Link and Effect Model for Performance Improvement of Railway Infrastructure

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ABSTRACT

Railway traffic has increased over the last decade and it is believed to increase further with transportation shifting from road to rail, due to rising energy costs and the demand to reduce emissions. To manage railway infrastructure assets effectively against agreed-upon and set objectives, performance must be measured and monitored. Different systems are used to collect and store data of traffic, failures, inspections, track quality, etc., for subsequent analysis and data exchange. Performance indicators (PIs), e.g. for RAMS (reliability, availability, maintainability, safety), are continuously developed to support infrastructure managers (IMs) in identifying performance killers in order to make efficient and effective decisions. However, they are often *ad hoc* and seldom standardised. Moreover, the use of standards and the need for harmonisation of railway operations have grown with interoperability, e.g. building of a trans-European railway network. The efficiency and effectiveness of railway infrastructure can be improved if an appropriate performance measurement (PM) system is identified and specifically developed. In traditional PM systems, PIs are given threshold values, indicating when an action needs to be taken, i.e. they can to some extent be reactive. Also, PIs are often aggregated measures, which can make them abstract. By this trend in transportation and shortcomings in performance measurement, there is a need to improve the strategic planning and measurement of performance for more proactive decision making and future standardisation.

In this research, a link and effect model for performance improvement of railway infrastructure is developed. It provides a continuous methodology for breaking down objectives into operational requirements and linking them to results, using performance indicators, and algorithms for data analysis and simulation, for decision support.

Keywords: railway infrastructure, performance, RAMS, maintenance, dependability, indicators, link and effect, decision support

LIST OF APPENDED PAPERS

Paper A
Stenström, C., Parida, A., Kumar, U., and Galar, D. (2012) Maintenance value drivers, killers and related indicators. Accepted for publication in: *International Journal of Strategic Engineering Asset Management.*

Paper B
Stenström, C., Parida, A., and Galar, D., Performance indicators of railway infrastructure. Submitted for publication in: *International Journal of Railway Technology.*

Paper C
Stenström, C., Parida, A., Galar, D., and Kumar, U., Link and effect model for performance improvement of railway infrastructure. Submitted for publication in: *Journal of Rail and Rapid Transit.*

LIST OF RELATED PAPERS

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

Stenström, C., Famurewa, S. M., Parida, A., and Galar, D. (2012) Impact of cold climate on failures in railway infrastructure. Accepted for publication in: *2nd International Conference on Maintenance Performance Measurement and Management (MPMM2).*

Kumar, U., Galar, D., Parida, A., Stenström, C., and Berges, L. (2011) Maintenance performance metrics: A state of the art review. Galar, D., Parida, A., Schunnesson, H., and Kumar, U. (eds.), *1st International Conference on Maintenance Performance Measurement and Management (MPMM)*, 13-15 Dec., pp. 3-34, Luleå University of Technology.

Galar, D., Stenström, C., Parida, A., Kumar, R., and Berges, L. (2011) Human factor in maintenance performance measurement. *Industrial Engineering and Engineering Management (IEEM), 2011 IEEE International Conference on*, 6-9 Dec. 2011, pp. 1569-1576.

Galar, D., Parida, A., Kumar, U., Stenström, C., and Berges, L. (2011) Maintenance metrics: A hierarchical model of balanced scorecard. *Quality and Reliability (ICQR), 2011 IEEE International Conference on*, 14-17 Sep. 2011, pp. 67-74.

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ACKNOWLEDGMENTS

Christer Stenström
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Part I

CHAPTER 1

Thesis introduction

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

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

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

1.1 Background

1.1.1 The need for railways

Railway traffic has increased over the last decade and it is believed to further increase 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 [1, 2]. 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 [2]. At the same time, the crude oil output reached its all-time peak in 2006 [3]. The available capacity of the railways has to be enhanced and become more green if we are to meet these new transportation demands.

1.1.2 The need for measuring performance

As railways are capital intensive and have a long life span, their management 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 management objectives and strategies must steer operation and maintenance activities in the right direction. Overarching objectives must be broken down into quantitative operation and maintenance objectives to achieve a high level of robustness, punctuality and capacity within the operational budget, at the lowest life cycle cost, with no or an acceptable level of risk. For further discussion of developing maintenance strategies for railway infrastructure, see [4].

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 developed for, and applied to, railway infrastructure maintenance activities. Measuring entails data collection, but since raw data does not give any information by itself, it must be analysed. This consumes resources, especially if the wrong things are measured, 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 [5]. It is more important to know whether the trend is up or down and how the current value compares to historical measures. Consistency is therefore especially important to capture long term trends, predict future development and take the appropriate corrective actions at an early stage. Moreover, since there are many players 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.

In traditional PM systems, PIs are given threshold values, indicating when an action needs to be taken, i.e. the PIs can to some extent be reactive. Also, PIs are often aggregated measures, which can make them abstract. In the link and effect model studied here, PIs are analysed with emphasis on the underlying performance drivers and killers, giving vital information for improvements and future development of the PIs.

Lastly, it is essential to thoroughly analyse what to measure, as large costs and equally large savings are associated with measuring.

1.1.3 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 [6, 7]. The resulting necessity to harmonise and standardise the operation of railways has led to increased use of standards. Harmonisation and standardisation of strategic planning and performance measurement practices enables the use of comparison to determine best practice, i.e. benchmarking. Not least, standardisation can reduce the need for discussions of definitions and practices [8].

1.2   Problem statement

Congestion of roads and sky, increasing energy costs and the need to reduce emissions have led to the increased usage of railways and the consequent need for more capacity [1, 2]. 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 been shown to improve business performance, creating more efficient and effective management [9, 10]. However, the implementation process of such systems is critical for their success [11, 12]. Schneiderman [12] has noted that to be successful, 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, indicating the weaknesses of traditional performance measurement (PM) systems. Traditional PM systems commonly rely on a set of PIs with thresholds; these give a signal if a threshold is passed, i.e. they can make the system reactive if not appropriately used. Moreover, PIs can be abstract, signaling failure but not indicating the underlying factors responsible. With better PM systems, rail transport can meet the requirements of capacity and deliver a dependable mode of transportation.

In this work, a PM system is developed for railway infrastructure, namely, a link and effect model. In this model, strategic planning is connected to performance measurement with an emphasis on the underlying performance drivers and killers, rather than on thresholds as in traditional PM systems.

1.3   Purpose statement

The purpose of this research is to develop a link and effect model to improve the performance of railway infrastructure by facilitating better decision-making.

1.4   Research questions

To fulfill the above purpose, the following research questions must be answered:

RQ 1 How can the indicators drive the organisation to achieve the maximum return on investment?

RQ 2 Which indicators are used for measuring railway infrastructure performance and how can they be grouped to improve the performance?

RQ 3 How can performance improvement of railway infrastructure be measured by a link and effect model?

1.5   Objectives

More specifically, the objectives of this research are:

1. Mapping railway infrastructure operation and maintenance at a higher/strategic level (RQ 1)

2. Reviewing how to measure investments and improvements in maintenance (RQ 1)

3. Mapping railway infrastructure performance indicators (RQ 2)

4. Creating a link and effect model for maintenance decision support, using a top-down and bottom-up approach (RQ 3)

5. Carrying out a case study to demonstrate the link and effect model, i.e. breaking down objectives, analysing data for performance killers and suggesting improvements (RQ 3)

1.6   Interlinkage of purpose, research questions and papers

The interlinkage between the research questions and the technical report/papers published is shown in Figure 1.1 below.
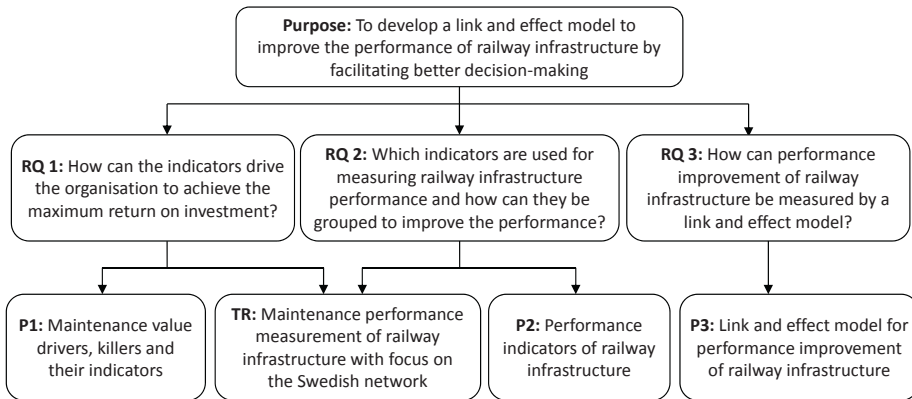
Figure 1.1: Interlinkage of purpose, research questions, technical report (TR) and papers (P1-3).

