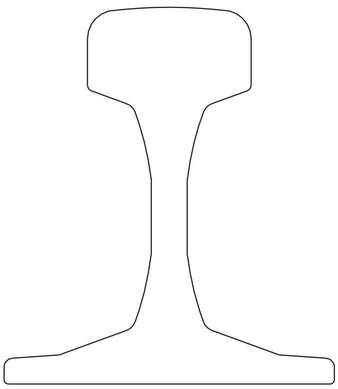
RESEARCH REPORT

Link and Effect Model for Maintenance of Railway Infrastructure



Christer Stenström
Aditya Parida

LULEÅ UNIVERSITY OF TECHNOLOGY

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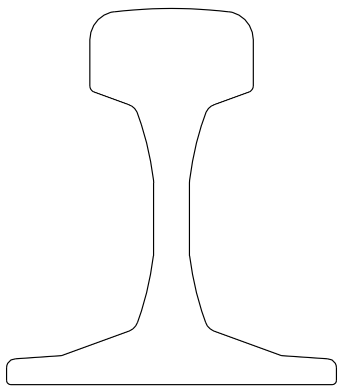

Luleå Railway Research Center (JVTC)

Division of Operation, Maintenance and Acoustics
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Executive summary

Railways are large linear assets of electrical and mechanical systems, and consequently the infrastructure managers (IMs) are extensive with many stakeholder involved. The railway infrastructure and the IMs consist of technical and organisational levels: system, subsystem and component levels, and strategic, tactical and operational levels, respectively. The purpose of this project is to develop a methodology for improving performance measurement systems for railway infrastructure, which integrates both the technical and organisational perspectives, vertically and laterally. It involves several objectives, hundreds of parameters and indicators, data collection, and aggregation of information.

The work that has been carried out is as under:

- Overall mapping of the operation and maintenance of the Swedish railway infrastructure through interviews and literature review. (Section 4.1)
- Railway infrastructure performance indicators have been mapped, structured and compared to European Standards, to act as a reference. About 120 measures were identified and 11 are similar to European Standards maintenance key performance indicators. (Section 4.2 and Appendix A)
- A link and effect model has been developed to facilitate improvement of performance measurement systems, by combining performance measurement and engineering principles. It is based on the plan-do-study-act (PDSA) cycle with emphasis on the key components of strategic planning. A case study on the Swedish Iron Ore Line has been carried out to verify the model. (Section 4.3)
- An index, or composite indicator, for operation and maintenance of railway infrastructure was developed within the case study, similar to risk matrices and failure mode effect analysis (FMEA). The index is based on infrastructure failures and train delays with equal weighting. (Section 4.3)
- Another index has been developed in a continuation of the case study that also includes maintenance times and further weighting. (Section 4.4)
- The impact and significance of cold climate on failures in railway infrastructure has been studied in another case study on the Iron Ore Line and the Coast-to-Coast Line in Sweden. (Section 4.5)
- A railway RAMS (reliability, availability, maintainability and safety/supportability) analyser software has been developed to demonstrate cost-effective analysis, data presentation and simulation. (Section 4.6 and Appendix B)
- As a prestudy, maintenance possession time (maintainability) has been simulated in terms of the actual time to repair as a function of track capacity utilisation, set-up/clearance time and required active repair time. (Section 4.7)

The common factor in the work is dependability, i.e. RAMS. Possible use of the work that has been carried out in this project is as follows:

- The mapped performance indicators can be used as a reference when reorganising the performance measurement and scorecards for operation and maintenance of railway infrastructure.
- The link and effect model can be used or implemented in the strategic planning process and in policy making. It will assist in the breakdown of objectives, aggregation of data, analysis and presentation of data, continuous improvement and in defining the key components of strategic planning.

- The developed operational risk indicator and the composite indicator can be implemented in IMs' maintenance scorecard to present railway performance in a single figure. Additional individual indicators can also be considered for further development.
- The study on cold climate gives insight on the seasonal effect on failures in railways: in north and south Sweden; at system and subsystem level; ice and snow related failures; non ice and snow related failures, temperature related failures and yearly deviations. Failures and maintenance predictions can be done but with low precision.
- The developed RAMS analyser demonstrator can be used for analysing railway infrastructure. Matlab code can be made standalone. Also, a programmer can work further with improving the analysis and add preventive maintenance. The same is true for the maintenance possession time simulation tool. Also made in Matlab.

The railway infrastructure data analysis part in this project has been on failure work orders, train delays and the maintenance times, i.e. corrective maintenance. As a continuation of this research, further work could be to carry out similar analysis on the preventive maintenance, followed by adding costs. This would then give a ratio of corrective and preventive maintenance, and by comparing a set of railway lines, a balance between corrective and preventive maintenance can be found. Also the return on maintenance investment scenarios would be possible to simulate. This work is to be undertaken in phase two of the link and effect model.

Keywords: Railways, train delays, Swedish Iron Ore Line, operation and maintenance, dependability, RAMS, reliability, availability, maintainability, supportability, safety

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> Per Hurtig, Vivianne Karlsson, Ulla Ericson, Peter Söderholm, Stefan Jonsson, Helena Eriksson, Veronica Henriksson, Hans Morin, Monika Knutsen, Håkan Sjödin, Jan Spännar, Per Kvick, Rikard Granström, Kenneth Natanaelsson and Arne Nissen.

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Contents

1 Introduction

1.1 Background

Railway traffic has increased over the last decade and it is believed to grow further as passenger and cargo transportation shift from road to rail, due to rising energy costs, congestion of roads and sky, and the demand to reduce emissions (EC 2010, EC 2011). 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, i.e. conventional, output reached its all-time peak in 2006 (IEA 2010). Thus, the available capacity of the railway infrastructure needs to be enhanced and become more compatible and competitive to meet these new demands in the transport sector.

1.1.1 The need for measuring performance

As railways are capital intensive and have a long life span, their operation and maintenance requires a long term and sustainable strategy. Ongoing technical and economic assessments are necessary to optimise the performance of railway infrastructure and receive the best return on investment (ROI). Long-term asset objectives and strategies must steer operation and maintenance activities in the right direction. Overarching objectives must be broken down into specific 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. For further discussion of developing maintenance strategies for railway infrastructure, see U. Espling et al. (2004).

To manage assets effectively within these agreed and set objectives, the effect of maintenance activities must be measured and monitored. Key metrics in the form of performance measures or indicators for reliability, availability, maintainability and safety (RAMS), capacity, etc., must be identified and/or developed for planning and follow-up of railway infrastructure maintenance activities. Measuring entails data collection, but since, raw data does not give any information by itself, it must be processed before use. This consumes resources, especially when the wrong data are collected, i.e. those not aligned to the overall organisational objectives. However, a good performance measurement system does not necessarily require a high level of precision (W. Kaydos 1991). It is more important to know the indicators trend movements, i.e. how the current value compares to historical values. Consistency is therefore especially important to capture long-term trends, predict future development and take the appropriate corrective actions at an early stage. Moreover, since there are many stakeholders in railway infrastructure with conflicting requirements, there is a need to study the relationship between, and effect of, various performance measures, to build a robust measurement system that can handle changes in objectives and policies.

1.1.2 The need for harmonisation and standardisation

Mobility is vital for the economy and society in general, facilitating economic growth, job creation, cultural learning and leisure. Increased interoperability and building of a trans-European railway network are goals of the European Union (EC 1991, EC 1996). The resulting necessity is to harmonise and standardise the operation of railways, which has led to increased use of standards. Harmonisation and standardisation of strategic planning and performance measurement practices enable the use of comparison to determine best practice, i.e. benchmarking. Not the least, standardisation can reduce the need for discussing definitions and practices (J. Kahn et al. 2011).

1.1.3 The need for a link and effect model

Railways are large linear assets of electrical and mechanical subsystems, and consequently the infrastructure managers (IMs) are large with many stakeholder involved. Both the railway infrastructure and the IMs consist of several levels: system, subsystem and components, and strategic, tactical and operational. The aim of a link and effect model is a methodology for improving performance measurement system that integrates both the technical and organisational perspectives, vertically and laterally. It involves several objectives, hundreds of parameters and indicators from data collection and aggregation of information. Therefore, thorough analysis is required for developing an effective performance measurement system. See Chapter 2 for further background to the need for a link and effect model.

1.2 Problem statement

Congestion of roads and sky, increasing energy costs and the need to reduce emissions have led to the increased use of railways and the consequent need for more capacity (EC 2010, EC 2011). Railway capacity can be enhanced by (postulation): expanding infrastructure; improving the efficiency and effectiveness of operation and maintenance; and by introducing better technology. Performance measurement systems and scorecards have confirmed improvement of business performance by creating more efficient and effective management (R.S. Kaplan et al. 1992, R.S. Kaplan et al. 1993). However, the implementation process of such systems is critical for their success (M. Bourne et al. 2002, A. Schneiderman 1999). A. Schneiderman (1999) has noted that to be successful, balanced scorecards must be viewed as the tip of the improvement iceberg. Organisations use various systems to collect and store data for analysis of their business performance. However, these tools are often used in an *ad hoc* manner. With improved performance measurement of railways, rail transport can meet the requirements of capacity and deliver a dependable mode of transport. This issue has also been considered in several other railway projects, such as AUTOMAIN (Augmented Usage of Track by Optimisation of Maintenance, Allocation and Inspection of railway Networks) and BGLC (Bothnian Green Logistic Corridor). Specifically, through improved use of railway infrastructure data, the maintenance planning and optimisation of corrective and preventive maintenance can reduce costs, maintenance possession time in track and interruption of train operation.

In this work, a link and effect model is developed to improve the effectiveness of the maintenance system of railway infrastructure. The link and effect model is a methodology for developing performance measurements systems, by combining performance measurement and engineering principles for proactive operation and maintenance of physical assets.

1.3 Project purpose

To develop a link and effect model to improve the effectiveness of the maintenance system for railway infrastructure.

1.4 Project objectives

More specifically, the objectives of this research are:

1. Map operation and maintenance activities of railway infrastructure assets
2. Develop key values and monitoring methods for RAMS (reliability, availability, maintainability and safety/supportability) and LCC (life cycle costing) in maintenance infrastructure contracts
3. Develop similar methods and tools for the exchange of key data among stakeholders involved in the railway system, i.e. infrastructure managers, traffic companies, supplier, contractor, etc.
4. Develop a link and effect model to measure and monitor changes that affect the operation of the assets

1.5 Approach and methodology

Phase I

1. To undertake literature studies, interviews and real life experiences for process mapping of railway infrastructure
2. Factors identification of strategic engineering asset management and its policy as input for the model
3. Identification of key performance indicators (KPIs) and key result areas (KRAs) (A. Parida et al. 2007) for desired policy modifications and improvements

Phase II

1. Application of the link and effect model for results demonstration and verification as a pilot case study
2. Based on the results of the pilot study, an implementation plan will be developed for the policy formulation

1.6 Scope and limitation

The study mainly focussed on link and effect model within the maintenance system of railway infrastructure. A case study will also be carried out to verify and demonstrate the model.

1.7 Outline of the report

Chapter 2 deals with literature review of performance measurement, associated issues & challenges, RAMS, performance drivers & killers, etc. Chapter 3 describes the data collection process. Within the project, a technical report and several articles have been published; Chapter 4 summarise the findings of the publications. The results are discussed in in Chapter 5, followed by conclusions and scope for further research in Chapter 6. The report also includes two appendices; performance indicators of railway infrastructure and RAMS analyser software demonstrator.

2 Literature review

This chapter goes through basic concepts and definitions related to the research subject, as well as providing a background to the link and effect model.

2.1 Performance measurement

Performance measurement can be described as the process of quantifying the efficiency and effectiveness of action (A. Neely et al. 1995) or the study of whether outcomes are in line with set objectives.

A performance measurement system can be described as the information system that is at the heart of the performance management process and integrates all the relevant information from all the other performance management systems (U.S. Bititci et al. 1997). Performance management is the process by which a company manages its performance in accordance with its corporate and functional strategies and objectives.

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 (M.L. Emiliani 2000).

Measuring can give large savings and business safety, if measuring leads to more proactive management. However, additional costs are associated with measuring. It is therefore important to thoroughly analyse what, where, when, how and for whom to measure (A. Parida et al. 2004).

2.2 Scorecards and performance measurement systems

A scorecard is a statistical record used to measure achievement or progress towards a particular goal (Oxford Dictionary 2011). Balanced Scorecard is a method that uses the scorecard to guide organizations.

With increasing competition, internationalisation and HSE (health, safety and environment) legislation, traditional accounting with only financial measures is insufficient to assess business performance (H.T. Johnson 1983, R.S. Kaplan 1984). New performance measurement methods, scorecards and frameworks have been developed to take into account quantitative and qualitative non-financial measures, including efficiency, effectiveness, internal and external perspectives (R.S. Kaplan et al. 1992, D.P. Keegan et al. 1989, L. Fitzgerald et al. 1991, R.S. Kaplan et al. 1996). Scorecards are also important for grasping a large number of indicators and for identifying the most important ones.

Further discussion and review of this topic can be found in work by (A. Neely 1998, A. Neely et al. 2000, M. Bourne et al. 2003, IDeA 2006, P. Taticchi et al. 2010, S.S. Nudurupati et al. 2011).

2.3 Performance measurement of the maintenance function

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).

As the maintenance function constitutes a key element in business success (L. Swanson 2001, A.H.C. Tsang 2002, A. Parida et al. 2006), it has benefited from the development of more holistic and balanced performance measurement systems. Maintenance accounts for a large part of the costs in many businesses, improvements can result in large savings, as shown in work by (B. Danielson 1987, M. Cross 1988, J.D. Campbell 1995b, R. Dekker 1996, D.N.P. Murthy et al. 2002, H. Ahlmann 2002, B.S. Dhillon 2002). Furthermore, the evolution of maintenance from a necessary evil to a valuable and integral part of the business process has been described in research by Pintelon et al. (2008).

Maintenance differs from other business functions by being multidisciplinary; it is largely engineering but its values are hard to measure in simple financial terms (D.N.P. Murthy et al. 2002).

Maintenance performance measurement (MPM) has been extensively reviewed by (U. Kumar et al. 2008, U. Kumar et al. 2011, J.M. Simões et al. 2011, H.A. Samat et al. 2011). See also work by Parida and Chattopadhyay (2007) for various developed MPM frameworks/scorecards.

2.4 Performance measurement of railway infrastructure

This subject is reviewed and discussed in the technical report, which is a part of this project (C. Stenström 2012a). Chapter 4 of the technical report gives a review of the performance indicators used by researchers in the field of railway maintenance, as well as reviewing European railway project reports and documents from the Swedish infrastructure manager Trafikverket, such as policy documents and handbooks. Chapter 5 of the report gives a similar review of scorecards in railways.

2.5 Challenges in the implementation process

Performance measurement systems have been shown to increase the performance and competitiveness of organisations by providing more balanced metrics, e.g. see Kaplan and Norton (1992, 1993), however, implementation issues exists. In a literature review, Bourne et al. (2002) listed the following issues that researchers have noted in the implementation of performance measurement initiatives:

- A highly developed information system is called for
- The process can be time-consuming and expensive
- Lack of leadership and resistance to change
- Vision and mission are not actionable, especially when there are difficulties in evaluating the relative importance of measures and problems identifying true “drivers”
- 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
- Metrics are often poorly defined
- There is a need to quantify results in areas that are more qualitative in nature

Bourne et al. (2002) continued with a case study on performance measurement implementation, considering three out of six participating companies as successful and identifying four main factors that hinder success, namely:

- The effort required
- The ease of data accessibility through the IT systems
- The consequences of measurement
- Being overtaken by new parent company initiatives

Kaplan and Norton (2000) have listed several of the issues recorded by Bourne et al. (2002) and emphasise on problems which result from: firstly, hiring inexperienced consultants, and secondly, 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. (2009b) have made similar observations in maintenance data processing; the gap between data processing and knowledge management is too large, probably due to an inability to identify stakeholder requirements.

Concerning the problem with a large number of 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 (C.E. Davis et al. 2010).

A human can only monitor a limited number of indicators and consequently the number of strategic level indicators depends on the number of senior managers. Therefore, data aggregation is needed; however, aggregation of data is a weakness of traditional performance measurement systems, as the underlying factors can be hidden.

2.6 Dependability and RAMS[4]

Dependability is a central term in maintenance that demonstrates its complexity in a dense form. A common description is given by International Electrotechnical Commission (IEC) (Figure 1). Another description is given by European Standards EN 13306:2011 (Figure 2), and a third description is given by International Journal of Performability Engineering (IJPE), also taking into account sustainability (Figure 3).

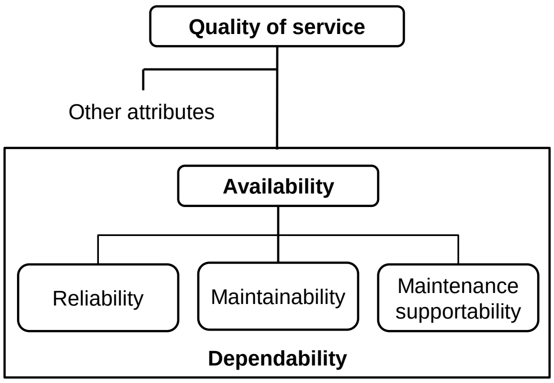


Figure 1: Dependability and RAMS (reliability, availability, maintainability and maintenance supportability) as described by International Electrotechnical Commission. Adapted from (IEC 1990).

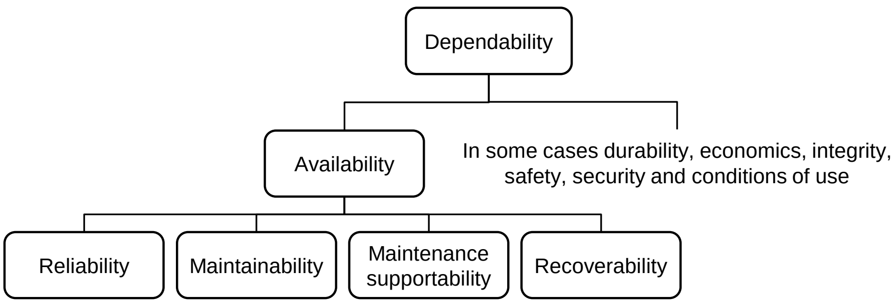


Figure 2: Dependability and RAMS according to EN 13306:2011 (CEN 2010).

RAMS (reliability, availability, maintainability and safety or maintenance supportability) is a central term in both IEC and CEN. However, the letter S in RAMS can stand for supportability, safety, sustainability or security, i.e. RAMS[4]. In Figures 1 and 2 it stands for maintenance supportability, but in Figure 3 and in railways it stands for safety, e.g. railway specification EN 50126:1999, Figure 4 (CEN 1999). It can be noticed that there is no single definition of dependability. A conclusion is put together in Figure 5.

