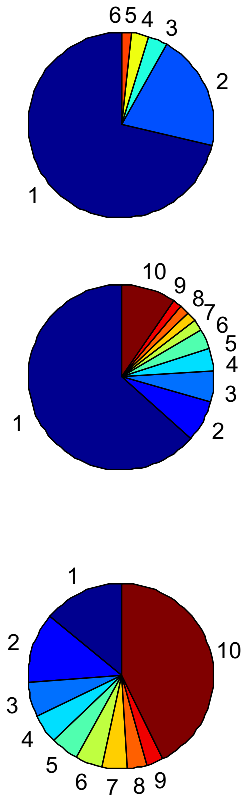



*Figure A.4: Summary statistics of rectified potential failures (remarks).*

*Table A.6: Top train-delaying failures regarding total train delay, logistic time and repair time.*

| Description | Cause/action taken | Train delay [min] | Logistic time | Repair time |
|---|---|---|---|---|
| **The five longest train delays** | | | | |
| Loss of power. Contact wire broken. | Probably fallen tree. Replacement of singalling cabinet | >1000 | 55 min | >1 day |
| Derailed train. Three wagons | Repair | >1000 | 84 min | >1 day |
| Contact wire hanging down | Fatigue and repair | >1000 | 46 min | 16 hours |
| Derailed train. Two wagons | Repair | >1000 | 123 min | >1 day |
| Interlocking failure. Lightning. Signalling cabinet replaced | Lightning. Signalling cabinet replaced | >1000 | 27 min | 16 hours |
| **The five longest logistic times** | | | | |
| Network station failure | Coil failed and replaced | 831 | >1 day | >1 day |
| Switches out of position | Snow and ice in switches. Heating system turned on too late | 108 | >1 day | 0 hours |
| Hot box detector gives alarm on all axles | Unit failed and replaced | 68 | >1 day | 3.8 hours |
| Faulty signal | Relay failed and replaced | 33 | >1 day | 3 hours |
| Water supply in track side facility failed | Inspection and repair | 5 | >1 day | >1 day |
| **The five longest repair times** | | | | |
| Poor track geometry | Sleepers failed and replaced | >1000 | 28 min | >1 day |
| Embankment falling apart | Wall and embankment: repaired | 23 | 170 min | >1 day |
| Undefined singalling failure | No fault found | 6 | 45 min | >1 day |
| Landslide detector has given several alarms the last year | Alarm cable: replaced | 287 | 62 min | >1 day |
| Rail breakage provisionally repaired. Daily inspections | Rail failed and replaced | 5 | 0 min | >1 day |