1.7 Scope and limitations

Based on the research questions and objectives, the scope of the research is limited to:

- Performance of railway infrastructure, i.e. aspects like rolling stock or contracting are not considered

- A case study is to be carried out to demonstrate the link and effect model, which is limited to specific indicators and their main underlying performance killers

1.8 Outline

Problem description and justification of the research appear in this chapter. Further literature review is found in the next chapter, along with the technical report. Chapter 3 contains the research methodology, and Chapter 4 has a summary of the technical report and the appended papers. Results and research questions are discussed in Chapter 5, and finally, conclusions, contributions and scope for further research are derived in Chapter 6.

CHAPTER 2

Literature review

This chapter goes through basic concepts and definitions related to the research subject.

2.1 Performance measurement

Performance measurement can be described as the process of quantifying the efficiency and effectiveness of action [13] 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 [14]. 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 [15].

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 [16].

2.2 Scorecards and performance measurement systems

With increasing competition, internationalisation and HSE (health, safety and environmental) legislation, traditional accounting with only financial measures is insufficient to assess business performance [17, 18]. New performance measurement methods, score-

cards and frameworks have been developed to take into account quantitative and qualitative non-financial measures, including efficiency, effectiveness, internal and external perspectives [19, 20, 9, 21]. 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 [22, 23, 24, 25, 26, 27].

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 [28, 29].

As the maintenance function constitutes a key element in business success [30, 31, 32], it has benefited from the development of more holistic and balanced performance measurement systems. As maintenance accounts for a large part of the costs in many businesses, improvements can result in large savings, as shown in work by [33, 34, 35, 36, 37, 38, 39]. The evolution of maintenance from a necessary evil to a valuable and integral part of the business process is described in research by [40].

Maintenance differs from other business functions by being multidisciplinary; it is largely engineering but its values are hard to measure in simple financial terms [37].

Maintenance performance measurement (MPM) has been extensively reviewed by [41, 42, 43, 44]. See also work by [45] for various developed MPM frameworks/scorecards.

2.4 Performance measurement of railway infrastructure

This subject is reviewed and discussed in the technical report that is a part of this study but not appended. 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 [9, 10], however, implementation issues exists. Some claim that 70 % of scorecard implementations fail [46]. In a literature review, Bourne et al. [11] list 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 [11] 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 [47] have listed several of the issues recorded by [11] and have stressed problems which result first from hiring inexperienced consultants and second from overlooking strategy, instead introducing a rigorous data collecting computer system. Davenport et al. [48] 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. [49] 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 [50]. 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 forgotten.

2.6   Quality of service and dependability

Quality of service can be described as: the collective effect of service performance which determines the degree of satisfaction of a user of the service [28]. Dependability, an element of service quality, is a central term in maintenance that demonstrates its complexity in a dense form. It is a collective term used to describe the availability and its influencing factors: reliability, maintainability and maintenance supportability [28, 29]. See Figure 2.1, which is an important input to Paper C.
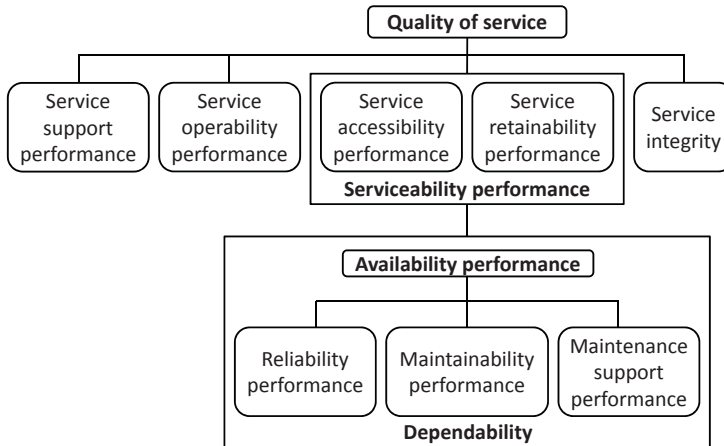
Figure 2.1: Quality of service. Adapted from [28].

2.7   Strategic planning

Strategic planning can be described as the process of specifying objectives, generating strategies, and evaluating and measuring results [51]. The terminology of strategic planning can vary between organisations and researchers. The following list describes the key components of strategic planning, deduced from [52, 53, 54, 55, 9, 21] and from maintenance focused work by [32, 45, 29]:

- Vision: outlines what the organisation wants to achieve

- Mission: outlines the organisations purpose. 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: are the desired long term results that are to be reached to come closer to the vision

- Objectives: midterm or short term specific actions with specific quantitative values. Objectives can also be an overarching term for goals and objectives

- Strategy: planning actions to achieve objectives

- Key result areas (KRAs): areas where results are visualised, e.g. maintenance

- Critical success factors (CSFs): the factors required to achieve the objectives of the KRAs, e.g. fewer failures in physical assets

- Performance indicator (PI): quantitative assessment of some activity, process, audit, physical asset, etc.

- Key performance indicator (KPI): a PI of special importance comprising a single or an aggregated measure

- Indicators, metrics and measures: general terms of measurable factors on a scale

- Parameters: low level measures, often without aggregation

2.8   Performance drivers and killers, and cost drivers

A performance driver is a supporting input element to a process, driving the process or business performance, while a performance killer is an input element to a process that performs poorly or hinders performance. Performance killers are similar to cost driver but more intangible since it does not directly affect costs.

These terms are discussed in appended Paper A.

2.9   Asset management

Asset management can be described as the process of maintaining assets, both tangible and intangible. There are many definitions of asset management, often built around terms like life cycle cost and risk. Various definitions can be found in a study by [56].

2.10   Model and process

Both the terms model and process are extensively used in this study and in the description of the link and effect model. A process is a set of interrelated tasks that together transform inputs into outputs [57, 58, 59], while a model is a standard for imitation or comparison [60].

CHAPTER 3

Research methodology

Research and experimental development comprise creative work undertaken on a systematic basis to increase the stock of knowledge, including knowledge of man, culture and society, and the use of this stock of knowledge to devise new applications [61]. Research, in its simplest form, can consist of three steps [62]:

1. Posing a question

2. Collecting data to answer the question

3. Presenting an answer to the question

Scientific research, also known as scientific inquiry or scientific method, is often misrepresented as a fixed sequence of steps; rather, it is a highly variable and creative process [63]. The choice of steps in research can therefore vary between subjects and researchers. For further discussion, see for example [64].

3.1 Research design

The research in this thesis has been designed in the following way, using deductive reasoning, i.e. from general to more specific:

1. Background: identifying the research problem, using a literature review in the subject area to identify gaps in the knowledge

2. Problem statement: presenting the problem and possible solution, as postulated by this study

3. Purpose statement: presenting the overall goal of the study

4. Research questions: specifying the purpose

5. Objectives: specifying the research questions, and supplementing the research questions to guide the study

6. Gathering data: both quantitative and qualitative data are collected

7. Analysis of data: transforming data into information

8. Conclusions: deduced from the information

An alternative research design is to use hypotheses. Research questions and hypotheses are similar in that both narrow the purpose statement [65]. However, hypotheses are predictive, proposed explanations subject to testing.

Research steps 1-5 have been reviewed in Chapter 1; the next step is gathering data. Literature review and interviews were used to build a foundation and to answer the dissertations RQ 1 and 2, resulting in Paper A, Paper B, the technical report, and the literature review in Chapter 2. The link and effect model, described in Paper C, and responding to RQ 3, was developed after further literature study, gathering railway operation and maintenance historical data and analysis. Matlab software was used to analyse the data and develop a demonstrator.

3.2 Gathering data

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

3.2.1 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, as this related to Trafikverket and the railway network in Sweden. The questions included the following:

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

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

- Is there any documentation related to the strategic planning and planning of maintenance, e.g. policies, handbooks, strategies?