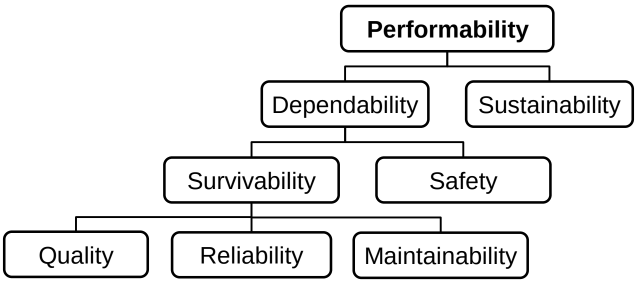


Figure 3: Performability and dependability. Adapted from International Journal of Performability Engineering (IJPE).

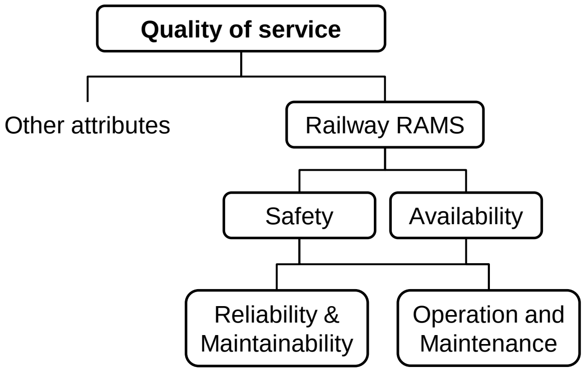


Figure 4: Railway RAMS (reliability, availability, maintainability and safety) (CEN 1999).

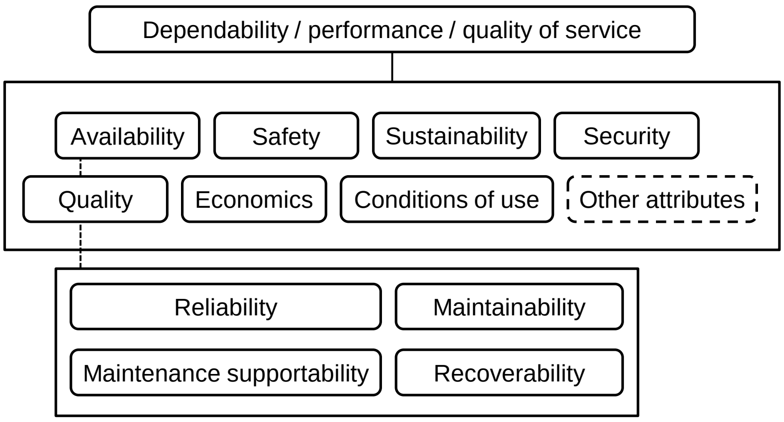


Figure 5: Harmonisation of IEV, SS-EN 13306, IJPE and EN 13306, which together include RAMS[4].

2.7 Strategic planning

Strategic planning can be described as the process of specifying objectives, generating strategies, and evaluating and measuring results (J.S. Armstrong 1982). The terminology of strategic planning can vary between organisations and researchers. Therefore, key elements, or components, of strategic planning are described in Table 1.

Table 1: 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).
Mission statement	A statement describing the key functions of an organisation (U.S. Dept of Energy 1993). 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 (E.A. Locke et al. 1981). Goals are commonly broad, measurable, aims that support the accomplishment of the mission (L.P. Gates 2010).
Objectives	Translation of ultimate objectives (goals) to specific measureable objectives (J.S. Armstrong 1982), or targets assigned for the activities (CEN 2010), or specific, quantifiable, lower-level targets that indicate accomplishment of a goal (L.P. Gates 2010).
Strategy	Courses of action that will lead in the direction of achieving objectives (U.S. Dept of Energy 1993).
Key result areas (KRAs)	Areas where results are visualised (J. Boston et al. 1997), e.g. maintenance.
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 (J.K. Leidecker et al. 1984), e.g. high availability.
Key performance indicators (KPIs)	The actual indicators used to quantitatively assess performance against the CSFs (D. Sinclair et al. 1995). A KPI is a PI of special importance comprising an individual or aggregated measure.
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 (R.D. Pritchard et al. 1990).
Indicator	A thing that indicates the state or level of something (Oxford Dictionary 2011).

2.8 Performance drivers, performance killers, cost drivers, etc.

A performance driver is a supporting input element to a process, driving the process or business performance, while a performance killer or problem is an input element to a process that performs poorly or hinders performance (C. Stenström et al. 2011). Terms like value drivers, performance drivers, leading indicators, etc., are commonly used in the field of physical asset management, but descriptions are mostly missing. Stenström et al. (2011) have reviewed literature in the topic with the aim of describing these terms (Table 2) and put them into the context of the maintenance process (Figure 6).

Table 2: Description of terms related to performance measurement (C. Stenström et al. 2011).

Term	Description
Process	A process is a series of activities or steps, with required input elements taken, to achieve or produce a desired product or service output. Note: All the inputs together form and drive the process or business performance, i.e. a process is all the inputs working together.
Performance driver	A supporting input element to a process, driving the process or business performance.
Performance killer	An input element, to a process, that performs poorly or hinders performance. Note: Similar to cost driver but more intangible since it does not directly affect costs.
Cost driver	An input element to a process that causally affects or drives costs. Note 1: A cost driver is tangible, as it is a cost object.
Bottleneck	An element that limits the performance of a process or system. Note: A bottleneck is a performance killer.
Leading indicator	Indicator measuring the inputs to a process, giving indication of future events. Note 1: Preventive maintenance indicators, e.g. inspections and sensors, can be interpreted as leading indicators since they control the outputs, and thus the lagging indicators. Note 2: Whether an indicator is leading or lagging is subjective as it depends on the perspective.
Lagging indicator	Indicator measuring the outputs of a process, giving indication of events that have already taken place.
Coincident indicator	Indicator measuring events at the same time as they occur. Note: Maintenance inspections and sensors can be interpreted as coincident indicators, giving indication of the actual condition of engineering assets.

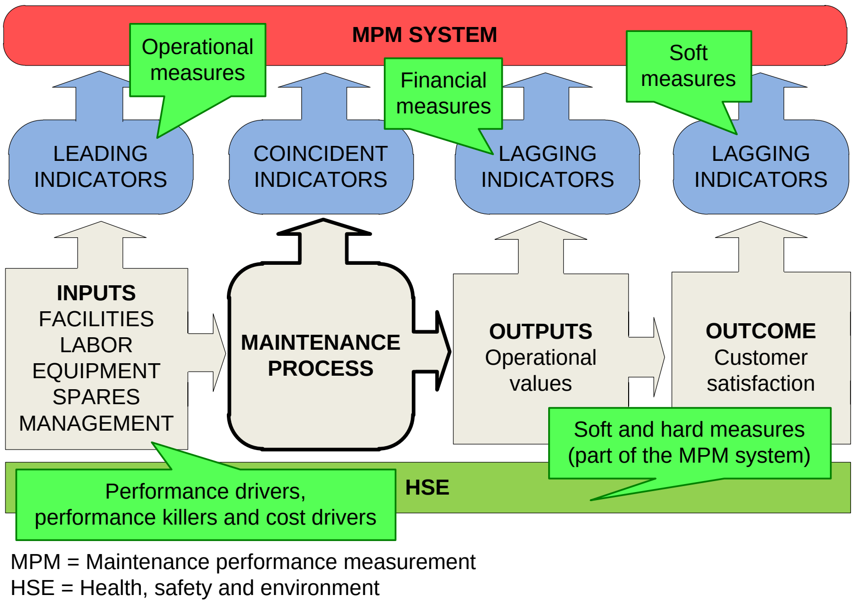


Figure 6: Input-process-output model (IPO-model) with integral MPM-system. Indicators and measures are synonymous in the figure. Adapted from (C. Stenström et al. 2011)

2.9 Outsourcing railway maintenance

Statens Järnvägar (SJ) (Swedish State Railways), founded in 1856, was a Swedish agency responsible for operating and maintaining the state's railways. In 1988, the railways and the infrastructure management were separated from SJ to form a new agency, Banverket (BV) (Swedish Rail Administration). Ten years later, new policies in 1998 divided Banverket into a client and contractor in order to increase efficiency and effectiveness (U. Espling et al. 2008). The first outsourcing of maintenance started shortly thereafter (Banverket 2008). More on the Swedish deregulation of railways can be found in: (D. Spaven 1993, N. Bruzelius et al. 1994, S. Hultén 2000, A. Jensen et al. 2007, G. Alexandersson et al. 2008, J. Nilsson 2003).

The demonopolisation in the EU began in 1991 when the various European states were commissioned to separate the operation of traffic from the IMs, sprang from directive 91/440/EEC (EC 1991). It is difficult to directly compare states' deregulation processes, as their approaches differ. G. Alexandersson and S. Hultén (2008) call the Swedish process the incremental approach, the British process the rationalist process, and the German and Dutch process the wait and see incremental process. Comparing with the US, the deregulation of railways in started 15-25 years before the EU deregulation, but the process is different, as it is predominantly a freight market (G. Alexandersson et al. 2008). More work on railway deregulation processes can be found in: (C. Nash 2008, S. Bulcsu 2011, M. Mäkitalo 2011, M. Laisi 2011, P. Cantos et al. 2010).

In 2001, the Swedish railway operator SJ was disbanded and incorporated into six companies, all owned by the government (U. Espling et al. 2008). Two of the companies are train operators, SJ AB and Green Cargo. The monopoly of the train operation was ended in 2009, allowing free competition. In 2010, 42 operators submitted applications for the annual timetable of 2011 (Trafikverket 2010a). TRV is one of the applicants, e.g. for maintenance activities.

TRV continuously works to outsource the railway maintenance. In September 2010, 87 % of the primary regional maintenance contracts were out under free competition; 13 % were contracted to Infranord, formerly part of Banverket, without free competition (Trafikverket 2010b). The goal of free competition is to make the procurement process of maintenance more efficient and effective. TRV uses performance-based contracts whereby the condition of the track is assessed before a contract is set up. A bonus and fee system connected to the contracts will come into effect if the condition of the assets is changed. There are around 35 contracts for primary regional operation and maintenance with a total annual value of 1.5 billion SEK (Trafikverket 2010b). All new contracts are performance-based with fixed payments for five years with an option of two more years. Although uniform contracts are preferable, there are a number of older contracts with different agreements. See S.M. Famurewa (2013) for discussion on performance-based railway infrastructure contracting.

Today, there are five entrepreneurs in the railway maintenance business in Sweden: Infranord AB, Balfour Betty Rail AB, Strukton Rail AB, VR-track, and Infratek AB. The Norwegian company, Infratek, is a new arrival, receiving its first five year contract in 2010.

The deregulation and demonopolisation of the Swedish network is an ongoing process, and the outcome is not clear. Alexandersson and Hultén found that the tendering of passenger services in Sweden led to a reduction in operation subsidies of 20 %; similarly, the freight sector gained from reduced costs and new business concepts (G. Alexandersson et al. 2008). In a 2011 statistical analysis, VTI (2011) found that contracting out maintenance has resulted in 14 % lower costs, with no effect on failure rate in Sweden. U. Espling (2004, 2007) studied several aspects of outsourcing maintenance, finding, for example, that cost decreased. More work on railway efficiency and productivity can be found in: (A. Couto et al. 2009, S.H. Lim et al. 2009, M. Asmild et al. 2009, G. Friebel et al. 2010, R. Merkert et al. 2010, L.-B. Li et al. 2011).

Keeping the main or core activities of an organisation in-house is often recommended to ensure competitiveness, growth and innovation, i.e. business safety. Activities with the best potential to be successful are routine and easily managed, measured and supplied (J.D. Campbell 1995a, R. McIvor

2000). Whether maintenance is a suitable candidate is debatable and depends on the business, e.g. industry, facilities and railways (M. Levery 2002). A commonly held view is that any contracts have to be managed tightly by the client to ensure performance. In the end, it may be more important to know what one's core business is. TRV's core business is the responsibility (planning) of transportation, see Swedish code of statutes SFS 2010:185 (Näringsdepartementet 2010).

A further complicating factor in the deregulation is the risk of separation between the tracks and vehicles, since both of them will be in a similar condition (D. Lardner 1850).

A number of studies have investigated whether one gets more maintenance for the money in railways through free competition, but several aspects make the analysis complicated, e.g. indirect costs, confidentiality agreements and various types of contracts. More studies are needed to include these elements. Studies have not been able to show how the safety of the railways has been influenced by deregulated maintenance; the small statistical base is limiting quantitative studies. A larger qualitative study is one possible way to answer the question, similar to the work of U. Espling (2004, 2007).

2.10 Link and effect model

Following the review in Section 2.2, performance measurement was developed with further holistic perspective, emphasising on cross-business, cross-organisational, cross-disciplinary and cross-hierarchical perspectives (A. Parida et al. 2007, J.P. Liyanage et al. 1999, J.P. Liyanage et al. 2003), see Figure 7. These ideas were later on adapted to railways by T. Åhrén (2008). T. Åhrén mapped maintenance performance indicators used by the Swedish infrastructure manager (17 in total), linked them to objectives, balanced scorecard, key result areas and critical success factors. Furthermore, T. Åhrén and A. Parida (2009a, 2009b) studied maintenance performance indicators of the Swedish and Norwegian infrastructure managers for benchmarking and development of a composite indicator for overall railway infrastructure effectiveness (ORIE).

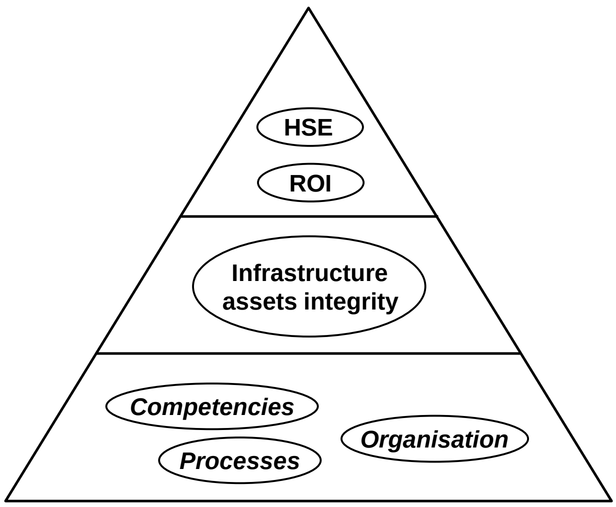


Figure 7: Link and effect model with its main elements. Adapted from (J.P. Liyanage et al. 1999).

The link and effect model concept is adopted and further defined in this project and described as: a methodology for developing performance measurements systems, by combining performance measurement and engineering principles for proactive operation and maintenance of physical assets. See Section 4.3 and Figure 11 for details.

3 Data collection

Data have been collected from interviews, literature review, and railway operation and maintenance historical data for understanding the strategic planning process, maintenance of railway infrastructure, performance measurement, etc. The following types of literature related to operation, maintenance and performance of railways have been reviewed:

- Railway peer review journal and conference papers
- Performance measurement and strategy peer review journal and conference papers
- European Union project reports
- 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

The interviews and literature review were carried out to meet the project objective of mapping the operation and maintenance activities of railway infrastructure assets (Objective 1).

3.1 Interviews and information from experts

In the early phase of the project, 14 people at the Swedish IM, Trafikverket, were interviewed. 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). An open-ended interview was chosen to map the operation and maintenance of railway infrastructure in Sweden. The interviews complemented the literature study. The questions included the following, amongst others:

- Can you tell me about the strategic planning process, e.g. breakdown of goals?
- Can you tell me about the planning of maintenance of railway infrastructure?
- Is there any documents 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?

In addition to interviews, regular meetings with Trafikverket took place to discuss the progress, issues and future direction. See Table 3 for interviewees' positions at Trafikverket.

Table 3: Interview respondents at Trafikverket. The asterisk is according to 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*

3.2 Collection of operation and maintenance historical data

In the process of designing a performance measurement system, existing data should be used to avoid implementation issues including (see Section 2.5 for references):

- The need for a highly developed information system
- Time and expense
- Undermining success by striving for perfection
- Diluting the overall impact by having too many measures
- Poorly defined metrics

The collected historical operation and maintenance data for the case studies have been of failure work orders, train delays, weather data and asset structure data. Simple data quality checks have been carried out on the failure data; see Figure 8. Each work order consists of 71 fields. Data fields with 100 % usage means that all work orders have some text or numbers in those fields. For example, field number one is the work order identification number. To notice, a low usage of a data field does not necessarily mean that the data quality is low; it may just not be applicable for every work order. The figure gives information regarding which data of the work orders are suitable for case studies. Also, in this way it is possible to improve the work order process, e.g. by removing unnecessary fields and improving the way of completing other fields.

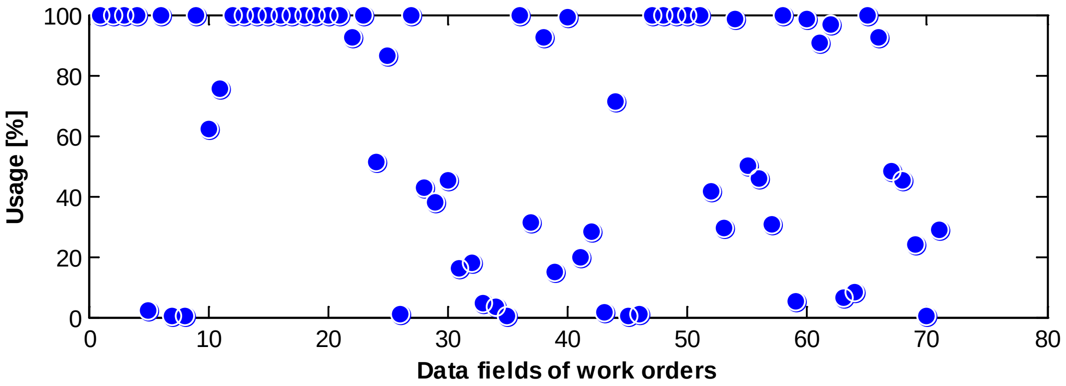


Figure 8: Usage of fields in failure work orders. Each work order consists of 71 fields. Fields with 100 % usage means that all work orders have some text or numbers filled in.

For details on the collection and data processing for each case study, see references given in Chapter 4.

4 Summary of the results

The project work has been carried out in several parts; this chapter gives a summary of the results.

4.1 Technical report: Maintenance performance measurement of railway infrastructure with focus on the Swedish network

Based on the literature review, interviews, data collection and analysis, a technical report was prepared as part of the deliverables of this research project. The details can be seen by an Internet search on ISBN: 978-91-7439-460-3. A summary of the Technical report is as under.

4.1.1 Performance indicators of railway infrastructure

Performance indicators (PIs) were identified by reviewing 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 infrastructure managers (IMs). Interviews with Trafikverket were also carried out. To manage the large number of indicators, they have been grouped into two overall groups; managerial and infrastructure condition indicators (Figure 9). 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.

The PIs were further categorised into a scorecard (Appendix A; Table A.6) according to European Standards for maintenance key performance indicators, EN 15341 (CEN 2007), and the infrastructure asset structure of Trafikverket. 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. The groups can also be called key result areas (KRAs); the few areas where the result and indicators are visualised (J.K. Leidecker et al. 1984).