- How is railway infrastructure performance measured?

- What performance indicators are used?

- Can you tell me about the outsourcing of maintenance?

In addition to interviews, meetings with Trafikverket took place every second to third month to discuss the progress, issues and future direction. See Table 3.1 for interviewees' positions at Trafikverket.

Table 3.1: 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*

3.2.2   Literature review

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

- Railway peer review journal and conference papers

- 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

3.2.3   Gathering operation and maintenance 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

3.3   Analysis of operation and maintenance data

The link and effect model is built around four steps, see Paper C. The third step concerns data analysis. Operation and maintenance data of a Swedish railway section were collected for a case study; data consisted of corrective maintenance work orders and train delays. See Paper C for details of the data. Each maintenance work order consists of 71 data fields; while extensive information can be extracted, one can question if all data are vital. Matlab software was used to integrate work orders with train delay data, for basic control of data quality, and for data analysis. Algorithms were developed to take raw spreadsheets as inputs for efficient analysis and to make simulations possible by modifying the input spreadsheets. A graphical user interface was created to enhance efficiency and to create a demonstrator. The analyses include the following:

- Integration of data: processing spreadsheets and connecting train delays to work orders (Figure 3.2)

- Basic data quality check: analysing the usage of each data field within the work orders (Figure 3.1), i.e. calculating of empty cells; and analysing of data consistency over time

- Work orders: analysing the number of work orders per system, component, geographical region, failure symptom, failure cause, remedy and over time

- Train delay: calculating the percentage of work orders causing delays and calculating delays per system, component, geographical region, failure symptom, failure cause, remedy, etc.

- Maintenance times: determining administrative delays, logistic delays and active repair times per system, component, geographical region, failure cause, etc.

- Simulation: testing showed that modification of the data at the component level of switches and crossings can be seen on the indicators at the system level in terms of risk ranking, failures, delay and maintenance times. It is then possible to simulate the effect on system level before carrying out improvements at the component level

The method is efficient at the cost of effectiveness, as the data cleaning process is simple. Data quality was analysed by studying the usage of the data fields within the work orders. This method was used for Paper C to identify the frequently used fields of the work orders. See Figure 3.1 below.
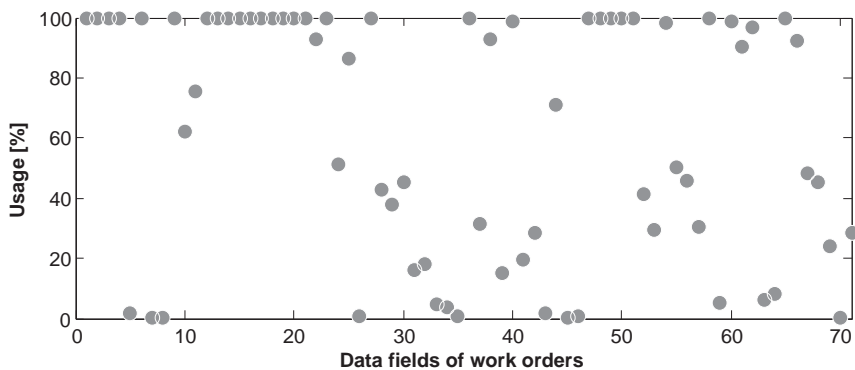
Figure 3.1: Usage of work order fields. 34 fields are used in over 90 % of the work orders.

The resulting figures generated by the algorithms used in the case study of Paper C were verified manually with the input spreadsheets. To demonstrate the algorithms, the integration of data is illustrated in a flowchart; see Figure 3.2.
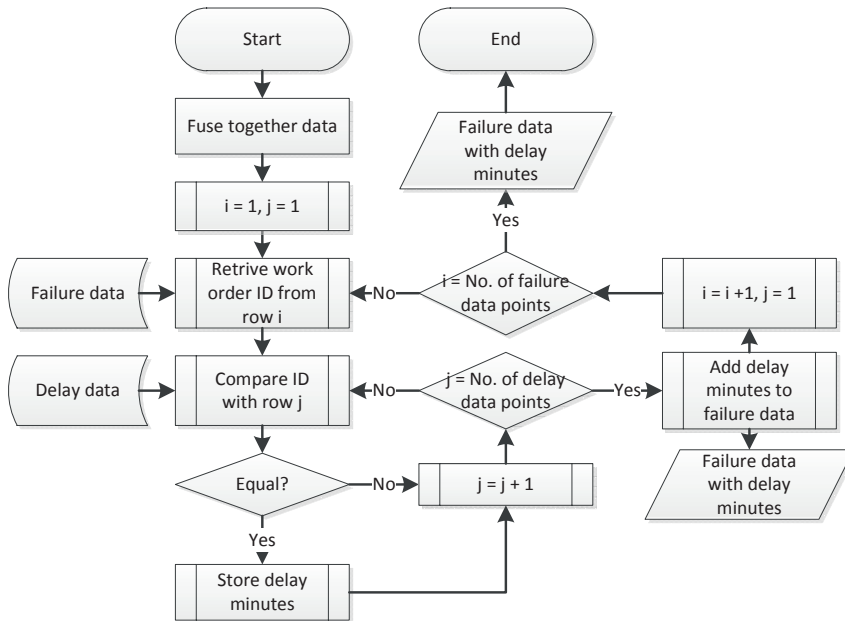
Figure 3.2: Flowchart of the integration of data algorithm.

CHAPTER 4

Summary of the technical report and appended papers

4.1 Technical report

Purpose: Review the maintenance and performance measurement of railway infrastructure with a focus on Sweden.

Findings:

- Performance indicators (PIs) were identified by reviewing research papers, European railway project reports and documents from the Swedish infrastructure manager, Trafikverket, e.g. policy documents and handbooks. The PIs were categorised into a scorecard according to European standards for maintenance key performance indicators, EN 15341 [66], and the infrastructure asset structure of Trafikverket. About 130 indicators were mapped; similar indicators were treated as the same, but some indicators can be found twice, e.g at system and component levels

- Several maintenance scorecards of European infrastructure managers were identified by reviewing research papers and project reports

- Punctuality and regularity are preferably studied together. Canceled trains (lower regularity) can increase the punctuality and vice versa; few canceled trains can decrease the punctuality. Negatively correlated indicators should therefore be presented together, e.g. punctuality and regularity. This could prevent suboptimising

- The literature review of quantitative research projects with statistical results showed that the raw 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. Performance measurement systems need to be dynamic with continuous improvement (kaizen)

4.2 Paper A

Purpose: Map the most essential indicators for assessment of the net present value (NPV) of value driven maintenance (VDM); to this end, review the terminology of performance drivers and killers.

Findings:

- Performance drivers and killers, and related terminology are identified after a review of the literature

- Indicators for calculating the NPV are identified through European standards on maintenance key performance indicators (KPIs), EN 15341 [66]. The KPIs of the standard are constructed by taking the ratio of two factors, or PIs. The factors (numerators and denominators) are seen as level 0 indicators, the easiest to calculate and the most essential to a business. Identified indicators are grouped according to level 0 indicators and level 1-3 indicators

4.3 Paper B

Purpose: Map and group PIs of railway infrastructure and compare with indicators of European standards on maintenance KPIs, EN 15341 [66].

Findings:

- PIs are identified by reviewing research papers, European railway project reports and documents of the Swedish infrastructure manager, Trafikverket, e.g. policy documents and handbooks. The PIs are categorised into a scorecard according to EN 15341, and the infrastructure asset structure of Trafikverket. About 130 indicators are mapped; similar indicators are treated as the same, but some indicators can be found twice, e.g at system and component level

- The key performance indicators (KPIs) of EN 15341 are constructed by taking the ratio of two indicators, or factors (numerators and denominators). 13 KPIs of the standard are found to be similar to combinations of railway indicators.

4.4 Paper C

Purpose: Develop a link and effect model to improve the performance measurement system of railway infrastructure by facilitating better decision-making.