About 120 indicators were mapped; similar indicators were treated as the same, but some indicators can be found twice, e.g. at system and component levels. See Figure 9.

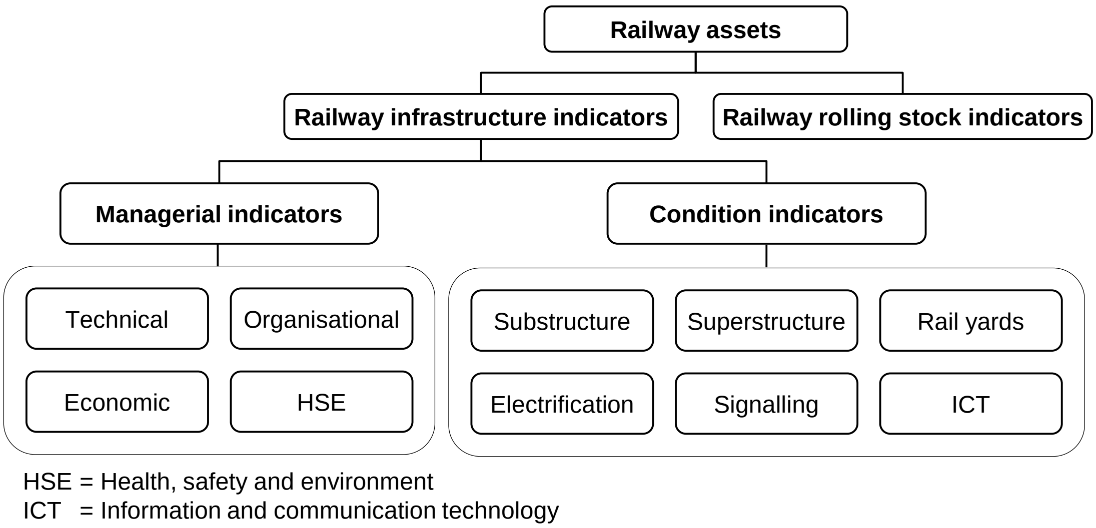


Figure 9: Structure of railway infrastructure performance indicators (C. Stenström 2012a, 2012b, 2013).

4.1.2 Maintenance scorecards and benchmarking

Scorecards have been described and discussed in Section 2.2. Benchmarking is often used when comparing something, but to be more strict, benchmarking is to evaluate something by comparison with a benchmark (reference point or best practice).

Several maintenance scorecards of European infrastructure managers were identified by reviewing research papers and project reports; see Chapter 5 of the technical report. Eight maintenance scorecards were identified through the 'Asset Management Club Project' (BSL 2009).

Regarding benchmarking, the project 'Lasting Infrastructure Cost Benchmarking (LICB)' may be the best known in railways (UIC - LICB 2008). 14 European IMs participated. Maintenance and renewal costs per track-km were harmonised for single track/double tracks, switches and crossings, etc., but details are not given due to confidentiality

Another method for benchmarking is data envelopment analysis (DEA). Benchmarking of production efficiency, given as the production output divided by the input, can be challenging as different operational circumstances for each unit makes it hard to find common weights for the inputs and outputs. With DEA, relative weights are used by calculating the most favourable weights for each unit subject to the others, making benchmarking possible. DEA is a non-parametric statistical method that can be studied for its possibility to be used in this topic. DEA has been used in some railway studies, e.g. by S.A. George et al. (2008) and by R. Malhotra (2009).

4.1.3 Punctuality and regularity

Punctuality and regularity are preferably studied together. Cancelled trains (lower regularity) can increase the punctuality and vice versa; few cancelled trains can decrease the punctuality. Negatively correlated indicators should therefore be presented together, e.g. punctuality and regularity. Furthermore, if a track quality index (TQI), e.g. the Q-value, is taken into account as a third factor, a measure of overall railway effectiveness (ORE) is achieved. The formulas are as follows:

$$Railway\ Effectiveness = Regularity^{\,a} \times Puctuality^{b} \in [0,1] \tag{4.1}$$

$$\begin{aligned} ORE &= Availability^{\,a} \times Performance^{\,b} \times Quality^{c} \\ &= Regularity^{\,a} \times Punctuality^{b} \times TQI^{\,c} \in [0,1] \end{aligned} \tag{4.2}$$

The constants a, b and c can be chosen for giving different weights to the parameters to satisfy specific needs. See Figure 10 for an example. The figure shows that punctuality and regularity are negatively correlated. Suboptimising is prevented by combining these two indicators into one, since both have to be high for the aggregated indicator to be high.

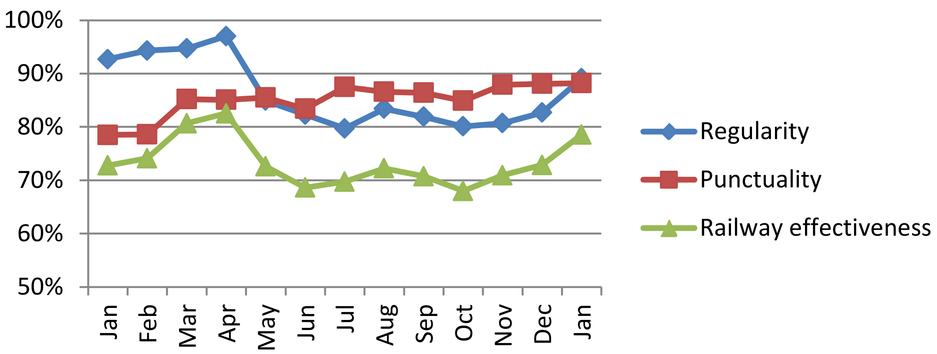


Figure 10: Railway effectiveness of the Swedish railway network from Jan 2011 to Jan 2012. The constants *a* and *b* equal one. Adapted from (C. Stenström 2012a).

4.1.4 Further findings

The literature review of quantitative research projects with statistical results showed that presentation of the data cleaning process is sometimes left out, making the quality of the output by some means unknown.

A main benefit of measuring is that current performance can be compared with previous performance, i.e. tracking trends. However, this benefit is often lost due to new ways of measuring, changed objectives, or organisational changes. This problem can be avoided by keeping the old ways of calculating for a while during change, i.e. overlapping. Also, performance measurement systems need to be dynamic with continuous improvement (kaizen).

4.2 Performance indicators of railway infrastructure

Based on the railway infrastructure indicators mapped in the technical report, a journal article was written (C. Stenström et al. 2012b, 2013). In addition, it includes a comparison to European Standards EN 15341 (CEN 2007).

The indicators of EN 15341 consist of 71 key performance indicators (KPIs) categorised into three groups and three levels. 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 4 and 5. Indicators at the same row are considered to be closely related to each other.

Table 4: Relationship between railway and EN 15341 indicators (C. Stenström et al. 2012b, 2013).

Railway indicators		EN 15341 indicators	
#	**Name**	**#**	**Name**
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 / Maintenance 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 / Maintenance cost	E16	Preventive maintenance cost / Total maintenance 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 potential 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 5: Relationship between railway indicators and EN 15341 factors (C. Stenström et al. 2012b, 2013).

Railway indicators #	Railway indicators Name	EN 15341 indicators #	EN 15341 indicators Name
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 potential injury to people

11 indicators were found to be similar, which can facilitate external benchmarking. Moreover, the study provides a background for a possible future standardisation of railway indicators. Nevertheless, harmonising between infrastructure managers for benchmarking is a challenge, since the operational and geographical conditions varies extensively.

4.3 Link and effect model: Model development and case study

Based on the literature review in Chapter 2 and the technical report (C. Stenström 2012a), a link and effect model was developed and verified in a case study as a continuation of the research by J.P. Liyanage and U. Kumar (2003), and T. Åhrén (2008). A summary of the work is as under.

4.3.1 Dynamic performance measurements

Infrastructure managers (IMs) have grown with the expansion of railways, and consequently the operation and maintenance practices have grown with the specific needs of each IM and country. However, harmonisation and increased use of standards have come with the globalisation, especially in the European Union, considering increasing interoperability and building of a trans-European railway network (EC 1996). Therefore, performance measurement needs to be dynamic and versatile. Another important element in performance measurement is the fast development of new technologies, including computers (hardware and software) and condition monitoring. Changes in the enterprise resource planning (ERP) system or the computerised maintenance management system (CMMS) within an organisation can alter the performance measurement practices and monitoring of historical asset condition data. Besides globalisation and technological changes, organisational changes can also affect the success of measuring performance. In overall, performance measurement systems need to be proactive and dynamic to handle changes like the following:

- 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 economy, i.e. the business cycle

Therefore it is essential to have a strong continuous improvement process.

The literature study on railway infrastructure maintenance has been on publications from academia, European projects, consultancies, infrastructure managers and from the European Commission. It has been found that many improvement methods have its basis in a continues improvement process, like the plan-do-study-act (PDSA) cycle, also known as the Deming cycle, Shewhart cycle or Kaizen cycle (M. Imai 1986). Furthermore, it has been found that organisations use the key components/elements of strategic planning differently, e.g. vision, mission, goals, objectives, etc. The link and effect model is therefore based on the PDSA cycle with emphasise on the key elements of strategic planning.

In traditional PM systems, PIs are given threshold values, indicating when an action needs to be taken, and since PIs commonly are of aggregated data, e.g. total delay, PIs can appear abstract. Therefore, the aggregated PIs with thresholds can make the system reactive if not appropriately used. To meet these problems, in the link and effect model, PIs are analysed for the underlying factors responsible for the performance, providing a starting point for improvements.

The link and effect model aims to solve some of the problems of traditional performance measurement systems. More specifically, the model put emphasize on:

- Continuous improvement
- The key elements of strategic planning
- The underlying factors responsible for the performance

4.3.2 Development of the model

The link and effect model is a methodology for continuous improvement of performance measurement systems, by combining performance measurement and engineering principles. It has two main components: a four-step continuous improvement process, and a top-down and bottom-up approach (Figure 11).

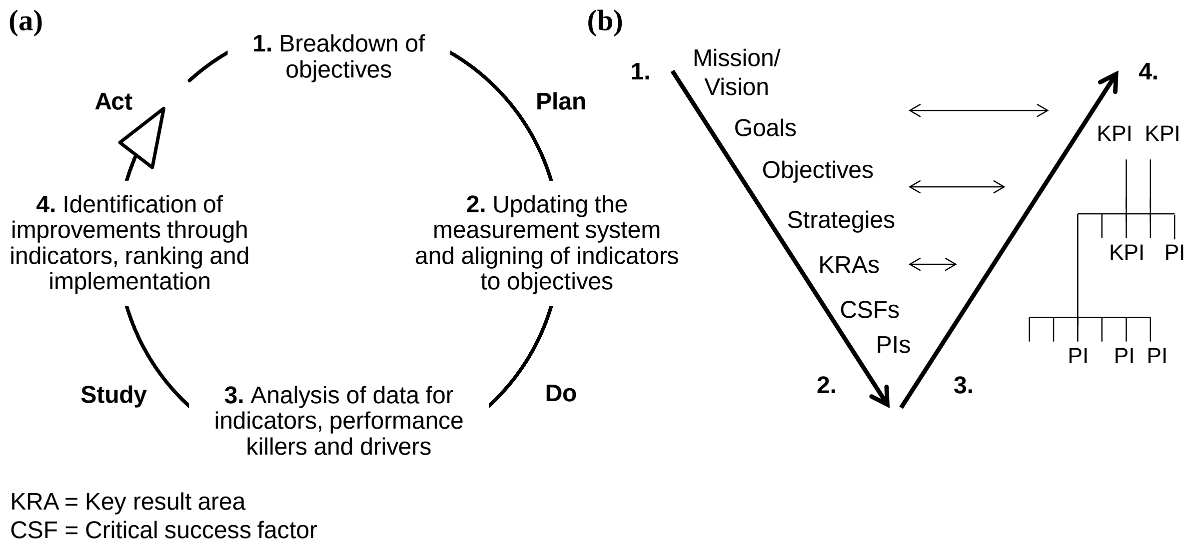


Figure 11: The link and effect model, based on (a) a four steps continuous improvement process and (b) a top-down and bottom-up process. The numbers in (b) represents the steps in (a). See Section 2.7 for description of the key components of strategic planning.

Step 1: The first step of the link and effect model concentrates on the strategic planning, which also include gathering stakeholders' objectives, which usually are conflicting, and assembling them into a common framework. Example of conflicting goals are IMs and train operators objectives. For railways in the EU, aligning and harmonisation start at the European level and are broken down to national governmental and infrastructure manager levels, i.e. from strategic to operational planning. The review of the elements of strategic planning in Section 2.7 (Table 1) was specifically carried out for this step. Furthermore, the EU project AUTOMAIN (2010) found that goals are expressed in many different ways between IMs, and they are not always related back to any standard, simply to terms such as sustainability and accessibility.

Step 2: The performance measurement system of organisations 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 according to new stakeholder demands and objectives. See Figure 12.

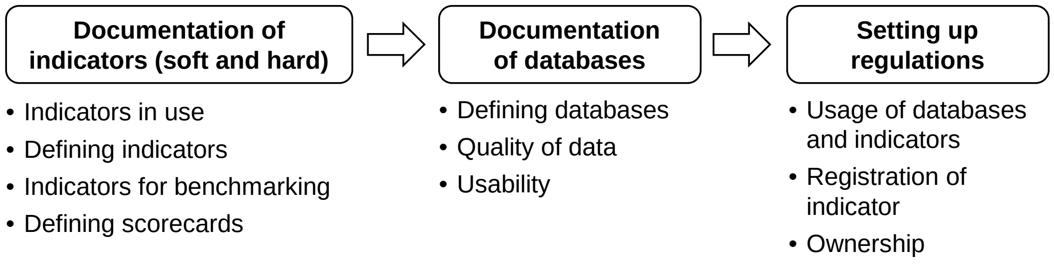


Figure 12: Key requirements of strategic planning.

Similarly, information on requested data should be collected to support innovation and the exchange of data with other stakeholders, which always should be done automatically, just as the calculation and presentation of indicators by IT (information technology). Moreover, risk analysis should not be forgotten, e.g. for changed financing.

Step 3: Organisations collect vast amount of data, but turning the data into information is often lacking (T.H. Davenport et al. 2001, R. Karim et al. 2009a). Accordingly, analysis methodologies are developed in Step 3 by use of various statistical methods, for construction of performance indicators and identification of performance killer and drivers. Since data collection cost resources, another important aspect in Step 3 is to identify what data is required and what data is superfluous.

Aggregation of data is a weakness of traditional performance measurement systems since it can make the indicators abstract as the underlying factors can be unknown, 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 performance; see Figure 13. 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.

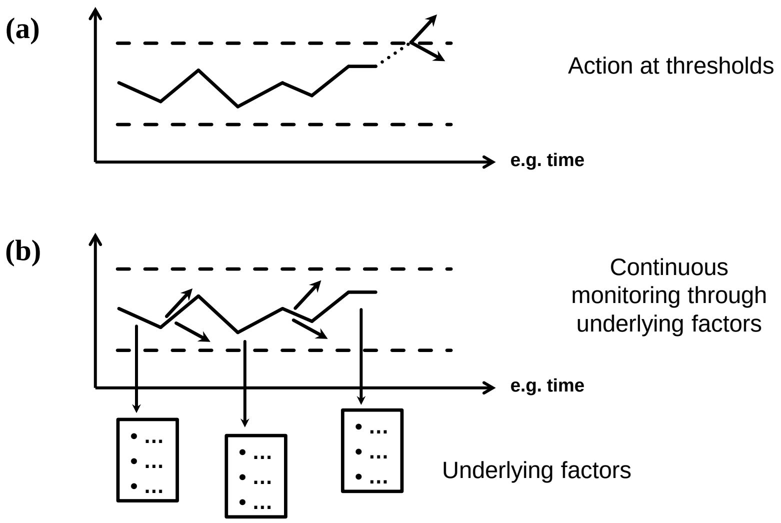


Figure 13: a) Traditional performance measurement system with thresholds. b) Link and effect model with indicator and the underlying factors responsible for the performance.

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

4.3.3 Case study

A case study was carried out on the Swedish Iron Ore Line to verify and demonstrate the link and effect model.

Step 1: Breakdown of objectives

The goal of Step 1 is to align the strategic planning of different stakeholders at the various organisational levels into a single frame. There are two challenges: firstly, identifying key elements and putting them into the same terminology; secondly, translating the high-level initiatives and goals, which can be conceptual, into specific operational tasks.

At the European level, the White Paper on the European transport system of 2011 identifies the key components of strategic planning as (EC 2011):

- **Vision:** Towards a competitive and resource efficient / sustainable transport system
- **Goals related to railways:** by 2030, 30 % of road freight over 300 km 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 KRAs (key result areas)

To notice, the vision and objectives are not explicitly written in the White Paper to be the vision and objectives deduced above, i.e. an experienced reader is required. The mission could not be identified. However, the goals are stated clearly. Similarly, experience is required to find the elements of strategic planning in Sweden as it is required to go through documents of the Swedish IM; Trafikverket, and the Ministry of Enterprise.

Key elements of the strategic planning of transportation in Sweden are:

- **Overall goal:** to ensure the economically 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 (P. Söderholm et al. 2011).

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

Once the goals and objectives are identified and put into a common framework, it is easy to align to operational measures. By studying the objectives, it is found that service quality is a key facilitator at both the international and the national level. According to International Electrotechnical Vocabulary (IEV), quality of service is the collective effect of service performance which determines the degree of satisfaction of a user of the service (IEC 1990); see Section 2.6.

As can be seen in Section 2.6, availability is a vital component of service quality. The focus in this case study is on availability, more specifically, on failures and down time in railway infrastructure; see Figure 14.

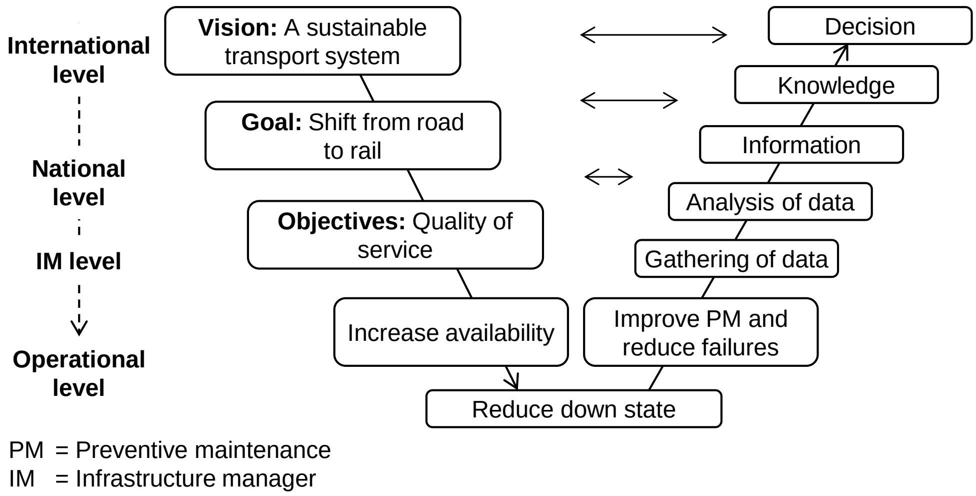


Figure 14: Breakdown of strategy into failures and down time.