Findings:

- In traditional performance measurement systems, PIs are given threshold values, indicating when an action needs to be taken, i.e. they can be reactive if used wrong. Also, PIs are often aggregated measures, which can make them abstract and the underlying factores responsible for the performance unknown or forgotten. A link and effect model was therefore design to emphasize on the underlying performance drivers and killers, rather than the thresholds as in traditional performance measurement systems

- The link and effect model is constructed as a four step continuous improvement process. The goal of the first step is to align the strategic planning of different stakeholders within the same frame. In the railway business, the various stakeholders use key components of strategic planning differently and to varying extents; thus, an experienced person is required to unite strategic, tactical and operational planning within a common terminology and on a top-down basis

- A case study is carried out with algorithms developed for data analysis and simulation. Systems and components of railway infrastructure are analysed in terms of work orders, train delays, repair times and the corresponding risk ranks, i.e. identifying performance drivers and killers. The analysis ends with presenting train delays with continuously updated underlying performance killers, fulfilling one of the main goals of the link and effect model

- Simulations showed that changes at component level are seen in indicators at the system level. In other words, it is possible to simulate the effect at the system level before carrying out improvements at the component level.

See Paper C for figures on work orders, train delays, repair times and corresponding risk ranks of various subsystems.

CHAPTER 5

Results and discussion

5.1 First research question

RQ 1: How can the indicators drive the organisation to achieve the maximum return on investment?

The answer to RQ 1 is provided in the technical report and Paper A (Ch.1: Figure 1.1).

Technical report: A review of the literature on the maintenance of railway infrastructure in Sweden and interviews finds that performance measurement tools and practices are often used in an *ad hoc* manner and that trend tracking is often lost due to new ways of calculating or measuring, e.g. changes in policies. Improvements in maintenance can be measured with proper indicators and trend tracking. Therefore, the technical report also maps indicators related to maintenance, which corresponds to RQ 2.

The review of the literature and the interviews also consider data aggregation. Punctuality and regularity are two PIs in the railway business. These PIs are preferably studied together, giving a measure of effectiveness. Cancelled trains (lower regularity) can increase punctuality and vice versa; fewer canceled trains can decrease punctuality. 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:

$$Railway\ effectiveness = Regularity^a \times Punctuality^b \in [0, 1] \tag{5.1}$$

$$ORE = Regularity^a \times Punctuality^b \times TQI^c \in [0, 1] \tag{5.2}$$

The constants a, b and c can be chosen for giving different weights to the parameters to satisfy specific needs. See Figure 5.1 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. Moreover, by combining these two indicators into one independent variable, management can concentrate on the most vital indicators.
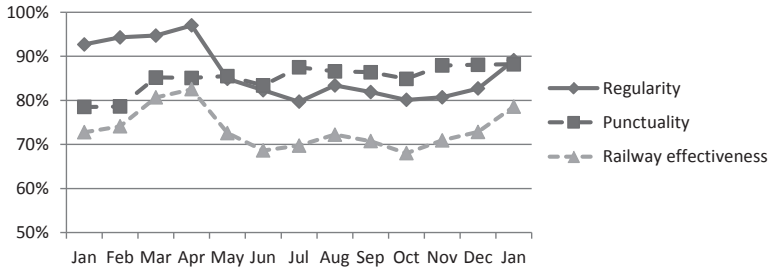
Figure 5.1: Railway effectiveness of the Swedish railway network from Jan 2011 to Jan 2012. The constants a and b equals one. Adapted from the technical report

Paper A: The first paper discusses the use of net present value (NPV) in maintenance, i.e. value driven maintenance (VDM). As the impact from investments in maintenance on production and customers are intangible in many aspects, the value of maintenance is hard to estimate. After the literature review and interviews (technical report), the study selected NPV to measure the investments and changes in maintenance, since managers of maintenance, operation and finance can all recognise and understand it, i.e. all players can perceive involvement. However, NPV requires that reliability can be measured, which, in turn, requires certain performance indicators. The purpose of Paper A is therefore to identify the most essential indicators for implementing VDM. Since there is no standard on performance indicators for linear assets, such as railways, the European standards EN 15341 [66] is chosen. Once railway indicators are linked to the European standard and the indicators of the European standard are linked to VDM, it is possible to link together railway indicators, to VDM grounded in a well known standard. Standardised indicators facilitate external benchmarking and the net present value of VDM makes investments in maintenance understandable by all stakeholders.

5.2 Second research question

RQ 2: Which indicators are used for measuring railway infrastructure performance and how can they be grouped to improve the performance?

The technical report and Paper B provide the answer to RQ 2 (Ch.1: Figure 1.1).

Technical report and Paper B: Performance indicators are identified by reviewing research papers, European railway project reports and documents from the Swedish infrastructure manager, Trafikverket, e.g. policy documents and handbooks.

The indicators used for managing railway infrastructure are somewhat comprehensive, and are therefore grouped into two overall groups with a number of subgroups. The two overall groups are: managerial and infrastructure condition indicators. The managerial indicators are extracted from different computer systems, e.g. enterprise resource planning (ERP), computerised maintenance management software (CMMS), etc., excluding condition monitoring (CdM) data. The infrastructure condition indicators group consist of all the indicators extracted by sensors and various inspection methods in the railway network. Managerial indicators are closer to a higher/strategic level compared to CdM indicators that are closer to the operational/lower level. See Figure 5.2

Increased interoperability and building of a trans-European railway network requires harmonisation and standardisation of the management, which have led to increased use of European standards. The identified managerial PIs have therefore been grouped according to European standard EN 15341 [66], i.e. economical, technical and organisational. In the standard, the health, safety and environmental PIs are in the technical group, but these indicators have been considered to have such importance for railways that they have been put into a separate group. The managerial indicators consists therefore of four groups, or key result areas (KRAs).
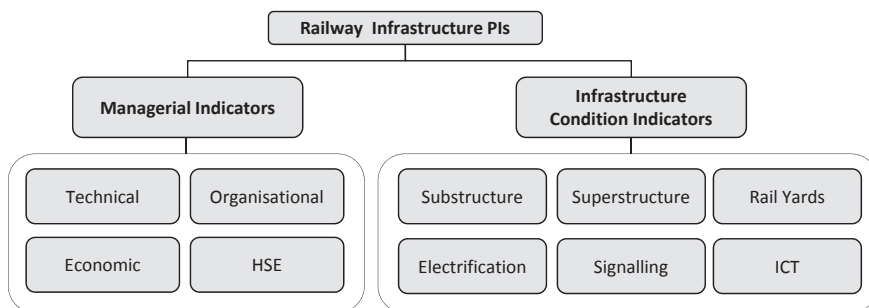
Figure 5.2: Structure of the railway infrastructure PIs.

About 130 indicators are mapped, similar indicators are treated as the same, but some indicators can be found twice, e.g. at system and component levels. Nevertheless, the indicators need to be studied in detail specific to IMs' requirements, as top management should focus on the most vital independent variables.

Paper B: The key performance indicators (KPIs) of EN 15341 are constructed by taking the ratio of two indicators, or factors (numerators and denominators); 13 KPIs of the

standard are found to be similar to combinations of railway indicators. These indicators in common should be given special concern in designing of railway scorecards since they have the potential to be used for external benchmarking.

5.3   Third research question

RQ 3: How can performance improvement of railway infrastructure be measured by a link and effect model?

Paper C answers RQ 3 (Ch.1: Figure 1.1).

Paper C: After relevant research, success and failure criteria of improvement initiatives were listed. Among other keys, improvement initiatives need to be understandable by all stakeholders, regardless of organisational levels, both internally and externally. The link and effect model is therefore built as a four step continuous improvement (kaizen) process for high survivability and to be dynamic (Figure 3).

In traditional performance measurement systems, PIs are given threshold values, indicating when an action needs to be taken, i.e. they can be reactive if used wrong. Since the PIs have only historical data, the underlying factors responsible for the performance are not considered before a threshold is passed, thus some PIs can be intangible and turned into black boxes. This is an issue since PIs are often aggregated measures of several indicators, e.g. delays in production or overall equipment effectiveness. In contrast, the link and effect model is designed with emphasis on performance drivers and killers, rather than on thresholds. By presenting indicators with continuously updated underlying factors, i.e. performance drivers and killers, the user is provided knowledge of the indicator and can act in a more proactive manner.