Step 2: Updating the measurement system and aligning indictors

Indicators need to be set up and aligned to measure the results. Indicators related to failures and down time specific to railways include (Appendix A):

- 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 as indicators on Trafikverket's QoS scorecard, i.e. failures, work orders, and down time will directly affect the 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.

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

Operation and maintenance data of the Swedish railway section 111 have been collected, verified and analysed. Section 111 is a 128 km 30 tonne mixed traffic section of the Swedish Iron Ore Line stretching from the border of Norway, Riksgränsen, to Kiruna city (Figure 15). The data consist of corrective maintenance work orders (WOs) from 2001.01.01 – 2009.12.01, i.e. 8 years and 11 months. Out of 7 476 WOs in total, 1 966 mentioned train delays, i.e. 26 %. This analysis is based on the 1 966 WOs connected to delays. In addition, the two percent longest delays were considered as outliers, reducing the number of WOs from 1 966 to 1 926. The outliers are preferably analysed before decision-making but this is out of scope of this study. See C. Stenström (2012b) for details on the work order data.

Figure 15: Section 111 of the Swedish Iron Ore Line between the border of Norway, Riksgränsen, and Kiruna city.

With reference to failure mode effect analysis (FMEA) and risk matrices, also known as probability-consequence diagrams, e.g. see (CEN 1999, ISO/IEC 2009), a composite indicator, or index, of operational risk was defined as:

$$R = \sqrt{(a\alpha)^2 + (b\beta)^2} \tag{4.3}$$

Were α equals the infrastructure failures and β the train delay. The *a* and *b* are constants for weighting. Figure 16 shows the resulting operational risk at the system level. The poorest performing systems are the switches and crossings (S&C) and the track. These two systems are further analysed in Figure 17.

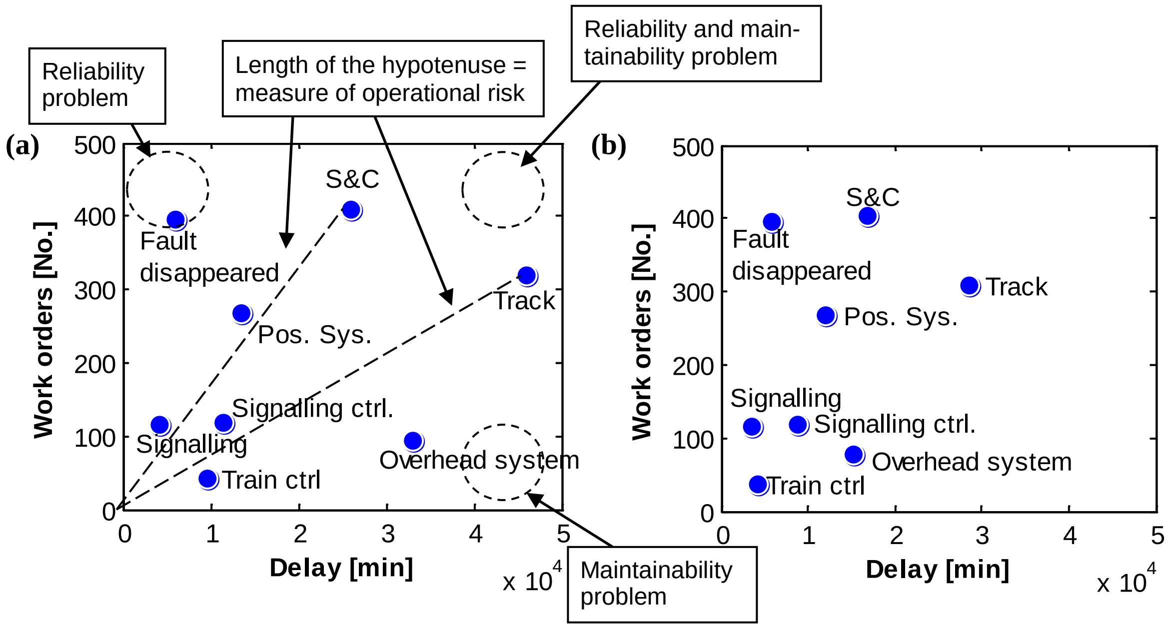


Figure 16: Probability-consequence diagram at the system level displaying failure work orders and the corresponding train delay. (a) Complete dataset and (b) data up to the 98th percentile regarding train delays.

Figure 17a shows that two subsystems of the S&C, namely the switch control system and the switch motor system, are deviating considerably from the other subsystems. The corresponding active repair times can be seen on the right hand side of the figure as box plots. On each box, the central mark is the median, the edges of the box are the 25th and 75th percentiles, and the whiskers extend to 1.5 IQR (interquartile range). Outliers are left out. The median time to repair of the frog, i.e. the switch crossing point, is over 200 minutes, while other systems take about 50 minutes.

The subsystems of the S&C are further broken down to the component level in Figure 17b. 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 17c. The figure shows that joints and rails are the subsystems responsible for the poor performance of the track. Interestingly, joints cause many failures, but not very much of delay (reliability problem). In contrast, the rail causes long delays but fewer failures (maintainability problem). The boxplot indicates that rail failures takes three times longer to repair; a possible reason for the long delays. Joints consist of insulation pads and insulation rings causing short circuits, the main reason for failure, while the main reason for rail WOs is breakage; a central safety risk due to derailment hazard (J. Santos-Reyes et al. 2005).

Table 6 summarise the results. The risk ranks equal the length of the hypotenuse after equal weighting the x-values to the y-values.

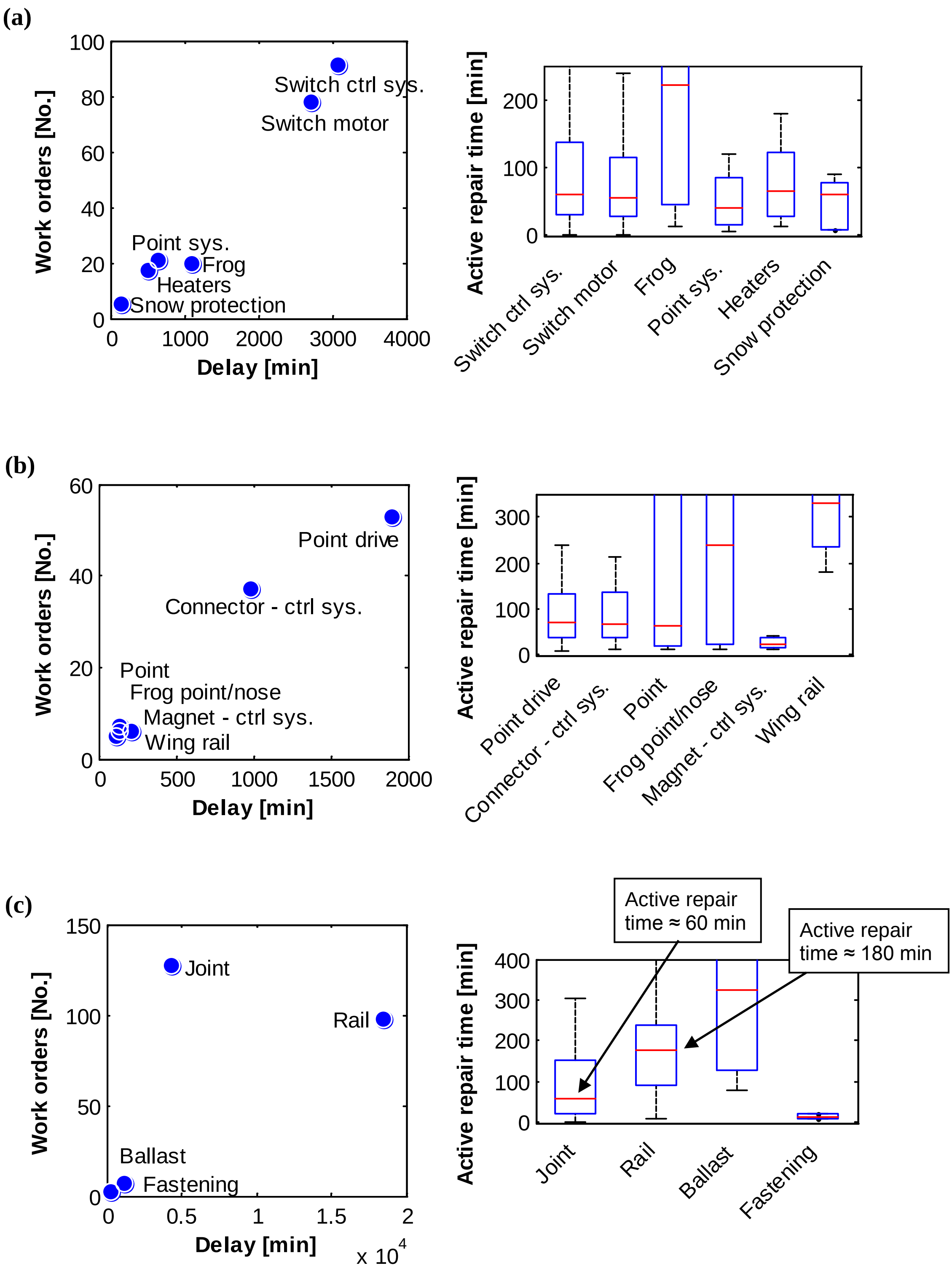
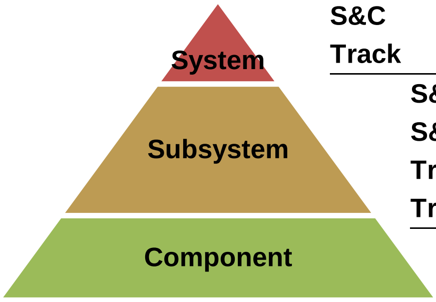


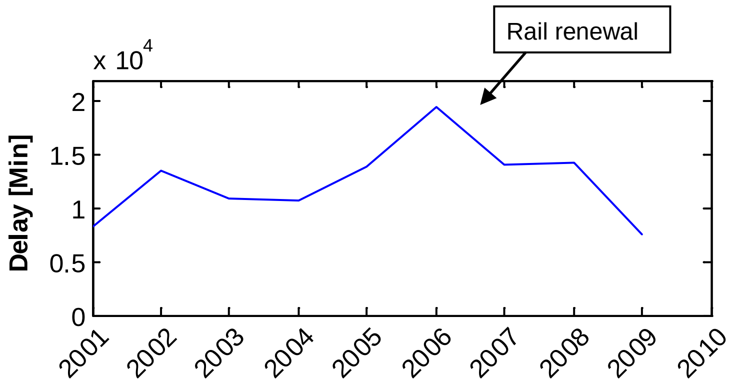
Figure 17: Analysis of the: (a) subsystems of S&C, (b) components of S&C and (c) subsystems of the track. Delay data up to the 98th percentile are used.

Table 6: Work orders (WOs) and train delays of performance killers. $R = (\alpha^2 + \{17 \cdot 10^{-3}\beta\}^2)^{½}$.



	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**

Table 6 gives figures of potential savings; however, aggregating data over nine years does not necessarily give accurate information of the present state. A goal of the link and effect model is to omit thresholds and present PIs with the underlying factors, thus providing a compass for improvements, rather than merely presenting an aggregated measure. See Figure 18. Letter B represents the track, i.e. rail, fastenings and joints. The track is in the top three regarding operational risk (poor performance) from 2001 to 2006. In 2006, the track disappears from the top three, coinciding with the rail renewal in Figure 19.



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
B: Track
C: Positioning
D: Fault dissappeared

Figure 18: Indicator of train delay per year showing the three underlying systems with the highest operational risk indices. The track (letter B) disappears after 2006 in the top three; see Figure 19.

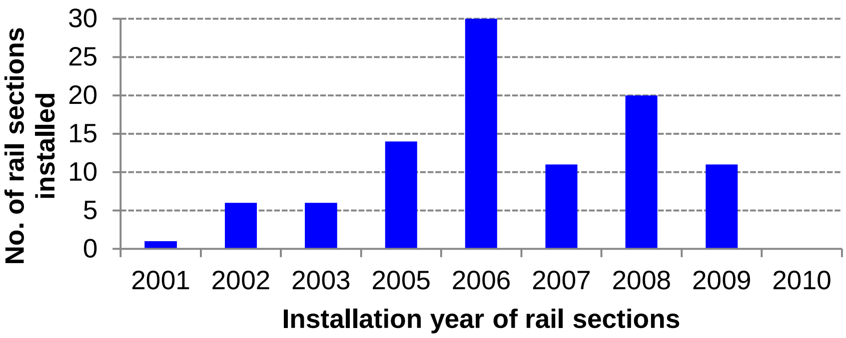


Figure 19: Renewal of rail sections. The large number of renewals in 2006 coincides with the disappearance of the track in the top three poor performing systems in 2006. See Figure 18. 99 out of 188 rail sections are replaced in the 2001-2010.

Step 4: Identification of improvements through indicators and implement

By redesigning or applying preventive maintenance to the identified items giving poor performance, the overall delay can be reduced. However, it is preferable to simulate improvements before moving to action. Figure 20 gives an example of simulation. In the figure, (a) shows the result on S&C when all the WOs of the switch controller system are removed from the dataset, i.e. the controller system never fails. Such a change in the dataset affects other factors at the system level. In (b) all WOs of the railway section are sorted by the actual faults found by the repair team. The black circles show the result from (a) when all the WOs of the switch controller system are removed from the dataset. It can be seen that interruption faults in the railway reduces most.

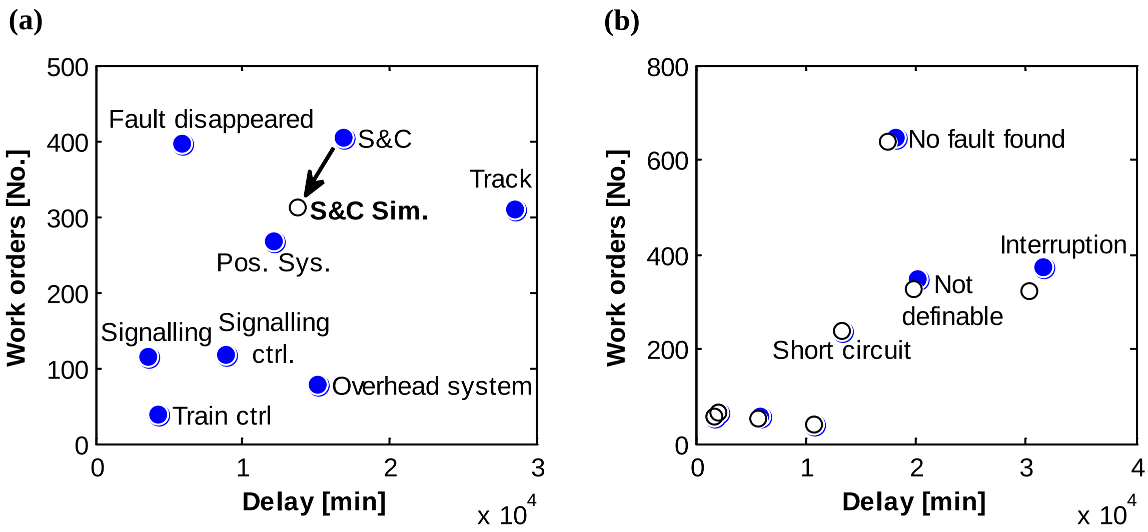


Figure 20: Simulation at system level of the railway section. (a) Impact on the system level when all the failures of the switch controller subsystem are removed from the dataset. (b) All failures sorted according to the registered actual fault. The circles show the result when all the WOs of the switch controller system are removed from the dataset; interruption maintenance work are less.

4.4 Composite indicators for railway infrastructure

Composite indicators can simplify the performance measurement by summarising the overall performance of a complex asset into a single number, easier to interpret than presenting multiple indicators and plots (M. Saisana et al. 2002, OECD et al. 2008, D. Galar et al. 2012). However, the development of such indicators are more complex as additional aspects need to be considered, like correlation and weighting.

In the link and effect case study, two parameters were used to acquire a measure of operational risk. This second case study aims at further developing the operational risk indicator by taking into account three parameters, namely infrastructure failures, train delay and maintenance time. It will then form a composite indicator or index. Nevertheless, combining two indicators could also be considered as and composite indicator. A summary of the study is given below. The findings are preliminary as the analysis is not completed yet; correlation and normalisation need to be taken care of.

4.4.1 Theoretical framework

With regard to failure mode effect analysis (FMEA) and risk matrices, e.g. see (ISO/IEC 2009), a composite indicator has been defined in the study using right-angle simplexes as:

$$R = \left(\sum_{i=1}^{N}\{W_i V_i\}^2\right)^{½} \quad (4.4)$$

Where N equals the total number of individual indicators, V_i equals the i^{th} individual indicator and the W_i is a weighting factor. There exist numerous methods of weighting, which can be divided into two main groups; statistical methods and expert opinion methods (L. Hudrlikova et al. 2011). Three methods are considered in Eq. 4.4, set as a product of: equal weighting (EW), expert opinion weighting and regression weighting:

$$W_i = \prod_{j=1}^{3} w_{ij} \quad (4.5)$$

The results shown here employs equal weighting and leaves out the other two weighting factors, thus $W_i = w_{i1} = w_i$. The equal weighting constants w_{i1} are found by setting:

$$w_{11}\bar{V}_1 = w_{21}\bar{V}_2 = w_{31}\bar{V}_3 = \cdots \quad (4.6)$$

Where:

$$\bar{V}_i = \frac{1}{n}\sum_{j=1}^{n} V_{ij} \quad (4.7)$$

Where n is the number of values of the i^{th} individual indicator. As an example, weighting according to individual indicator $\bar{V}_1$ would give $w_{11} = 1$, $w_{21} = \bar{V}_1/\bar{V}_2$ and $w_{31} = \bar{V}_1/\bar{V}_3$.

The expert opinion weighting is not considered in the case study as it is more or less subjective and therefore depends on the specific case. However, most composite indicators rely on equal weighting (EW), i.e. all variables are given the same weight (OECD et al. 2008).

4.4.2 Data selection

Important indicators for credibility and dependability of railway infrastructure with regard to the overall availability and capacity are considered to be: infrastructure failures [No.], train delay [min] and time to restoration (TTR) [min], i.e. $N = 3$. Railway infrastructure failures are corrective maintenance data consisting 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. Time to restoration (TTR) consists of administrative time, logistic time and active repair time, i.e. from fault found till rectified.

Recalling Eq. 4.4, the general theorem with $N = 3$ gives the three dimensional Pythagoras' theorem, i.e. the risk composite indicator R equals the diagonal's length of a cube:

$$R = \sqrt{(W_1 V_1)^2 + (W_2 V_2)^2 + (W_3 V_3)^2} \tag{4.8}$$

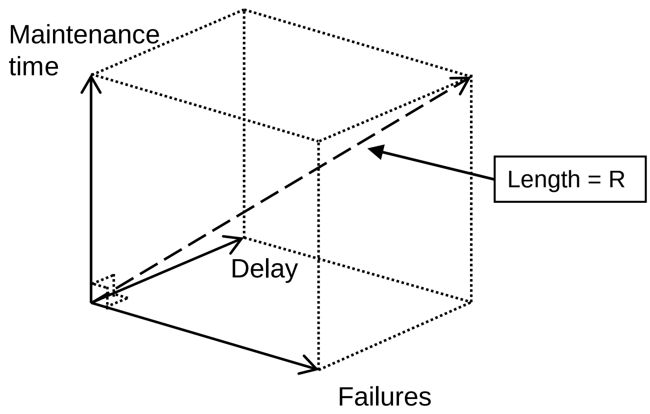


Figure 21: Illustration of the resulting composite indicator R. The length of the dashed vector responds to the R.

The selected line for case study is the Swedish Iron Ore Line. Three lines have been studied. See Figure 22.

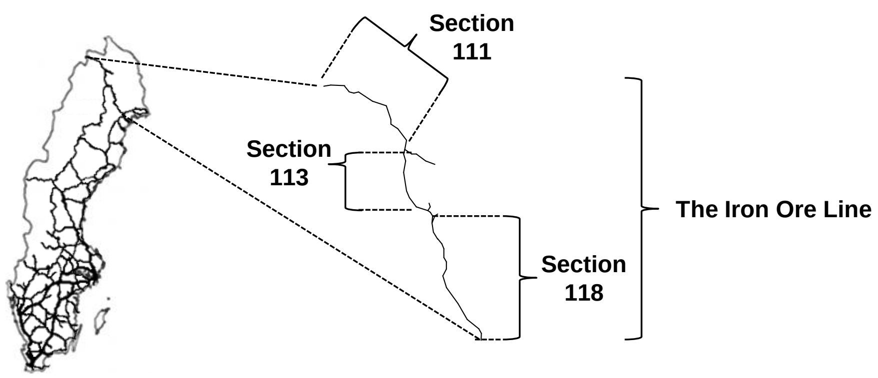


Figure 22: Sections of the Swedish Iron Ore Line subject to analysis.

The failure data are from 2010.01.01 – 2012.10.31, i.e. 1 035 days or 2 years and 10 months. Reported number of failures are 7 142, with 1 687 (24 %) infrastructure failures resulting in train delays. The train delay data have a skewed distribution with some long delays resulting in a long tail. The two percent failures with the longest delays are therefore considered as outliers. In terms of failure WOs, 1 640 out of 1 687 are considered.

See Figure 23 for the results. The figure shows the performance of the subsections of each of the three railway sections (see labels in figure). However, the three sections should not be compared to each other at this stage, since it is a working document.

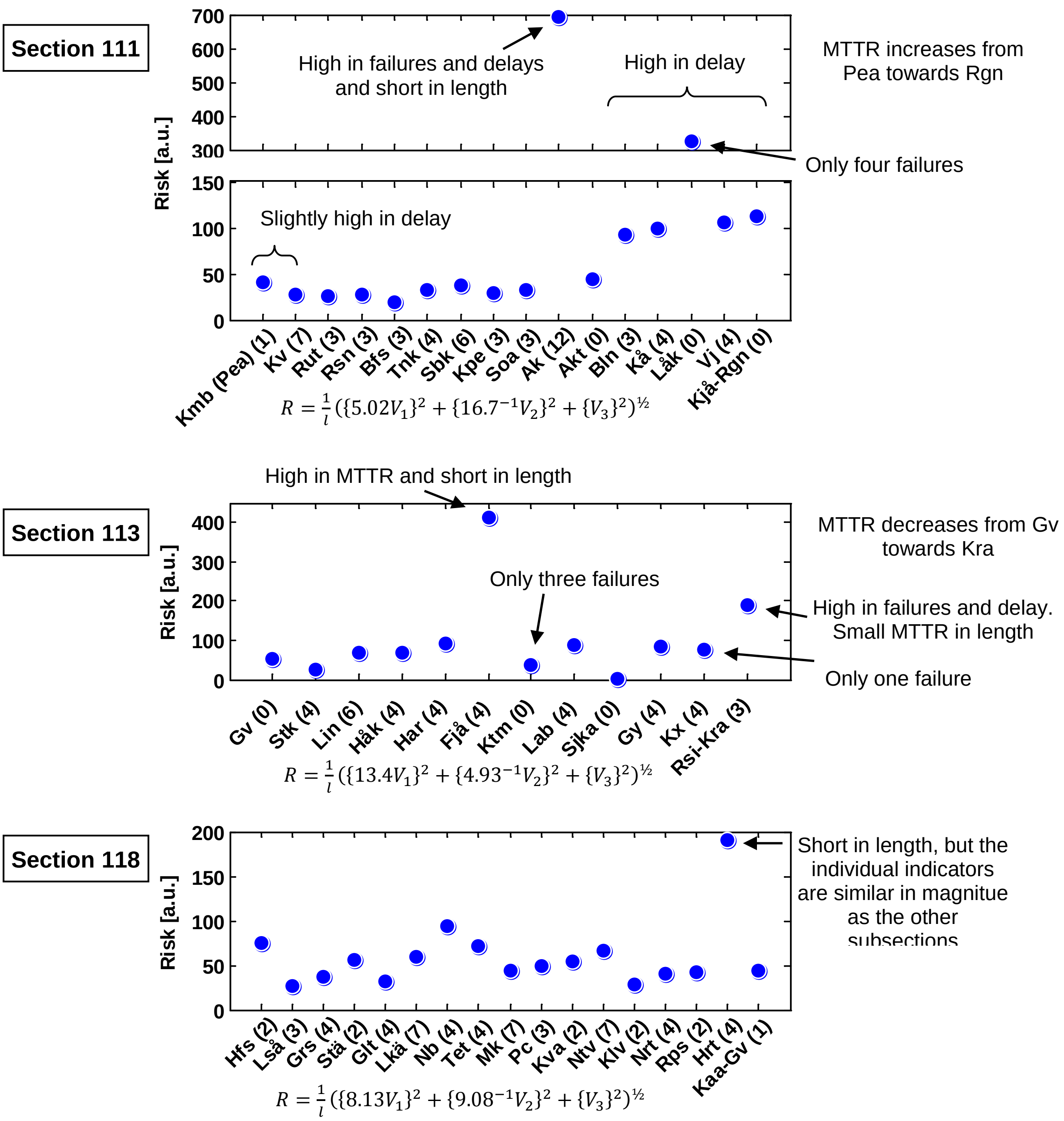


Figure 23: Subsection risks of sections 111, 113 and 118. The x-axis gives the subsection names with the number of S&Cs within parenthesis. The y-axis is the result from the equation given below each plot, i.e. the risk is divided by the section length. V_1, V_2 and V_3 equals train affecting failures, train delay and median maintenance time, respectively. The constants in the equations are for equal weighting. Comparison between sections is not applicable as normalising is missing.

4.5 Impact of cold climate on failures in railway infrastructure

One of the project objectives are to develop key values and monitoring methods for RAMS (reliability, availability, maintainability and safety) and life cycle costing (LCC), another is to develop a link and effect model to measure and monitor changes that affects the operation of the assets. Winter effects affects both key values and the operation of the assets; a study was thereby undertaken (C. Stenström et al. 2012a). A summary of the work is as follows.

4.5.1 Background

Cold climate is known to have an effect on railway infrastructure and its components. In Sweden, the winters were particularly harsh in 1965-66 (SJ 1966), 2001-02 (Banverket 2002), 2006-07 (VTI 2007), 2009-10 and 2010-11 (P. Unckel 2010, UIC 2011b, UIC 2011a).

Scientific publications on a cold climate and railways are sparse. In a survey carried out by the International Union of Railways (UIC), 11 European countries said their main winter rolling stock challenges stemmed from: train design (58 %) and infrastructure (34 %). Seventeen responses cited the main winter challenges in the infrastructure as: performance of equipment for snow clearance (29 %), switches and crossings (27 %) and rails and welding (20 %). VTI (Swedish National Road and Transport Research Institute) studied data from two Swedish railway sections in the period 2001-03 and found that the number of failures causing train delays was 41 % higher in winter than in summer (VTI 2007). The increase was 130 % in switches and crossings, and 24 % in the other railway infrastructure systems. Winter was considered as starting 1 October and ending 30 April, i.e. 58 % of the year.

The impact of cold climatic conditions depends on the type of asset. In fact, a major factor to consider is the effect of temperature on different materials. All carbon steels undergo a ductile-to-brittle transition, which reduces the impact toughness as the temperature is lowered (G.J. Roe et al. 1990, T.A. Siewert et al. 2000). The point of transition and the reduction in impact toughness, which can be reduced to one tenth, depend on the chemical composition of the material, the product processing and the service environment. A similar phenomenon, the glass transition temperature, occurs in amorphous materials, polymers and glasses (J. Zarzycki 1991, ISO 1999). Below the glass transition temperature, amorphous materials become stiffer and more brittle due to their molecularly locked state. Well known problems caused by temperature transitions include ship failures during World War II (G.J. Roe et al. 1990, T.A. Siewert et al. 2000) and the Space Shuttle Challenger accident in 1986 (Rogers Commission 1986).

In rolling stock, cold climate has been shown to increase wheel wear and damage, e.g. (M. Palo et al. 2012).

The aim of the work was to study railway infrastructure failures seasonal dependency regarding size and statistical significance. Studied railway lines are the Iron Ore Line and the Coast-to-Coast Line in Sweden, line 21 and 4 respectively, see Figure 24.

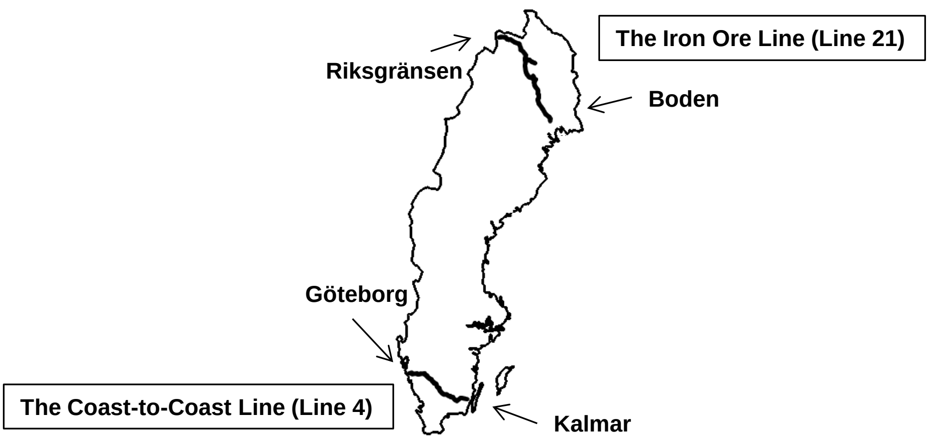


Figure 24: Railway lines 21 and 4 in Sweden. The distance between Boden and Kalmar cities is about 1300 km.

4.5.2 Results

Seasonal differences in the number of failures prove to be significant, and the seasonal effect is significantly more pronounced on line 21 than line 4. Statistical details can be found in C. Stenström et al. (2012a).

On average, the number of failures is twice as high in January and February in line 21 compared to the spring and autumn. This effect is not as pronounced in line 4. See Figure 25. However, the effect differ extensively from year to year, and thus it is not possible to predict for coming winters by just considering the average (Figure 26; standard deviation is 0.41 from year to year of line 21).

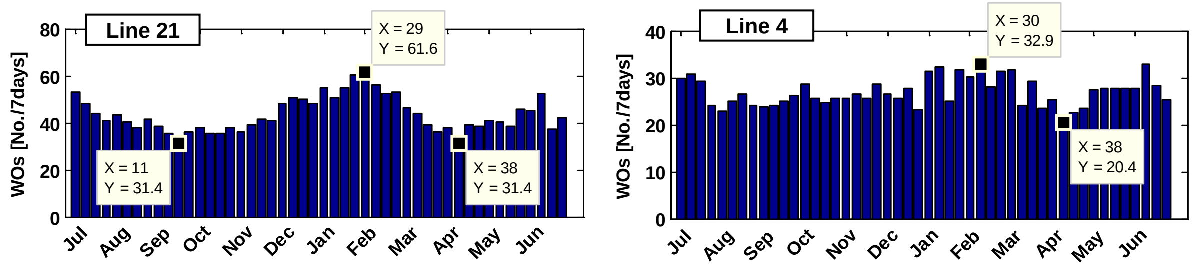


Figure 25: Number of failures per 7 days. 11 years mean.

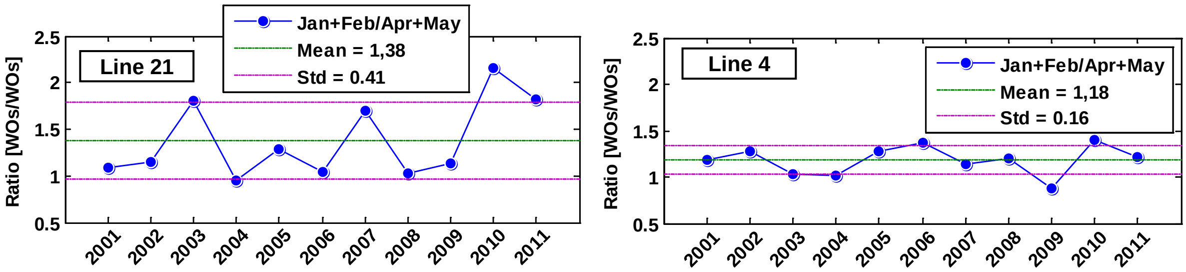


Figure 26: Winter to spring ratio of 2001-2011. Difference in number of days in months has been compensated. (Jan+Feb)/(Apr+May) is the number of failures in these months divided by each other.

Further studying line 21 and disregarding the 8 % of snow and ice related failures, the difference in the number of failures is about 60 % between summer and winter compared to 100 %, i.e. 40 % of the increase comes from the switches and crossings; figure in C. Stenström et al. (2012a).

Studying the switches and crossings, the number of failures is 2-3 times greater in winter than in summer for both lines 21 and 4 (Figure 27). Disregarding snow and ice problems, at line 21 it can still be seen an increase of 50 %; figure in C. Stenström et al. (2012a).

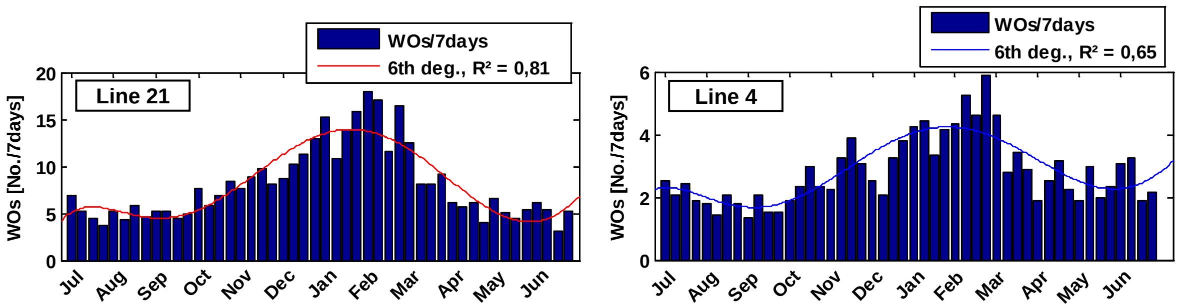


Figure 27: Failures in switches and crossings per 7 days. 11 years mean. Snow and ice problems are taken into account as well.

Failures as a function of temperature have been studied on a monthly basis. Goodness of fit (R^2) is not good when including all failures, but the failures seems to increase at both high and low temperatures and to be at its lowest around zero centigrade; see Figure 28. Analysing switches and crossings; it can be seen that the snow and ice failures have a big influence (Figure 29).

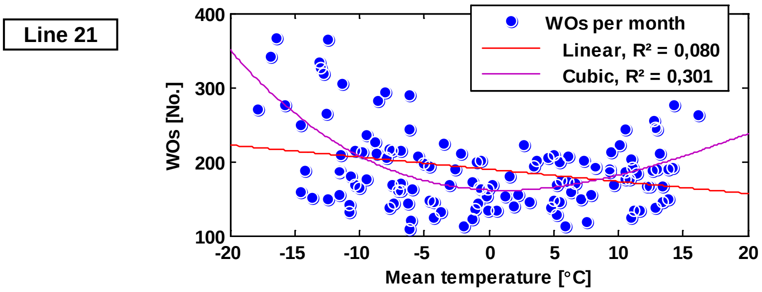


Figure 28: Work orders (WOs) and mean temperature per month of line 21.

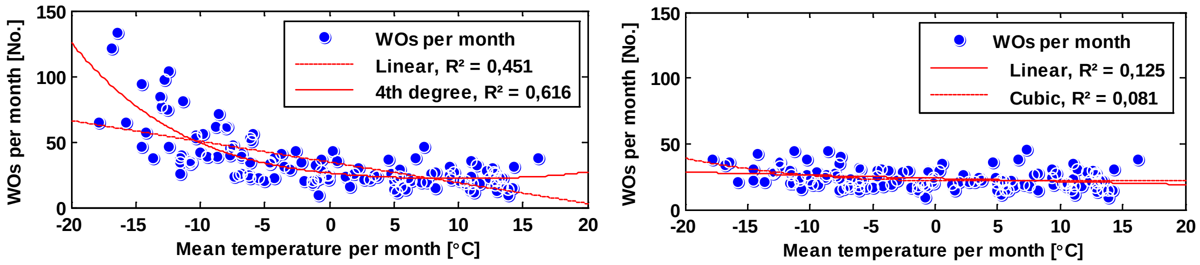


Figure 29: Mean number of failures in switches and crossings vs. mean temperature per month of line 21. At the left side of the figure; all failures are considered. At the right hand side; snow and ice related failures are disregarded. 11 years of data give close to 132 data points in the plots.

4.6 Railway infrastructure performance analyser software

The market for enterprise resource planning (ERP) systems and computerised maintenance management systems (CMMS) is large, counted in billions of dollars worldwide, e.g. see statistics from Gartner Inc. Tailoring enterprise software to meet specific needs is a balance between benefits and costs. An alternative approach is to develop software in-house or to complement the ERP system with specialised in-house developed software. By this reason, a demonstrator was developed to show how railway infrastructure data can be analysed cost-effectively for dependability and RAMS (reliability, availability, maintainability and safety/supportability). The following analysis can be performed by the software:

Merging of data: Merging failures and train delay together.

Data quality: Plotting work order fill rate. Used to study the work order process, e.g. why some fields are used frequently while other less frequently. Fill rate over time can also be studied to see the effect of policy or contract changes.

Seasonal and aging effects: Plotting failures per month for study of seasonal effects and over years to see if the failures are increasing in number (aging).