The model is validated in a case study, breaking down objectives from a European to a national (Swedish) level, followed by data analysis and simulation at system and component levels for performance drivers and killers. Data for a specific railway section is collected for a period of nine years. After data quality verification, algorithms for analysis of indicators are developed to identify performance killers and drivers. Number of work orders, i.e. failures, and the corresponding delays are used to calculate risk ranks at infrastructure system and component level (Table 1 and Figure 10). Risk ranks are presented for the nine years as a whole and as a yearly updated indicator of train delays, showing the systems with highest risks at present. Simulation is carried out by modifying the input dataset. The effect of changes at component level is studied at the system level (Figure 11). The results provide positive indication that such models can help infrastructure managers in appropriate decision-making.

CHAPTER 6

Conclusions and further research

6.1 Conclusions

The following conclusions have been made in this thesis:

- Performance indicators (PIs) are identified by reviewing research papers and other documents. The PIs are categorised into a scorecard according to European standards on maintenance key performance indicators (KPIs), EN 15341 [66], and the infrastructure asset structure of Trafikverket. About 130 PIs are mapped; similar indicators are treated as the same, but some indicators can be found twice, e.g. at system and component levels (technical report and Paper B)

- The mapped railway PIs are compared to EN 15341. The KPIs of EN 15341 are constructed by taking the ratio of two indicators, or factors (numerators and denominators); 13 KPIs of the standard are found to be similar to combinations of railway indicators (Paper B)

- Indicators for calculating the net present value (NPV) of maintenance are identified through EN 15341 (Paper A)

- Punctuality and regularity are preferably studied together. Canceled trains (lower regularity) can increase punctuality and vice versa; fewer canceled trains can decrease punctuality. Negatively correlated indicators should therefore be presented together, e.g. punctuality and regularity. This could prevent suboptimising. Moreover, by combining these two indicators into one independent variable, managers can concentrate on the most vital variables (technical report)

- In traditional performance measurement systems, PIs are given threshold values, indicating when an action needs to be taken, i.e. they can be reactive if not appropriately used. Also, since the PIs have only the historical data, the underlying factors responsible for the performance are not considered before a threshold limit

is passed, i.e. the PIs can be abstract and compared to a black box. This is an issue, as PIs are often aggregated measures of several indicators, e.g. delays in production or overall equipment effectiveness. In contrast, the link and effect model is designed to analyse with emphasis on performance drivers and killers, rather than on thresholds. If indicators are provided with continuously updated underlying factors, i.e. performance drivers and killers, the user can act in a more proactive manner (Paper C)

- The case study shows that stakeholders in railways use key components of strategic planning differently and to varying extents. Therefore, an experienced person is required to unite the strategic, tactical and operational planning within a common terminology and on a top-down basis (Paper C)

- In the case study, systems and components of railway infrastructure are analysed in terms of work orders, train delays, repair times and the corresponding risk ranks. The analysis ends with presenting train delays with continuously updated underlying performance killers in terms of risk ranks (Paper C)

- Simulations showed that changes at component level are seen in indicators at the system level. In other words, it is possible to simulate the effect at the system level before carrying out improvements at the component level (Paper C)

- Algorithms together with a graphical user interface were developed for simulation purpose and to provide a demonstrator of how indicators, e.g. risk ranks and data quality, can be analysed in a continuous manner without the need for manual data preparation (Paper C)

6.2   Research contribution

The research contribution is considered to be:

- Performance indicators for value driven maintenance and the net present value are mapped

- Various terms are studied for their specific meaning in performance measurement and the maintenance process, e.g. performance killer, cost driver and leading indicator

- Mapping and grouping of railway infrastructure performance indicators. About 130 indicators were mapped and grouped according railway infrastructure assets and European standards

- Railway infrastructure performance indicators are compared to European standards. 13 indicators are found to be in common

- A novel link and effect model is developed as a four step continuous improvement process to meet some of the issues in the measurement of performance

- Algorithms are developed to analyse railway infrastructure systems and components in terms of risk ranks, which is validated in a case study on a specific railway section

- Simulations are carried out in a case study to analyse the effect on the railway infrastructure system level by making changes in the failure data of subsystems and components

6.3   Further research

Further research should consider the following:

- PIs of railway infrastructure have been mapped and linked to European standards, which in turn have been linked to value driven maintenance (VDM), the net present value (NPV) of maintenance. A topic of further research is to link the railway PIs to the VDM and NPV, making investments and changes in maintenance quantifiable

- The mapped PIs of railway infrastructure have not been studied in detail; this is required to further define a scorecard of railway infrastructure. Once an overall railway scorecard includes strategic, tactical and operational levels, it will be possible to integrate it with the link and effect model

- The negatively correlated indicators punctuality and regularity have been combined into one independent variable, showing interesting results. Further research on this can give a measure of railway effectiveness

- Algorithms for data analysis and simulation are required to be further developed towards a more efficient and effective performance measurement and for increasing the knowledge of the interactions within railways

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Part II

Paper A

Maintenance Value Drivers, Killers and Related Indicators

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Maintenance Value Drivers, Killers and Related Indicators

C. Stenström, A. Parida, U. Kumar and D. Galar

Abstract

Value driven maintenance (VDM) is a fairly new maintenance management methodology based on four maintenance value drivers and the formula of discounted present value (DPV) to calculate the value of different maintenance strategies. However, the dependability of the engineering assets needs to be assessed in order to make an estimation of the DPV. Therefore, standardised indicators have been critically analysed to find the most essential indicators for the four value drivers and for estimation of the DPV. Terminology containing drivers and killers are common in the field of asset management, but not many publications can be found for their detailed descriptions. One section in this paper is therefore dedicated to review these terms.

1 Introduction

Value driven maintenance (VDM) is a maintenance management methodology developed about four value drivers in maintenance, which are; asset utilisation, resource allocation, cost control and HSE (health, safety and environment) [1]. These four drivers are used to calculate the value of maintenance strategies using the formula of discounted present value (DPV). However, an effective maintenance performance measurement (MPM) system is needed to build up knowledge of the four drivers and to be able to make an estimation of the DPV. The European standard on maintenance key performance indicators (KPIs) EN 15341 is providing a battery of indicators for this purpose [2]. However, due to the ratio-based construction of the indicators, even the common indicators of the standard can be challenging to implement in an organisation without previous experience in data collection and analysis. The most essential indicators and easiest to implement is therefore the indicators found in the numerators and denominators of the KPIs in the European standard.

In this paper, the indicators of highest importance for organising a MPM system for the four value drivers of VDM have been extracted from EN 15341 standards.

Terms like; value drivers, performance drivers, etc. are commonly used in the field of asset management, but descriptions are mostly missing. Therefore, the paper starts with a review on the use of this terminology. No standards have been found for the terms; performance driver and performance killer. The review is therefore concentrated on authors that are using the terms.

2 Performance drivers and killers

Kaplan and Norton [3, 4] use the term performance driver in their work with the Balanced Scorecard (BSC), which complements financial measures of past performance with operational measures of the future performance. Financial measures are commonly considered as lagging indicators, i.e. output, or outcome measures. Therefore, performance drivers can be interpreted as the inputs to a process, whereas performance killers are the ones which obstruct the performance.

Indicators measuring inputs to a process are often considered as leading indicators [5]. Thus, lagging indicators measure the outputs.

The financial perspective of the BSC consists mainly of output measures, while the other perspectives of the BSC are more of input measures and thus drives the performance. One example given by Kaplan and Norton is measures of on-time delivery; such a measure will be a useful performance measure for customer satisfaction and retention [4].

Tsang [6, 7] describes that performance drivers can be explained as lead indicators, which have the ability to predict future outcome. Parida and Chattopadhyay [8, 9] agree that a lead indicator is a performance driver which acts like an early warning system. Patra, Kumar and Larsson-Kråik [10] have the same stance of policy, i.e. a lead indicator is a performance driver. Concluding, a lead indicator is a performance driver, and, a performance driver can be a lead indicator. Whether an indicator is a lead or lag depends on the perspective and is subjective. As an example, a lag indicator may be a lead indicator when used for planning.

Markeset and Kumar [11] describe performance killers as factors/issues that reduce performance without being strong enough to stop a process. The authors give a number of examples of performance killers: equipment that is critical with respect to uptime, health, safety and environment; bottlenecks in capacity, administration and inventory; incompetence; lack of proper tools and facilities; faulty procedures and checklists; inadequate information and communication flow; etc. Furthermore, Parida, Kumar and Chattopadhyay [12, 9] have discussed a number of performance killers, which are unavailability of resources, materials, spares, personnel, IT support, project support, time etc., i.e. a performance killer can be non-availability of resources. This confirms the presumption that performance killers are process inputs that leads to poor performance.