Failure and train delay:	Plotting the most frequent types of work orders with the corresponding train delay, i.e. reliability and maintainability. The work orders can be analysed according to type of failure symptom, actual cause, remedy, system, subsystem, component or geographical zone. Also, some work order can have very long train delay, like the contact wire failures or if wrong data has been registered. Therefore, analysis can be carried out with disregarding some percentage of the longest train delays. The data is presented in bar, Pareto and pie charts.
Maintenance time:	Plotting administrative, logistic and active maintenance times, i.e. supportability and maintainability.

See Appendix B for an example of analysis.

4.7 Maintenance possession time simulation

The capacity utilisations of railways has a major effect on the maintainability and maintenance planning, which commonly is based on the present train time table. Especially in contracting, if it is shown that the capacity utilisation increases and it is not properly considered in the contracts, it can result in additional and costly negotiations. By simulating the maintenance possession time for different capacity utilisation scenarios, it is possible to improve the maintenance planning of railways. A prestudy was undertaken to simulate the actual time to repair (ATTR) due to train passages. The input parameters are:

- Train time table
- Safety/set-up/clearance time (t_{Safety})
- Active repair time (t_{Repair})
- Minimum fraction of t_{Repair} for doing maintenance ($t_{Min.}$)
- Arrival point in the time table

The output parameter is:

- Actual time to repair (ATTR)

4.7.1 Results

The maintenance possession time simulation is carried out on the single track railway subsection of Rautas (RUT), the Swedish Iron Ore Line. Train passages have been extracted from the train time table of 2011. Figure 30 shows the effect of different arrival times of the maintenance team, and Figure 31 shows the effect of longer required time for maintenance and the effect of t_{Safety}. The time at the x-axis starts at midnight.

A step further is to develop a model of the ATTR as a function of capacity utilisation, type of maintenance work and safety/set-up time requirements, but this is out of scope since it is a prestudy.

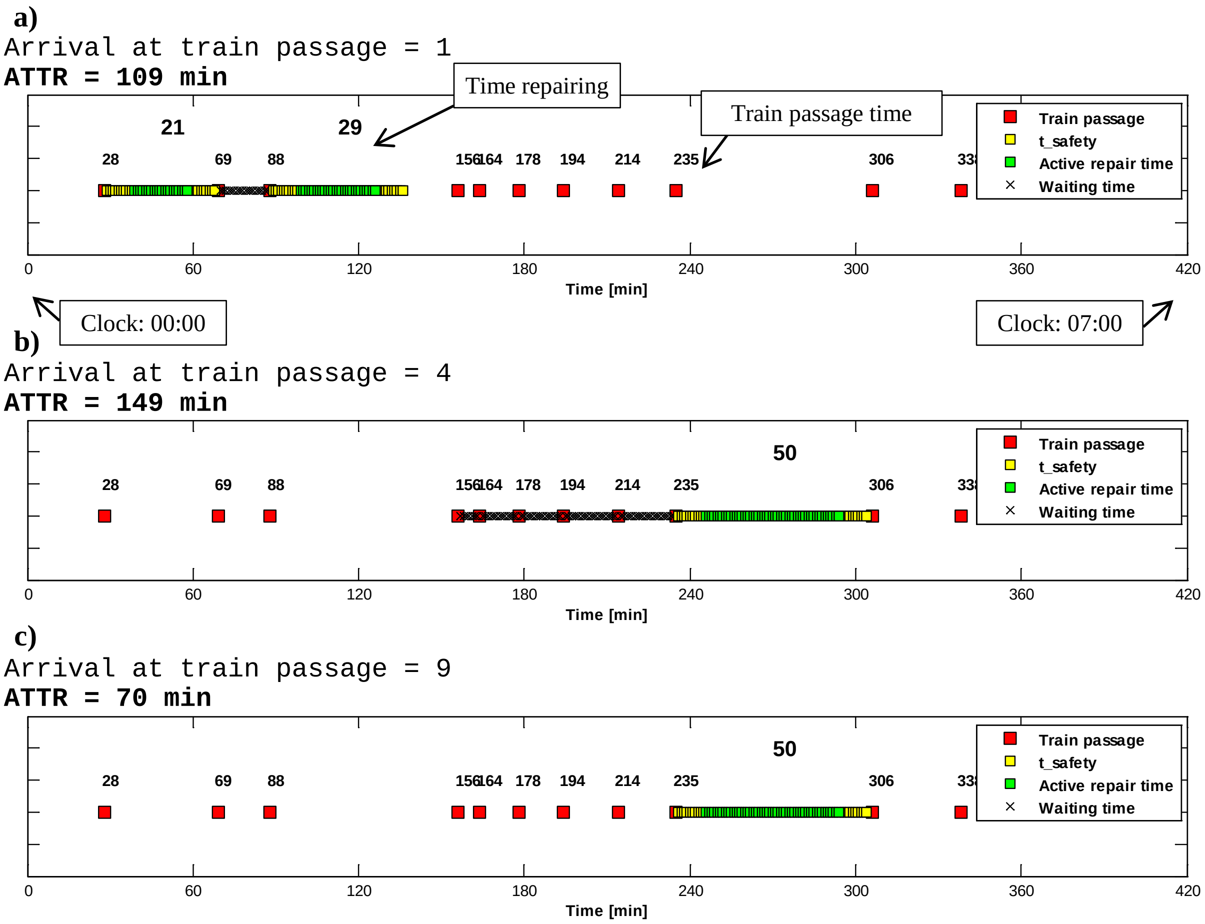


Figure 30: Effect of different arrival times on the actual time to repair (ATTR). The capacity utilisation is different at each arrival time. t_{Safety} = 10 min, t_{Repair} = 50 min and $t_{Min.}$ = $0.1t_{Repair}$ = 5 min. The waiting time is the time when the window for maintenance is too small.

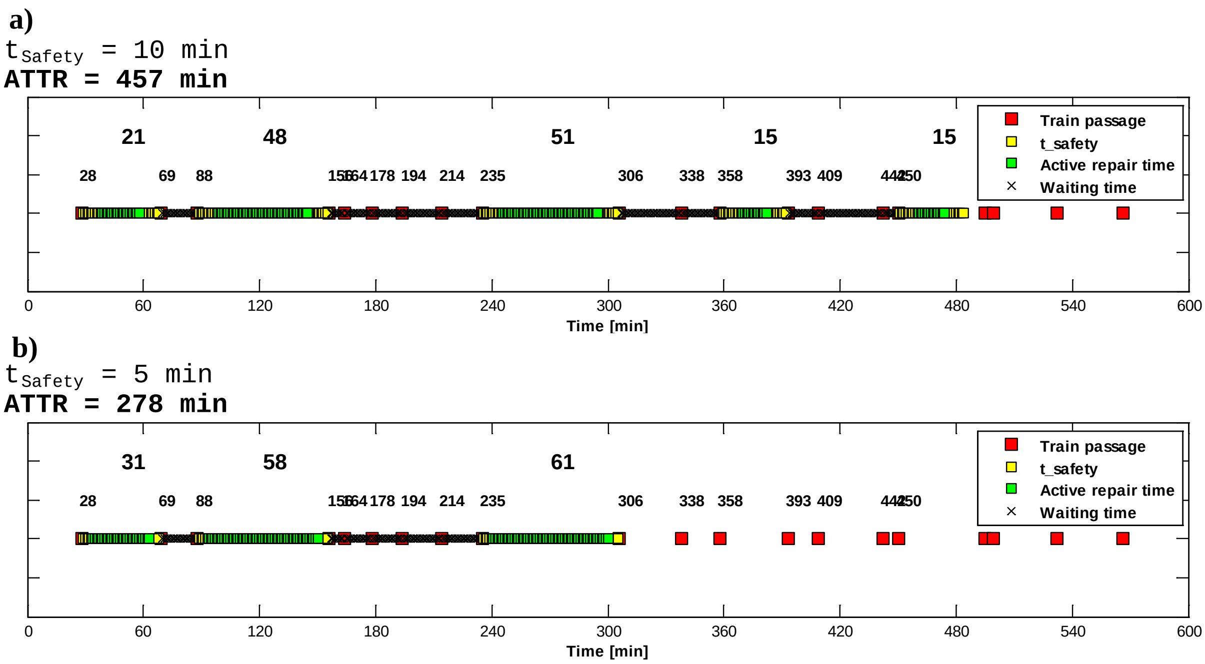


Figure 31: Effect of longer repair time and effect of t_{Safety} on the actual time to repair (ATTR). t_{Repair} = 150 min and $t_{Min.}$ = $0.1t_{Repair}$ = 15 min.

5 Discussion

The project purpose is to develop a link and effect model to improve the effectiveness of the maintenance system for the railway infrastructure.

A link and effect model has been developed for improving performance measurement systems, by combining performance measurement and engineering principles.

The need for performance measurement systems to be able to handle implementation issues and business changes has been discussed in Sections 2.5 and 4.3. That together with the problem that the elements of strategic planning are sometimes missing or used in different ways in organisations (Section 4.3.3), the link and effect model was developed with emphasis on:

- Continuous improvement
- The key elements of strategic planning
- The underlying factors responsible for the performance

The link and effect model differ from other performance measurement systems in its focus on three components, in providing a breakdown process with description of the key elements of strategic planning, but especially, in its focus on the underlying factors of performance indicators. In traditional performance measurement systems, PIs are given threshold values, 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.

5.1 Project objectives

Objective 1: Map operation and maintenance activities of railway infrastructural assets

The maintenance process at Trafikverket has been mapped through interviews and literature review at a strategic level (C. Stenström 2012a). The project also consist of two phases (Section 1.5) stating that key performance indicators (KPIs) and key result areas (KRAs) are to be identified; see mapping in Section 4.1-.2. About 120 indicators were identified (Appendix A). 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 or 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 (U. Espling et al. 2004, B. Nyström et al. 2003, R. Granström 2008). 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 rolling stock have been carried out in (EQUIP 2000, IMPROVERAIL 2001, W. Adeney 2003, R. Anderson et al. 2003, UTBI 2004).

The identified indicators have been compared to EN 15341 (CEN 2007) in Tables 4 and 5. 11 PIs were found to be 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 A.6 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 (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 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 life cycle costing (LCC) 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 (D. Ling 2005).

Objective 2: Develop key values and monitoring methods for RAMS (reliability, availability, maintainability and safety) and LCC analysis in maintenance infrastructure contracts

Measures for RAMS have been developed and demonstrated in case studies (Sections 4.3-.4 and 4.6). Reliability has been studied in terms of failures, maintainability in terms of active maintenance time and maintenance supportability in terms of administrative and logistic delay.

LCC analysis has not been carried out. Analysis to this point has been on corrective maintenance, which distribution is known quite well now from this study. In fact, the concern of how to put the weights for the composite indicator in Section 4.4 is solved, if costs are added to the number of failures, train delay and maintenance time. Preventive maintenance data has been collected for similar analysis as carried out for the corrective maintenance. It will then be straight forward to compare railway sections corrective and preventive maintenance costs ratios, followed by simulation of return on maintenance investment scenarios. This work is to be undertaken in phase two of the link and effect model.

Objective 3: Develop similar methods and tools for the exchange of key data among stakeholders involved in the railway system, i.e. infrastructure managers, traffic companies, supplier, contractor, etc. The work carried out in short is:

- Mapping of railway operation and maintenance of railway infrastructure
- Mapping of railway infrastructure indicators
- Development of a link and effect model
- Development of operational risk indicator and composite indicator
- Study of winter effects
- Development of a railway RAMS analyser software (demonstrator)

The mapping of indicators can be interesting for contractors to see what kind of data infrastructure managers are collecting and to find mutual indicators for exchange of data.

Regarding maintenance contractors, the link and effect model is interesting as business process improvement methods and tools are commonly claimed to be used in Fortune 500 companies, e.g. the balanced scorecard tool combined with the PDSA cycle and a detailed improvement method, such as six sigma, total quality management, ISO 9000, etc.

The figures from the winter effect analysis are interesting for both traffic operators and maintenance contractors to compare with their own experience and to use as a reference to build further research upon.

The RAMS analysis that has been carried out in this study has been basically on the operational level, specifically on sections and subsections. IMs and maintenance contractors may therefore find it interesting to see how the sections and subsections perform, e.g. where most failures takes place and where the maintenance time is longest, thereby facilitating appropriate decision making.

However, methods and tools for the exchange of key data among stakeholders have done been done in the project.

Objective 4: Develop a link and effect model to measure and monitor changes that affect the operation of the assets

Results: A link and effect model has been developed (see discussion on the project purpose). The model itself do not measure or monitor, it is a process improvement methodology for better measurement and monitoring. Rather the developed RAMS analyser software answer this objective and the maintenance possession time simulation algorithm.

According to the two phases of the project (Section 1.5), an implementation plan for the link and effect model should be developed. At this stage it is too early to make such plan. Implementation work will instead take place in the phase two of the project.

6 Conclusions and future work

This project resulted in the following deliverables.

6.1 Conclusions

The following conclusions have been made in this research:

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- Punctuality and regularity are preferably studied together. The motivation is that cancelling trains can increase the punctuality and vice versa. Punctuality and regularity can even be multiplied to give a measure of effectiveness (Figure 10). Suboptimising could be hindered in this way. See Section 4.1.
- A benefit of regularly updating indicators is that current performance can be compared with previous performance, i.e. trend tracking. As a result of new better ways of measuring, changed objectives, or due to organisational changes, the way that indicators are calculated can be changed. The benefits of measuring can then be lost, and therefore the old ways of calculating should be kept for a period of time and presented with the new ways of calculating, i.e. overlapping. Some indicators can give a good record for trend studies quite fast, while others need several years to be trustworthy. This is an ongoing work at Trafikverket.

Performance indicators of railway infrastructure

- A detailed review of the performance measurement of railway infrastructure was undertaken (C. Stenström et al. 2012b, 2013). As a result, performance indicators of railway infrastructure (mainly the track) have been listed and categorised into two groups; managerial and condition monitoring indicators. About 120 measures in total. The identified indicators have been compared to EN 15341 (CEN 2007); 11 indicators were found to be similar, which can facilitate external benchmarking. See Sections 4.1-.2.

Link and effect model

- A link and effect model has been constructed for improving performance measurement systems. It has its basis in the plan-do-study-act (PDSA) cycle and in a top-down to bottom-up approach. It put emphasise on: continuous improvement, the key elements of strategic planning, and the underlying factors responsible for the performance. See Section 4.3.
- Indicators are often aggregated measures of several assets or of several individual indicators, e.g. total delay or overall equipment effectiveness, which can make the indicators abstract as the reasons for the value, up or down, is unknown. Therefore, indicators should be presented with its underlying factors so actions can be taken faster. See Figures 13, 18 and 19.
- Failure work orders and train delay have been used in the link and effect case study. The failure work orders consist of three asset levels: system, subsystem and component levels. This gives the attribute of simulating the effect of component level changes at the system level (see Figure 20).

Indices (composite indicators) for railway infrastructure

- Three indices for operation and maintenance have been developed. One where punctuality, regularity and optionally track geometry are multiplied (Figure 10). Another based on failures and train delays (Figures 16-19). As well as an index based on failures, train delays and maintenance time (Figures 21 and 23).
- The track system in the case study on Section 111 of the Swedish Iron Ore Line has one of the three highest index values between the years 2001-2006. A major rail replacement was performed in 2006, which made the track disappeared from the top three. See Figures 18 and 19.

Impact of cold climate on failures in railway infrastructure

- Winter effects are statistically significant. The number of failures in January and February can be 100-200 % higher compared to spring and autumn. Snow and ice related failures are not alone responsible for the rise in failures; not at an overall level, nor in switches and crossings. However, it is not possible at this stage to predict and plan for coming winters since the variation between winters are high.
- Number of failures in the railway infrastructure appears to increase at both high and low temperatures and to be at its lowest around zero centigrade (Figure 28). For switches and crossings, the increase in failures with decrease in temperature is clear with a fairly good model fit (Figure 29). With the fitted model in Figure 29 and weather forecasts, failures and maintenance need can be predicted for up to ~10 days for switches and crossings. Similar prediction can be done for years ahead with use of climate models. However, a goodness of fit (R^2) of 0,62 together with the uncertainty in weather forecast and climate models are limiting the use.

Railway RAMS analyser software

- The development of the demonstrator shows that organisation-specific analysis can be carried out cost-effectively. The least costly data analysis process can be to combine in-house developed algorithms with purchased enterprise resource planning (ERP) systems as ordering specific analysis is a balance between costs and gains.
- Common RAMS (reliability, availability, maintainability and safety/supportability) measures are relatively easy to derive. However, reliability analysis with prediction is more complicated since age data is needed. For Trafikverket, the installation year of the assets in BIS software can possible be used for this purpose, e.g. installation year of rail sections.

The RAMS (reliability, availability, maintainability and supportability/safety/security/sustainability) acronym has been reviewed in Section 2.6. It has been found that dependability, quality of service and performance are similar in their description and hierarchical level.

Railway infrastructure failure work order data was collected for case studies. Each work order consists of 71 data fields, which were studied to identify fields suitable for case studies. However, this kind of analysis gives information on how the work order process can be improved, e.g. by removing unnecessary fields and improving the way of completing other fields. See Figure 8.

6.2 Scope for further research

Several subjects of future research have been identified in the research work, that is:

- Indicators for maintenance of railway infrastructure have been identified, but only few of them have been studied in detail, thus the indicators need to be studied closer, e.g. for purpose, importance, advantages, disadvantages, target levels, formula, frequency, etc. See Sections 4.1-.2.
- Standardised maintenance performance indicators and corresponding limits, or benchmarks, are lacking for railway infrastructure. Work on standardisation, similar to the European Standards EN 15341 and the Harmonisation project, could increase the maintenance performance, and thus the capacity of railway networks where it is applied (J. Kahn et al. 2011, CEN 2007).
- Taking the product of regularity and punctuality can give a measure of railway effectiveness (Figure 10). If a track quality index, e.g. Q-value, is also taken into consideration, a measure of the overall railway effectiveness is received, similar to the overall equipment effectiveness (OEE) used by in the production industry. These methods can be further evaluated to see if they can support railway operations.
- Knowing and finding the optimum share of preventive maintenance compared to corrective maintenance for different systems, such as railway sections or systems like switches and

crossings, can be challenging. Benchmarking a set of railway sections is a method that can be used to study this subject, where one method is to use production efficiency, given as production output divided by input. Benchmarking of different systems is then possible by comparing the efficiencies. However, finding common weights for the inputs and outputs are normally not possible due to different operational circumstances for each unit. With data envelopment analysis (DEA), relative weights are used by calculating the most favourable weights for each unit subject to the others, making benchmarking possible. DEA is a non-parametric statistical method that can be studied for its possibility to be used in this topic. See the technical report.