2.1 Cost drivers

Horngren, Foster and Datar [13] describes cost driver in accounting as any variable that causally affects costs over a given time span. Markeset and Kumar [11] have listed examples of cost drivers; unplanned maintenance, process bottlenecks, equipment with high energy requirements, potential liability issues, operational and/or maintenance costs, training costs, facility costs, disposal costs, etc.

Nyström [14] used Horngrens description to explain cost driver in a railway management context, as analogous to unpunctuality driver, which in turn are described as any factor that affects unpunctuality. Some examples of cost drivers in the context of railway

infrastructure management have been given by Espling and Kumar [15] as; labour, labour overtime, spare parts and infrastructure failures.

Consequently, a cost driver can be interpreted as an element that affects cost, or an element that increases costs considerably.

2.2   Conclusions on drivers and killers

Deduced from Kaplan and Nortons description of the Balanced Scorecard, a performance driver is an input to a process. Similarly, a performance killer is an input to a process that performs badly or hinders performance. According to the review and previous reasoning, performance killers and cost drivers are similar, but not the same. Both impair process outputs, but cost driver are tangible since they affects costs, i.e. more visible as it is a cost object, while a performance killer is less tangible; since, it does not directly affect costs, it hinders performance, e.g. inappropriate tools and clothing, faulty procedures, poor communication and bottlenecks.

A common indicator in accounting is the capacity utilisation, also called efficiency, often calculated as the actual output over the potential output. Another essential aspect in any process is the quality of the output. Therefore, any factor that reduces capacity, quality, punctuality, etc. can be a performance killer or cost driver.

The descriptions of the terms discussed in the reviewed literature are brought together in Table 1 and the input-process-output model (IPO-model) in Figure 1.
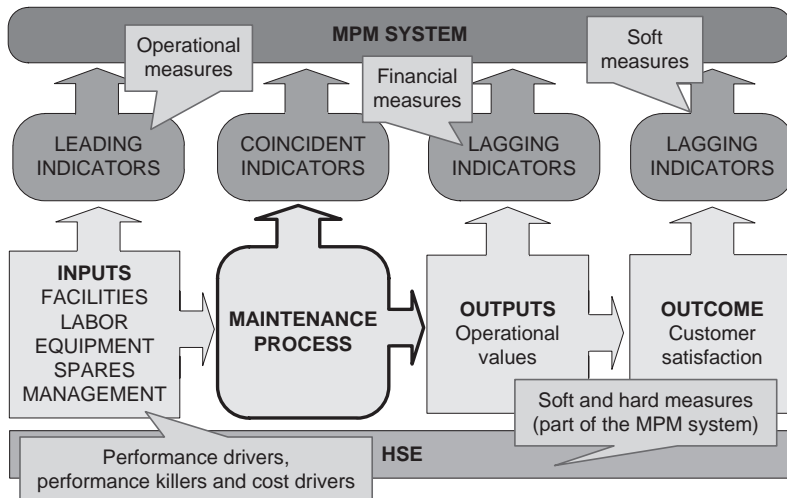

Figure 1: IPO-model with integral MPM system. Indicators and measures are synonymous.

Table 1: Description of terms.

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.
	    Note 2: a cost driver can be interpreted as an element that affects cost, or an element that increases costs considerably.

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 and 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.

As can be seen in Figure 1, coincident indicators and soft indicators are mentioned as well. Coincident indicators measure events at the same time as they occur, compared to leading and lagging indicators which measure future events, or events that already have occurred. Preventive maintenance indicators, e.g. from inspections and sensors, can be interpreted as coincident indicators, giving indication of the actual condition of engineering assets. Another perspective is that these indicators are leading indicators since they control the output, and thus the lagging indicators. Inspections and sensors facilitate for proactive actions before failures occur.

Soft measures (Figure 1) are the same as qualitative indicators, measuring intangible values, which can be used to measure customer satisfaction etc. In this context the customer is the user and maintainer of the engineering assets.

Regarding the term maintenance value drivers, used in VDM, the origin comes from the discounted present value (DPV), as the four value drivers are terms in the formula for calculating the value of all future cash flows. See Equation 1 in next section.

3 Indicators for value driven maintenance

The value drivers; asset utilisation, resource allocation, cost control and HSE of VDM, represent the core of the maintenance function in organisations; see Figure 2.

Maintenance managers must balance the importance of the value drivers in order to maximise stakeholders value. A business that experiences a high market demand may want asset utilisation to be increased and will therefore put more money on maintenance and resource allocation. On the other hand, a declining market does not require as high asset utilisation and the focus is therefore to control costs. Whereas, a business providing health care may put more focus on HSE.
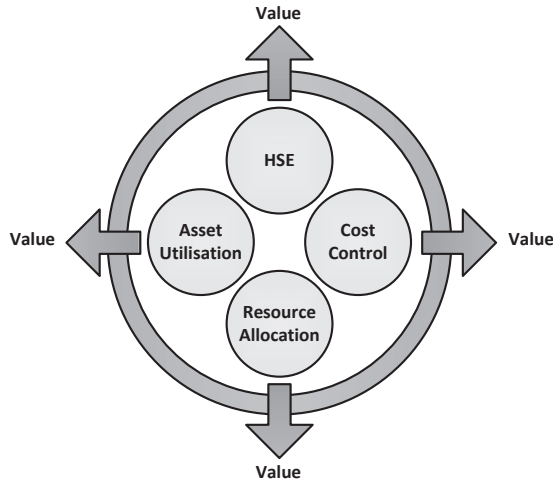
Figure 2: Maintenance value drivers. Adapted from [1]

Haarman and Delahay [1] have put together a formula to calculate the cash flows from the value drivers based on discounted cash flows. Recalling the discounted present value with multiple cash flows and by using the value drivers, the value of maintenance is:

$$DPV_{Maint} = \sum_{t=0}^{N} F_{HSE,t} \frac{CF_{AU,t} + CF_{CC,t} + CF_{RA,t} + CF_{HSE,t}}{(1+r)^t} \tag{1}$$

Where:

DPV = Discounted present value

CF_t = Future cash flow at time t

$F_{\text{HSE,t}}$ = Compliance with HSE regulations, $\in$ [0,1]

AU = Asset utilisation

CC = Cost control

RA = Resource allocation

r = Discount rate

After ascertaining the required asset utilisation and consulting involved engineers, e.g. reliability and performance measurement engineers, the maintenance and resource allocation objectives and strategies need to be adjusted. Equation 1 can be used to estimate the monetary value of alternative strategies, but this requires data to be collected, which has large costs and equally large savings associated to it. The most important performance indicators (PI) are therefore to be identified in order to know what data to collect for building up a maintenance performance measurement system. There are two major standards for this, the European standard EN 15341 and the North American SMRP Best Practice Metrics [2, 16]. The value for an organisation to use standardised indicators or metrics, such as the indicators from the standard EN 15341 or the SMRP metrics are [17]:

- Maintenance managers can rely on a single set of predefined indicators supported by a glossary of terms and definitions

- The use of predefined indicators makes it easier to compare maintenance and reliability performance across borders

- When a company wants to construct a set of company indicators or scorecard, the development process based on predefined indicators will be simplified

- The predefined indicators can be incorporated in various CMMS software and reports

- The predefined metrics can be adopted and/or modified to fit the companys or the branchs special specific requirements

- The need for discussion and debate on indicator definitions is ended and uncertainties are eliminated

EN 15341 has been used in this paper to find and connect the most relevant standardised indicators to the four maintenance value drivers of VDM. The standard consists 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 ones. HSE indicators can be found in the technical group. The most simple connection can be done by connecting the three groups

of indicators to the value drivers, see Figure 3. The indicators have been given letters and numbers for identification in the standard.
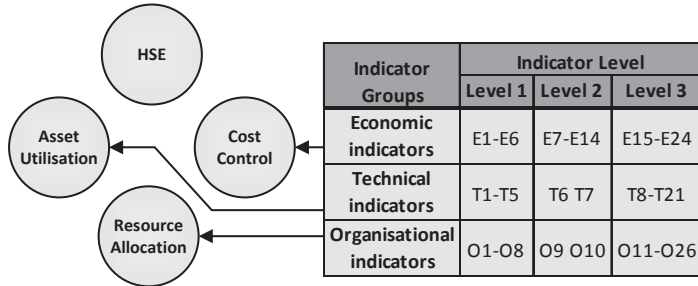
Figure 3: EN 15341 indicator groups connected to the value drivers of VDM.