- The study on railway infrastructure performance indicators has been mainly focused on the track. Further studies on indicators can be on other infrastructure assets, the rolling stock and for maintenance contracting. However, a couple of European projects have studied indicators and benchmarking for the rolling stock; see Chapter 5, p. 61, of the technical report.
- Further research could consider data quality in more detail. Failure work orders require a number of fields to be completed before closure, thus detailed analysis of practice and requirements for work order closure can enhance the understanding of its morphology and data quality.
- The developed composite indicator is built on corrective maintenance failures, train delays and maintenance times. The preventive maintenance work orders are many more than the corrective maintenance work orders. It could be interesting to further develop the composite indicator by including preventive maintenance.
- Since the failure distribution, train delays and maintenance times are known, costs can be added. The weighting issue would then be bypassed. Costs can be added in a similar way to the preventive maintenance. It would give the ratio between corrective and preventive, and benchmarking could then give the optimal ratio between corrective and preventive maintenance. This will take place in the phase two of the project.
- In the winter effect study (Section 4.5), failures as a function of temperature were modelled with curve fitting on a monthly basis. The goodness of fit was not good at the system level where all failures were included, but it was better when the subsystem switches and crossings was studied. Continuation of the study on subsystem and component levels with modelling on a daily basis instead of monthly, including temperature, precipitation and wind, is interesting. Together with weather forecasts, failures and maintenance need may then be predicted for up to ~10 days. With climate models, predictions may be done for years ahead.
- The maintainability of railways is strongly affected by the capacity utilisation. The prestudy suggest further study for model formulation of the actual time to repair (ATTR) as a function of capacity utilisation, train time table, maintenance work and safety/set-up time requirements. This is a work starting at Trafikverket.
- A number of studies have investigated whether one gets more maintenance for the money in railways through free competition, but several aspects make the analysis complicated, e.g. indirect costs, confidentiality agreements and various types of contracts. More studies are needed to include these elements. Studies have not been able to show how the safety of the railways has been influenced by deregulated maintenance; the small statistical base is limiting quantitative studies. A larger qualitative study is one possible way to answer the question, similar to the work of U. Espling (2004, 2007).

Appendix A

Refer to Section 4.2

Performance indicators of railway infrastructure

This appendix presents the railway infrastructure performance indicators from the mapping discussed in Sections 4.1-.2 (C. Stenström et al. 2012b, 2013). The indicator structure can be seen in Figure 9.

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 sections, 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 Table A.1.

Table A.1: Technical railway infrastructure maintenance indicators.

Technical indicators			
Category	**Indicators** (comments) [unit]	**Reference**	**#**
Availability	**System level**		
	Arrival punctuality [no. or %, passenger or freight]	(P. Söderholm et al. 2011, Banverket 2010)	T1
	Train regularity [no. or %, passenger or freight]	(Banverket 2010)	T2
	Failures in total [no.]	(CEN 1999, VTI 2011, B. Nyström et al. 2003, R. Granström 2008, R. Granström et al. 2005, B. Nyström 2009)	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 %]	(C. Stenström 2012a, C. Stenström 2012b)	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]	(VTI 2011, B. Nyström et al. 2003, R. Granström 2008, R. Granström et al. 2005, B. Nyström 2009)	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
Maintain-ability	**System level**		
	Mean time to repair (MTTR) (or Mean time to maintain (MTTM), or Maintainability)	(CEN 1999, INNOTRACK 2009)	T15
	Subsystem level		
	Mean time to repair (MTTR) per item (or Maintainability)	(B. Nyström et al. 2003, INNOTRACK 2009)	T16

Table A.1: Continuation.

Technical indicators			
Category	**Indicators** (comments) [unit]	**Reference**	**#**
Capacity	**System level**		
	Traffic volume [train-km or tonne-km]	(Banverket 2010, T. Åhrén et al. 2004)	T17
	Subsystem level		
	Traffic volume per line, line class or area [train-km or tonne-km/line, class or area]	(Banverket 2010, T. Åhrén et al. 2004)	T18
	Capacity consumption (or Capacity utilisation) (24h and 2h) [%]	(UIC 2004, Banverket 2010, T. Åhrén et al. 2004)	T19
	Harmonised capacity consumption (double track counted twice) [train-km/track-metre]	(C. 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]	(T. Åhrén et al. 2009b)	T22
	Data envelopment analysis (DEA) [-]	(S.A. George et al. 2008, R. Malhotra et al. 2009)	T23
Age	**Subsystem level**		
	Mean age of assets (Rail, S&C, OCS, ballast, etc.) [time]	(Trafikverket 2011)	T24

Quantitative indicators should always be complemented with qualitative indicators, like questionnaires quantified through Likert scale. This has special importance in the organisational perspective due to strong human interactions. See Table A.2 for quantitative organisational indicators.

Table A.2: Organisational railway infrastructure maintenance indicators.

Organisational indicators			
Category	**Indicators** (comments) [unit]	**Reference**	**#**
Maintenance management	**System level**		
	Preventive maintenance share (or Corrective maintenance share) [%]	(U. Espling et al. 2004)	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, INNOTRACK 2009)	O3
	Maintenance possession overruns [time or no.]	(U. Olsson et al. 2004)	O4
	Subsystem level		
	Preventive maintenance share (or Corrective maintenance share) per line, line class, area or item [%/line, class, area or item]	(C. 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 %]	(C. Stenström 2012a, C. Stenström 2012b)	O7
	Subsystem level		
	Faults in infrastructure with unknown cause per line, line class, area or item [no. or %/line, class, area or item]	(C. Stenström 2012a, C. Stenström 2012b)	O8

Many overall financial indicators are regulated by the ministry of the IM and are therefore easy to find; see Table A.3.

Table A.3: Economic railway infrastructure maintenance indicators.

Economic indicators			
Category	**Indicators** (comments) [unit]	**Reference**	**#**
Allocation of cost	**System level**		
	Maintenance cost (inclusive or exclusive management cost) [monetary]	(Banverket 2010, BSL 2009, 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]	(UIC - LICB 2008, Banverket 2010, BSL 2009, T. Wireman 2003)	E3
	Maintenance contractor cost	(Trafikverket 2011)	E4
	Corrective maintenance cost [monetary]	(C. 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, A. Nissen 2009a, A. Nissen 2009b)	E7

Maintenance staff are exposed to hazards and suffer from bad ergonomics due to unstandardized or non-routine work, lowered barriers, leakage, pressure, electricity, etc. (D. Galar et al. 2011). As in all forms of rail transportation, the safety is a critical factor. General HSE indicators are easy to find and often required by law, but specific indicators for maintenance are scarcer. Both types have been considered in Table 4.

Table A.4: HSE railway infrastructure maintenance 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.]	(C. Stenström 2012a)	H4
	Harmonised inspection remarks		H5
	Deaths and injuries (or casualties and accidents) [no.]	(BSL 2009, Trafikverket 2011, M. Holmgren 2005)	H6
	Accidents at level crossings [no.]	(BSL 2009, T. Åhrén et al. 2004)	H7
	Accidents involving railway vehicles [no.]	(T. Åhrén et al. 2004)	H8
	Incidents (or Mishaps, or Potential injuries) [no.]	(Trafikverket 2011)	H9
Safety – maintenance	Maintenance accidents and incidents (occurred and potential) [no.]	(M. Holmgren 2005)	H10
	Failure accidents and incidents (occurred and potential) [no.]		H11
	Derailments [no.]	(BSL 2009, Trafikverket 2011, S.M. 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]	(T. Åhrén et al. 2004)	H15
	Use of environmental hazardous materials [-]		H16
	Use of non-renewable materials [-]		H17

Condition monitoring indicators

The railway condition monitoring indicators have been divided into six groups; substructure, superstructure, rail yards, electrification, signalling and information communication technology (ICT). Condition monitoring of these assets has been mapped by studying various inspection methods, mainly in (BSL 2009, C. Esveld 2001, INNOTRACK 2008); see Table A.5. Ocular inspections and manual inspections using gauges have not been considered 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 rolling stock; 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 (D. Lardner 1850). See work by Bracciali (2012) for a state-of-the-art review on wayside detectors.

Table A.5: 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 and deflection speed	
Ballast contamination	- Thermographic imaging	- Contamination	Deduced: Contaminated ballast and bad drainage inspection remarks [no. or no./length]
Moisture content	- Resistivity tomography	- Moisture content (related to drainage)	
Track geometry			
Geometry	- Contact axles - Optical system - Gyroscope system - Inertial system	- Gauge - Cross level - Cant - Longitudinal level - Twist - Geometry of rails (spatial pos.) - Alignment - Wheel rail contact profile	- TQI (Track quality index), based on standard deviation, commonly for each 200 m. Deduced: - Track geometry inspection remarks [no. or no./km]
	- Failure reporting	- Bucklings (or Sun kinks)	Bucklings [no.]
Track surroundings			
Clearance and signal visibility	- Video system	- Vegetation clearance - Signal visibility	- Track surroundings inspection remarks [no. or no./km]

Table A.5: Continuation.

Features	Method	Parameters (component level)	PIs (subsystem level)
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 and fasteners	- Optical profile and surface sys. - Differential transformer (LVDT) corrugation sys. - Axle box accelerometers	- Profile - Gauge wear - Running surface wear - Rail inclination - Rail type - Corrugation (amplitude and λ)	Deduced: - Inspection remarks requiring grinding [no. or no./km] - Inspection remarks requiring rail replacement [no.] - Inspection remarks requiring component replacement - Rail breaks [no.]
	- Video system	- Rail breaks - Rail joints - Burns/patches - Corrugation - Fastenings	
Switches and crossings (S&C)			
Geometry and integrity	- Geometry car	- Track deflection at switches	Deduced: Switches deflection inspection remarks [no. or no./switches]
	- Continuous monitoring using sensors	Switch blade position; - Contact area of blade and rail - Switch flangeway (open distance) - Operational force - Power and current usage - Residual stress (retaining force) - Detector rods position	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.]
		- Temperature - Stress (longitudinal)	
	- Mechatronic system	- Gauge	Switch total deviation
		- Switch blades groove width	
		- Cross level	
		- Twist	
	- Ultrasonic testing	- Discontinuities at critical spots	Deduced: Ultrasonic testing remarks [no. or no./switches]
Electrification			
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	

Table A.6: Railway infrastructure performance measurement scorecard.

Perspective	Aspect	Indicators [No.]	
Managerial		**System**	**Subsystem**
Technical	Availability	7	7
	Maintainability	1	1
	Capacity	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	1	4
	Signalling	-	-
	Information communication tech.	-	-

Railway infrastructure performance analyser software

Graphical user interface: Christer Stenström and Mahantesh Nadakatti
Algorithms: Christer Stenström

A demonstrator was developed within the project for basic failure work order and train delay analysis. Matlab software has been used for analysis in this project. The demonstrator does not contain all the algorithms developed for the results in Chapter 4. The graphical user interface (GUI) is shown in Figure B.1. User instructions are provided in the help menu. Input parameters are changed in the input-field in the script files. For example, the failures, delays and maintenance times can be analysed per: system, subsystem or component level; failure symptom, cause or remedy; or geographical region, etc. Simulations can be carried out by changing the input spreadsheets, e.g. system levels effects by changes at the component level. Example of analysis is given in the figures below.

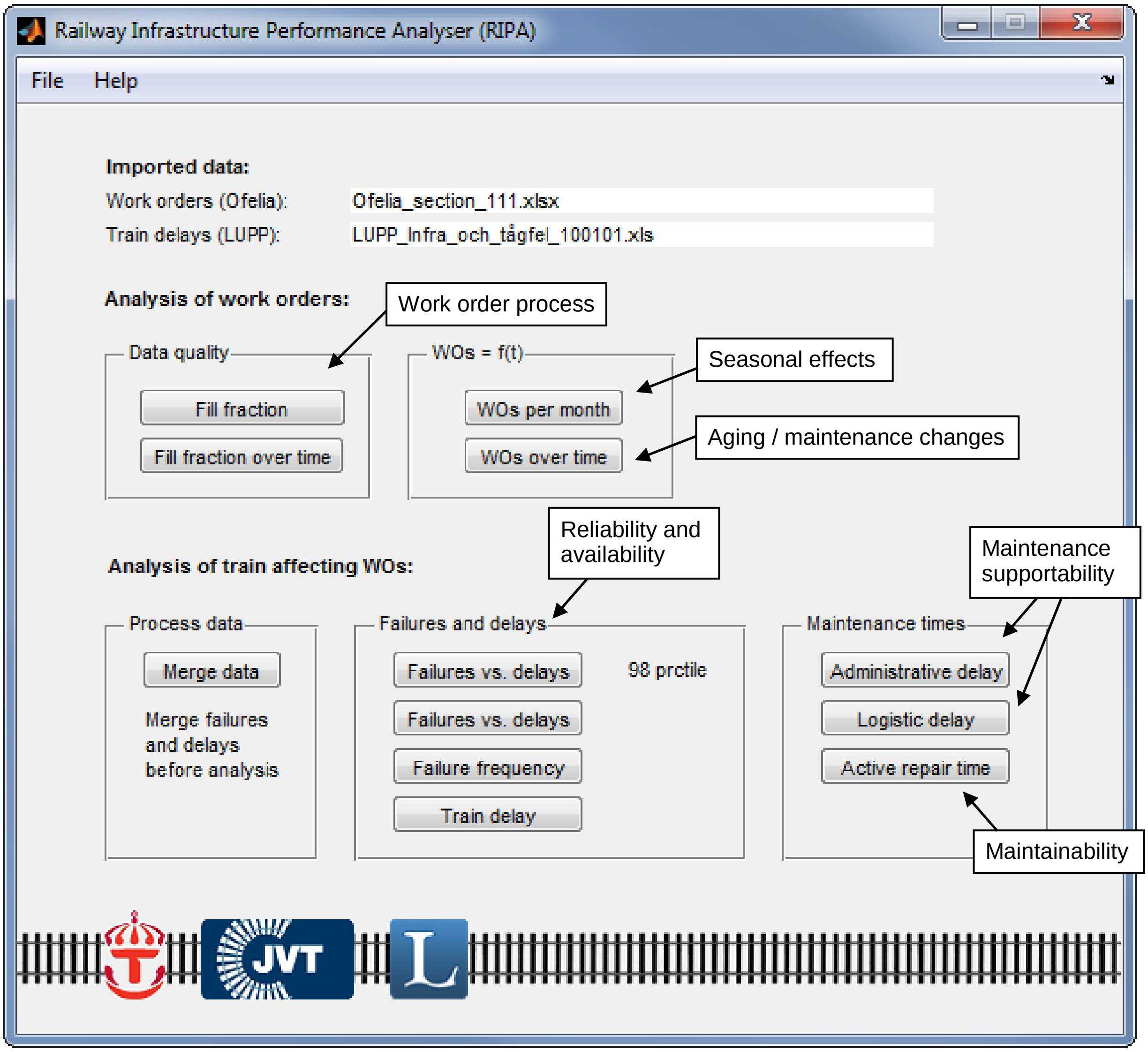

Figure B.1: The graphical user interface of the demonstrator.

Analysis of data field uses in failure work orders

Analysis of failure work order (WO) data field usage rate, i.e. part of data quality, and analysis of failure as a function of time. The data is from 2001.01.01-2012.01.01 of railway section 111 of the Swedish Iron Ore Line, stretching from Kiruna city to Riksgränsen border of Norway. The total number of work orders is 9 815.

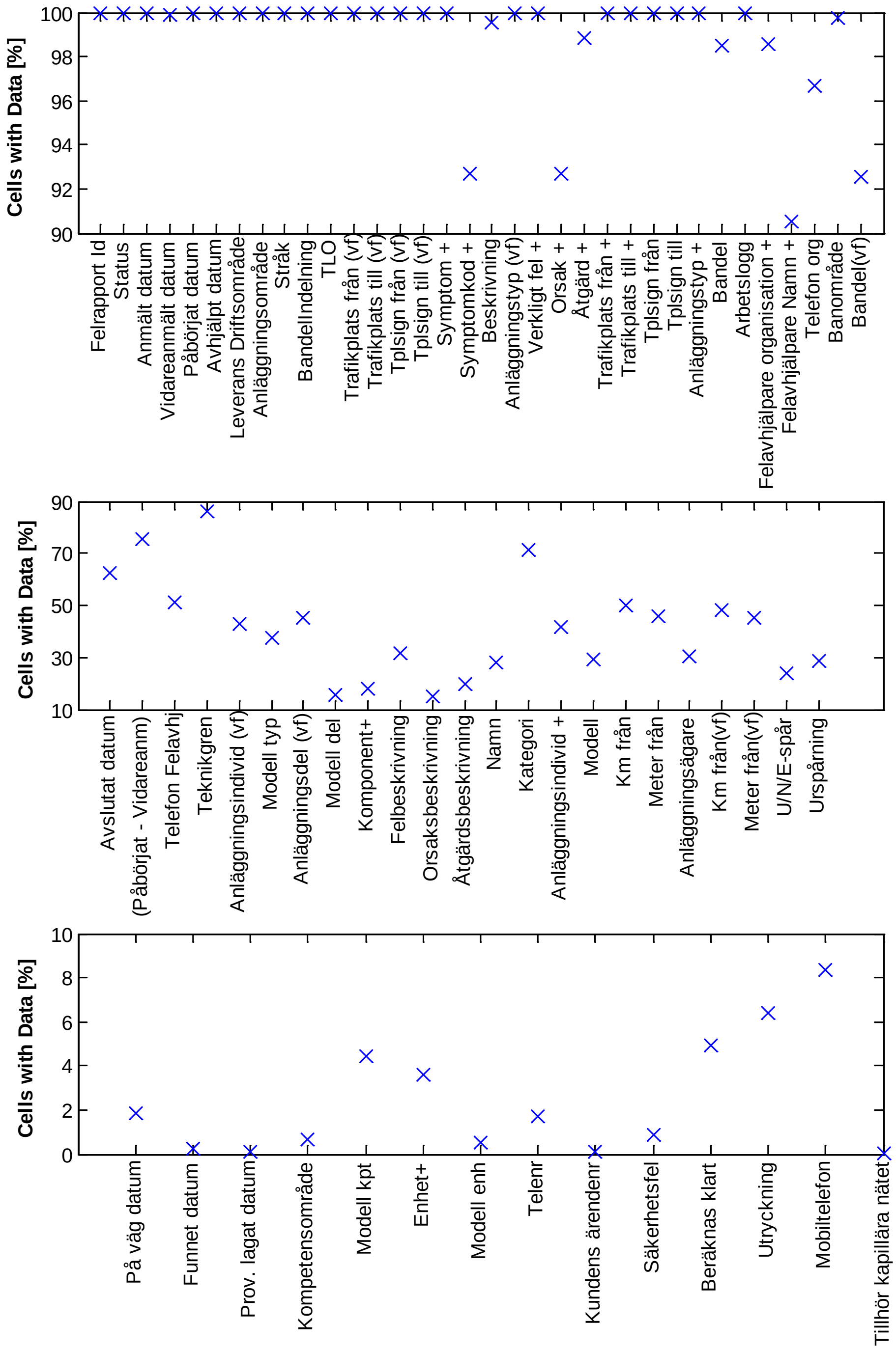

Figure B.2: Fill fraction of the 71 work order fields. x-labels are in Swedish. Discussion in Section 3.2.

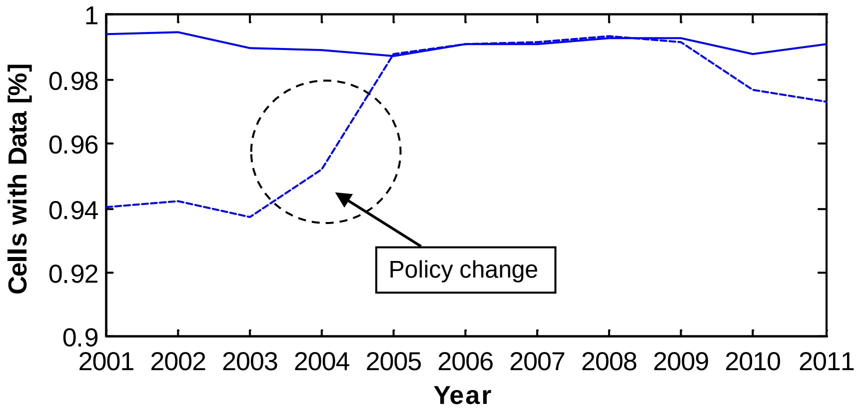

Figure B.3: Work order data fill rate over time. The solid line equals the mean fill rate of fields with a fill rate above 90 %. The dashed line equals the mean fill rate of fields with a fill rate above 80 %.

Analysis of work orders over time

Work orders over time provides information on seasonal effects, aging of facilities and maintenance policy. The data used is the same as in the previous section. See Figures B.4 and B.5.

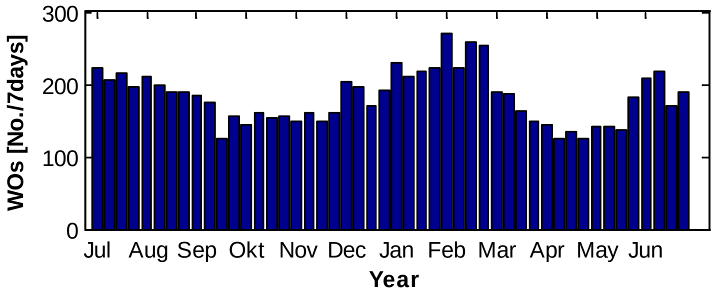

Figure B.4: Work orders per seven days. 12 years mean.

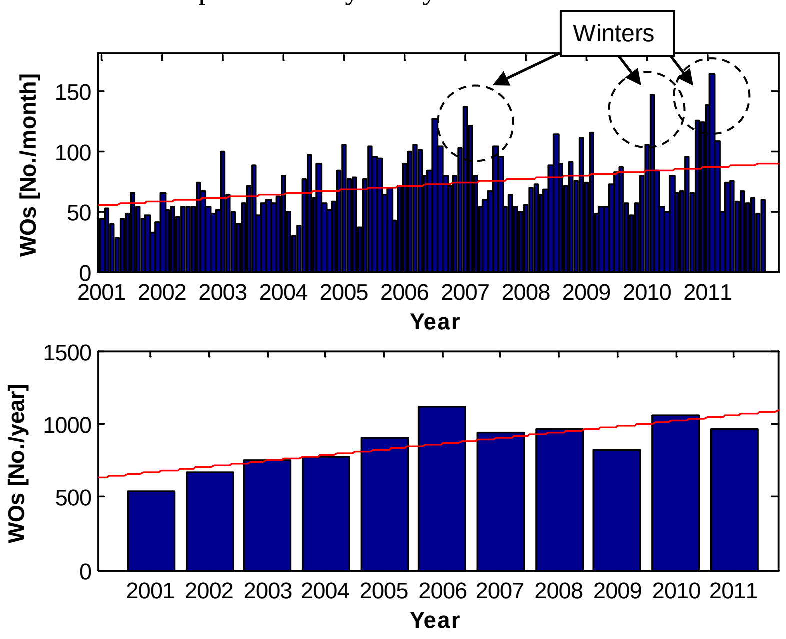

Figure B.5: Failures over time (increasing).

Analysis of train affecting failure work orders

The computer system and process for registration of train delays at Trafikverket was changed in 2009. Data analysis before and after the end of 2009 is therefore preferably analysed separately. The demonstrator can analyse the data both before and after the system change.

The analysis below is between 2010.01.01-2012.03.27. The number of work orders giving train delays are 686 out of 2 222 work orders. The analysis is on the 686 work orders, which includes: 562 infrastructure failures; 82 wheel and pantograph; and 42 animals in the track.

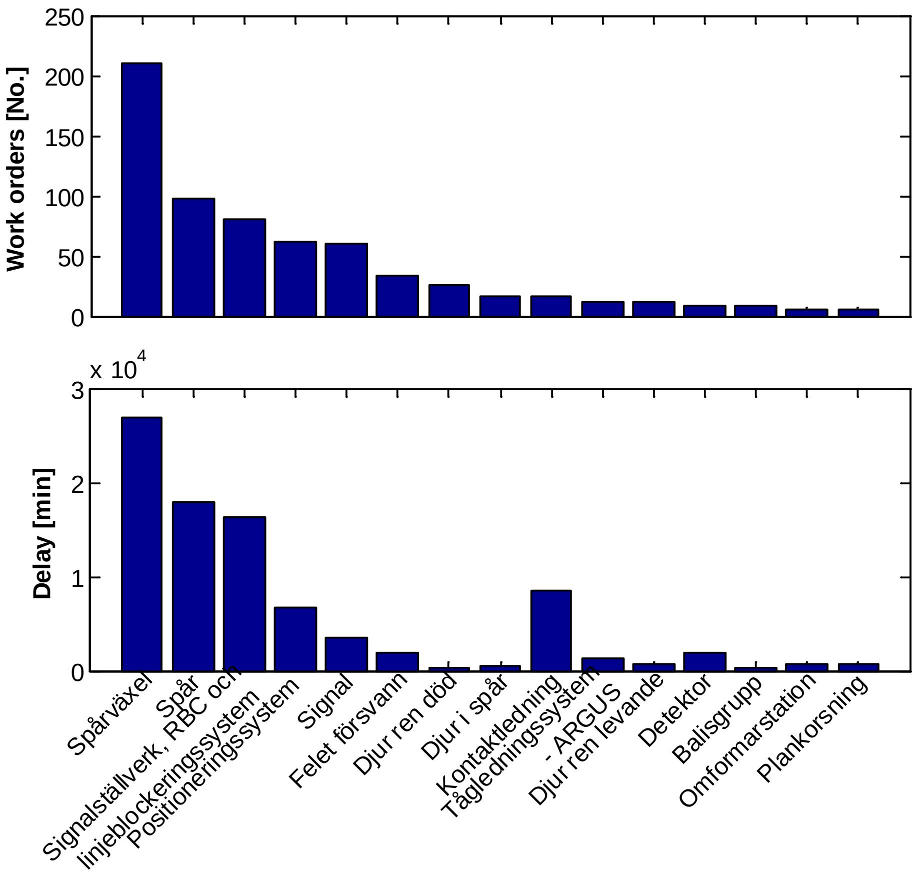

Figure B.6: Failures and corresponding delay at the system level. All work orders are considered.

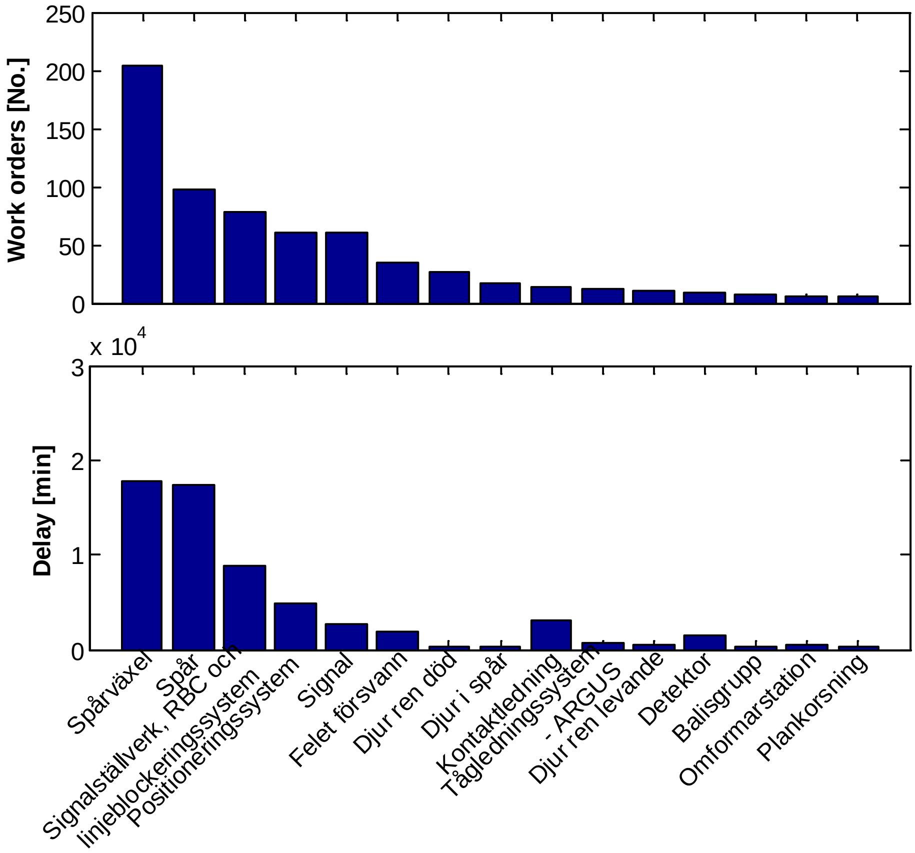

Figure B.7: Failures and corresponding delay at the system level. The 2 % of work orders giving the longest train delays are left out. Compare to Figure B.6.

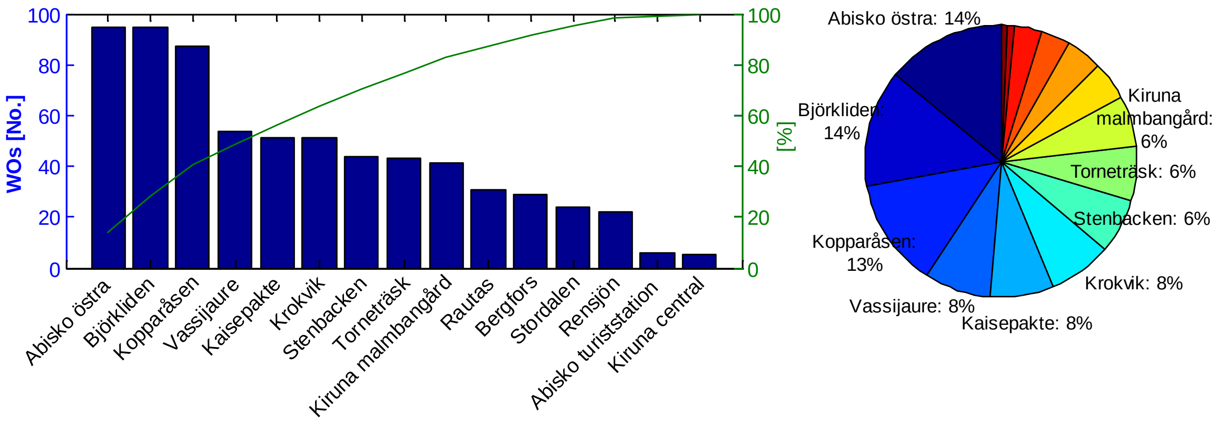

Figure B.8: Pareto and pie charts of railway subsections, i.e. geographical position.

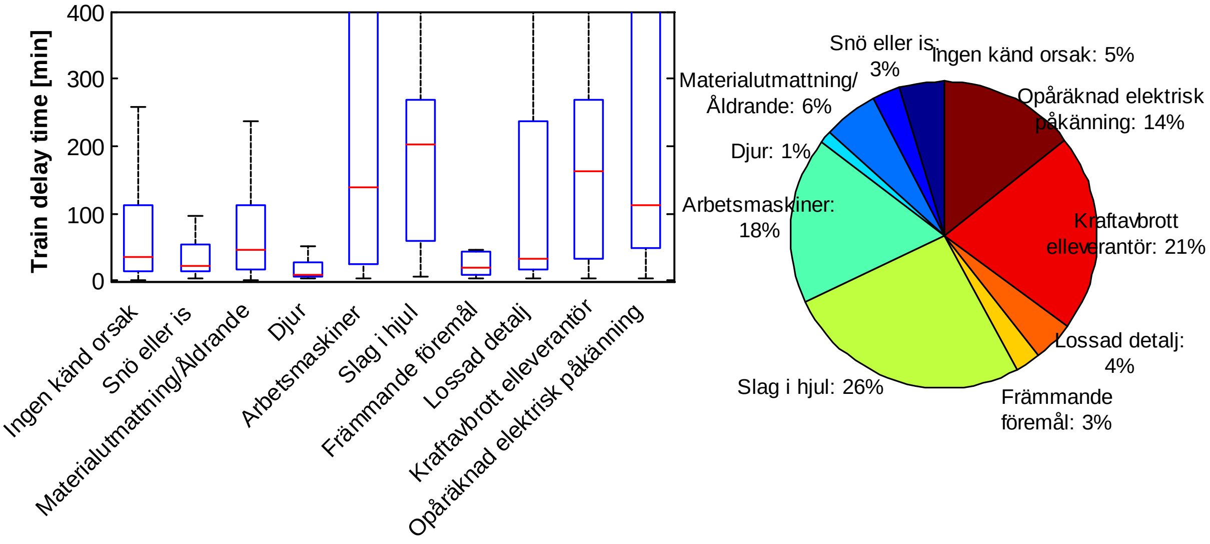

Figure B.9: Boxplot and pie charts of failure causes. Boxplot: the central mark is the median, the edges of the box are the 25th and 75th percentiles, and the whiskers extend to 1.5 IQR (interquartile range). The pie chart is based on the medians.

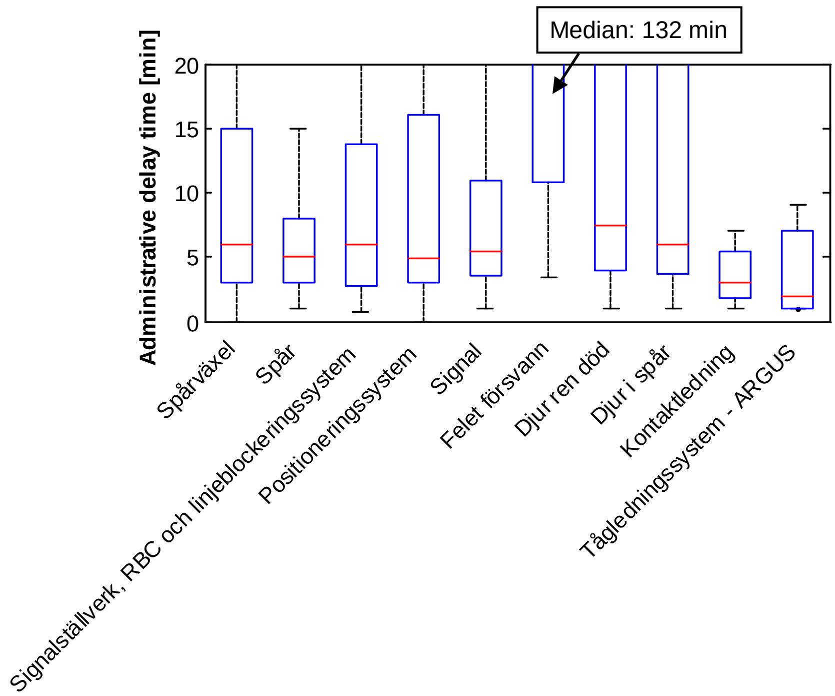

Figure B.10: Administrative delays; Operation central notification to maintenance contractor notification.

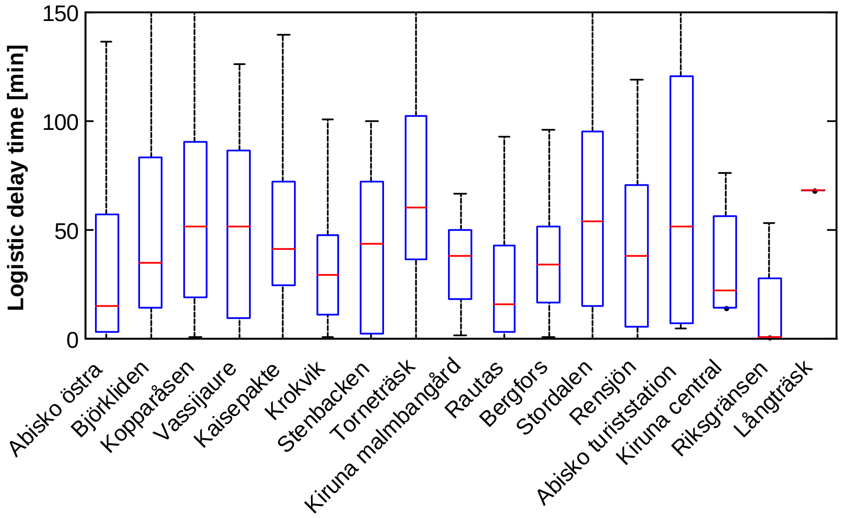

Figure B.11: Logistic delays per subsection (geographical location); Time for maintenance crew to arrive.

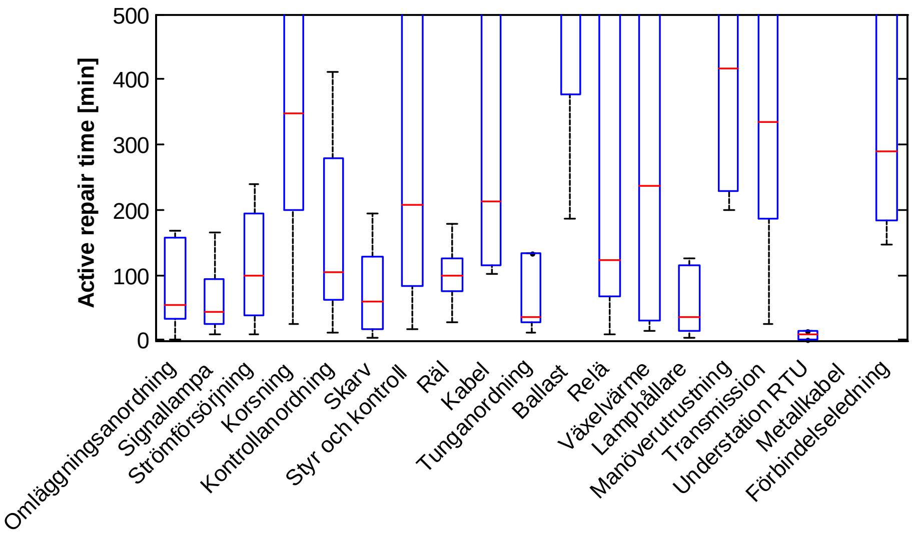

Figure B.12: Active repair times per subsystem level.

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