Every KPI has been constructed by taking the ratio of two factors, or PIs, i.e. data is need for at least two PIs in order to be able to calculate any of the KPIs in EN 15341. This makes even level 1 indicators challenging to calculate for organisations where this practice is new. Therefore, the factors (numerators and denominators) can be seen as level 0 indicators, easiest to calculate and most essential to have.

Out of the level 0 PIs, the easiest to calculate and most important ones have been deduced from EN 15341 standard and are presented in Figure 4 and Table 2.
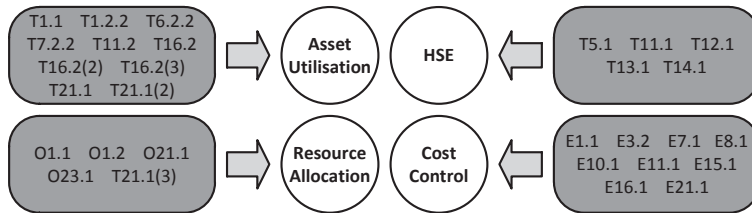
Figure 4: Level 0 PIs deduced from EN 15431.

Indicator names ending with .1 and .2 are referring to the numerator and denominator, respectively. The third number refers to first or second term in the numerator or denominator. The in indicators T16.2(2), T16.2(3), T21.1(2) and T21.1(3) are indicators not found in the standard, but considered important to have in a MPM-system. T16.2(2) and T16.2(3) are the number of corrective work orders and preventive work orders re-

spectively. T21.1(2) is the repair time (RT), a measure of maintainability. T21.1(3) is here called waiting time (WT), a measure of maintenance support performance [18].

Table 2: Level 0 indicators extracted from EN 15341.

Economic indicators		
$E1.1 = \sum \mathord{\text{€}}_{Cost}^{Maint}$	$E3.2 = \sum \#_{Output}^{Prod}$	$E7.1 = \sum \mathord{\text{€}}_{Value}^{Maint\ inventory}$
$E8.1 = \sum \mathord{\text{€}}_{Cost}^{Maint\ personnel}$	$E10.1 = \sum \mathord{\text{€}}_{Cost}^{Maint\ contractor}$	$E11.1 = \sum \mathord{\text{€}}_{Cost}^{Maint\ mtrl}$
$E15.1 = \sum \mathord{\text{€}}_{Cost}^{CM}$	$E16.1 = \sum \mathord{\text{€}}_{Cost}^{PM}$	$E21.1 = \sum \mathord{\text{€}}_{Cost}^{Maint\ training}$

Technical indicators		
$T1.1 = \sum t_{Up\ time}^{Prod}$	$T1.2.2 = \sum t_{Down\ time}^{Maint}$	$T6.2.2 = \sum t_{Down\ time}^{Failures}$
$T7.2.2 = \sum t_{Planned}^{Maint}$	$T11.2 = \sum \#_{Failures}$	$T16.2 = \sum \#_{WO}^{Maint}$
$T16.2(2) = \sum \#_{CM\ WO}^{Maint}$	$T16.2(3) = \sum \#_{PM\ WO}^{Maint}$	$T21.1 = \sum t_{Restoration}^{Item} = TTR$
$T21.1(2) = \sum t_{Repair}^{Item} = RT$		

Organisational indicators		
$O1.1 = \sum \#_{Personnel}^{Maint}$	$O1.2 = \sum \#_{Personnel}^{Tot\ internal}$	$O21.1 = \sum t_{Overtime}^{Maint}$
$O23.1 = \sum t_{Training}^{Maint}$	$O21.1(3) = \sum t_{Waiting}^{Item} = WT$	

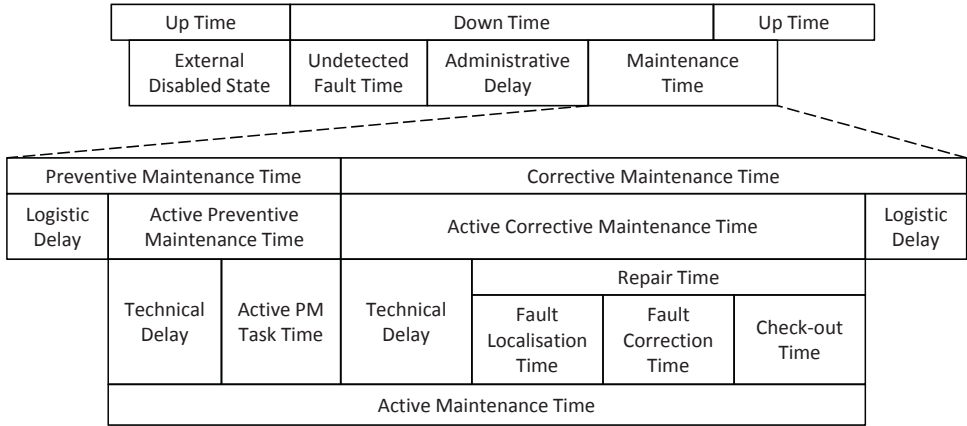| HSE indicators		
$T5.1 = \sum \#_{Injuries}^{Maint}$	$T11.1 = \sum \#_{Injuries}^{Failures}$	$T12.1 = \sum \#_{Pot\ injuries}^{Failures}$
$T13.1 = \sum \#_{Envir\ dmg}^{Failures}$	$T14.1 = \sum \#_{Pot\ envir\ dmg}^{Failures}$	

Acronyms: UT = Up Time, DT = Down Time, CM = Corrective Maintenance, PM = Preventive Maintenance, WO = Work Order, TTR = Time to Restoration, RT = Repair Time, WT = Waiting Time, Item = System or component

Explanation: E1.1 is read: total cost of maintenance; E3.2 is read: total number of output; T1.1 is read: total up time; and T21.1 is read: total time to restoration

Indicator T21.1, time to restoration (TTR), is the sum of WT and RT. The TTR can be further divided into smaller parts, but this may not be needed for basic requirements. Monitoring WT and RT can still be in alignment with standards, See Figure 5. High requirements, or high maturity, are according to IEV and EN 13306 [18, 19]. In basic requirements, technical delay is considered as zero, or part of the repair time. The waiting time is administrative and logistic delay added together.

For high requirements, or high maturity:

Up Time	Down Time			Up Time
External Disabled State	Undetected Fault Time	Administrative Delay	Maintenance Time	

Preventive Maintenance Time		Corrective Maintenance Time				
Logistic Delay	Active Preventive Maintenance Time	Active Corrective Maintenance Time				Logistic Delay
			Repair Time			
Technical Delay	Active PM Task Time	Technical Delay	Fault Localisation Time	Fault Correction Time	Check-out Time	
Active Maintenance Time						

For basic requirements (corrective maintenance):

Up State →
Down State
Waiting Time (WT) (Administrative and logistic delay)   Repair Time (RT) (Technical delay ≡ 0)
Time to Restoration (TTR)
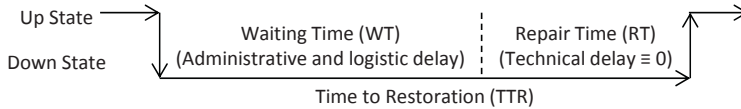
Figure 5: Morphology of an item under operation. High requirements, or high maturity, are according to IEV and EN 13306 [18, 19].

The extracted level 0 indicators can be used to calculate some of the level 1-3 KPIs. This has been carried out and is presented in Table 3 and Figure 6. These KPIs are considered to be the easier to calculate and most important indicators following the level 0 indicators. Three additional indicators within parenthesis can also be seen in Table 3 and Figure 6, which requires the asset replacement value (ARV) and maintenance inventory value. These have been added, since they give valuable inputs, but may not be the first indicators to be implemented by an organisation.

Table 3: Level 1-3 indicators based on the Level 0 indicators.

Economic indicators

$$E1 = \frac{\sum \text{\euro}_{Cost}^{Maint}}{ARV} \qquad E3 = \frac{\sum \text{\euro}_{Cost}^{Maint}}{\sum \#_{Output}^{Prod}} \qquad E7 = \frac{\sum \text{\euro}_{Value}^{Maint\ inventory}}{ARV}$$

$$E8 = \frac{\sum \text{\euro}_{Cost}^{Maint\ peronnel}}{\sum \text{\euro}_{Cost}^{Maint}} \qquad E10 = \frac{\sum \text{\euro}_{Cost}^{Maint\ contractor}}{\sum \text{\euro}_{Cost}^{Maint}} \qquad E11 = \frac{\sum \text{\euro}_{Cost}^{Maint\ mtrl}}{\sum \text{\euro}_{Cost}^{Maint}}$$

$$E12 = \frac{\sum \text{\euro}_{Cost}^{Maint\ mtrl}}{\sum \text{\euro}_{Value}^{Maint\ inventory}} \qquad E15 = \frac{\sum \text{\euro}_{Cost}^{CM}}{\sum \text{\euro}_{Cost}^{Maint}} \qquad E16 = \frac{\sum \text{\euro}_{Cost}^{PM}}{\sum \text{\euro}_{Cost}^{Maint}}$$

$$E21 = \frac{\sum \text{\euro}_{Cost}^{Maint\ training}}{\sum \#_{Personnel}^{Maint}}$$

Technical indicators

$$T1.1 = \frac{\sum t_{Up\ time}^{Prod}}{\sum t_{Up\ time}^{Prod} + \sum t_{Down\ time}^{Maint}} \qquad T17 = \frac{\sum t_{Up\ time}^{Prod}}{\sum \#_{Failures}} \qquad T21 = \frac{\sum t_{Restoration}^{Item}}{\sum \#_{Failures}}$$

   = Availability related to maint   = MTBF   = MTTR

$$T21(2) = \frac{\sum t_{Repair}^{Item}}{\sum \#_{Failures}}$$

     = MRT

Organisational indicators

$$O1 = \frac{\sum \#_{Maint}^{Personnel}}{\sum \#_{Employees}} \qquad T21(3) = \frac{\sum t_{Waiting}^{Item}}{\sum \#_{Failures}}$$

HSE indicators

$$T5 = \frac{\sum \#_{Injuries}^{Maint}}{\sum t} \qquad T5(2) = \frac{\sum \#_{Pot\ injuries}^{Maint}}{\sum t} \qquad T11 = \frac{\sum \#_{Injuries}^{Failures}}{\sum \#_{Failures}}$$

$$T12 = \frac{\sum \#_{Pot\ injuries}^{Failures}}{\sum \#_{Failures}} \qquad T13 = \frac{\sum \#_{Envir\ dmg}^{Failures}}{\sum \#_{Failures}} \qquad T14 = \frac{\sum \#_{Pot\ envir\ dmg}^{Failures}}{\sum \#_{Failures}}$$

Description: M in front of acronyms stands for mean.
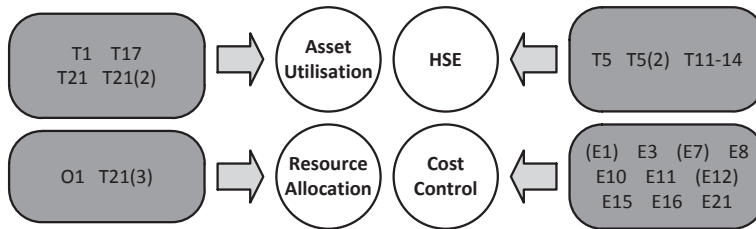
Figure 6: KPIs based on the level 0 PIs, with exception for the PIs within parenthesis, which requires ARV and inventory value.

The most important indicators to implement have been identified through EN 15341. Besides, connecting the indicators to the four value drivers of VDM, categorising according to leading and lagging indicators can as well be carried out. This has been shown as a last step in Figure 7. E15, E16 and E21 were put as leading indicators since they are measures of maintenance policy and personnel training.

Figure 7: Identified PIs categorised according to leading, lagging, etc.

4   Conclusions

Any process input that reduces the output (capacity, quality, punctuality, etc.) is a performance killer or cost driver, and vice versa regarding performance drivers. Leading indicators measure the process inputs, but the indicators and the measurement system can also have drivers and killers, since they are inputs to assist in driving the performance.
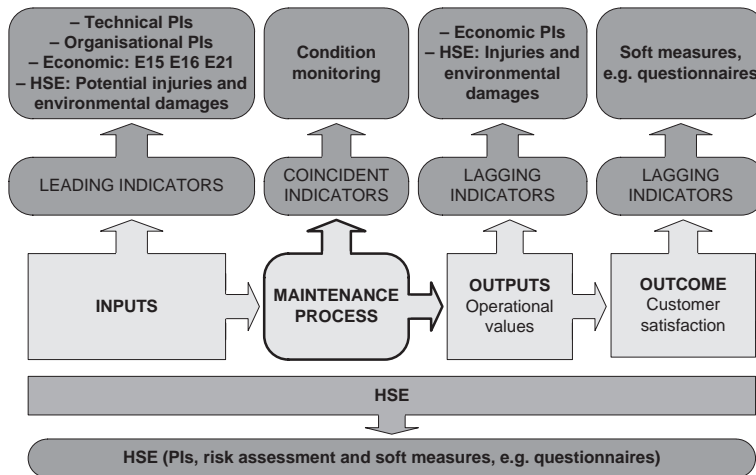
VDM uses the formula of DPV to estimate the monetary value of maintenance, which requires assessment of the dependability of the engineering assets in question. Knowing what to measure and analyse is a key factor, since large costs and equally large savings are related to the activity. EN 15341 has been used to answer this question. The indicators of EN 15341 are constructed as ratios of factors, which can be hard to implement for an organization new to the process of measuring and analysing their performance. Level 0 indicators have therefore been extracted from the standard as the most essential and first indicators to implement into the maintenance function. This battery of indicators is powerful to help in understanding the assets, facilitate reliability studies and benchmarking, at the same time as they provide confidence due to their standardisation. Furthermore, the level 0 indicators can be used to calculate some of the Level 1-3 KPIs, as a second step in constructing a MPM system for VDM.

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PAPER B

Performance Indicators of Railway Infrastructure

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Performance Indicators of Railway Infrastructure

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Abstract

Railway traffic has increased over the last decade and it is believed to increase further with the movement of transportation from road to rail, due to the increasing energy costs and the demand to reduce emissions. Railway capacity needs therefore to be increased, which requires more efficient and effective maintenance. To manage the assets effectively within the business objectives, the effect of maintenance activities must be measured and monitored. Performance indicators are continuously identified and developed to support infrastructure managers in decision making, but they are often ad-hoc and seldom standardised. In this paper, performance indicators for railway infrastructure have been mapped and compared with indicators of European standard. The listed indicators form a basis for constructing a maintenance performance measurement system for railway infrastructure.

1 Introduction

Railway traffic has increased over the last decade and it is believed to increase further with the movement of transportation from road to rail, due to the increasing energy costs and the demand to reduce emissions. The key goals of the White Paper 2011 for the European transport system include; a 50 % shift of medium distance intercity passenger and freight journeys from road to rail and waterborne transport, and a 60 % cut in transport CO_2 emissions by 2050 [1]. In 2008, annual oil production decline rate was 6.7 % in fields that had passed their production peak; this rate of decline is expected to reach 8.6 % by 2030 [2]. The available capacity of the railways has to be enhanced in order to meet these new demands in transportation.

As railway infrastructure and their components have a long life span, their management requires a long term sustainable strategy. On-going technical and economic assessments are necessary to optimise the performance of railway infrastructure and receive the return on investment (ROI) in a manageable timeframe. Long-term asset management objectives and strategies are developed to steer the operation and maintenance activities in the right direction. These objectives need to be broken down into quantitative operation and maintenance objectives to achieve a high level of robustness, punctuality and capacity within the operational budget, at the lowest life cycle cost, with no or an acceptable level of risk. See work by Espling and Kumar [3], for further discussion on developing maintenance strategies for railway infrastructure.

To manage assets effectively within the agreed objectives, the effect of maintenance activities must be measured and monitored. Performance indicators (PIs) for RAMS,

capacity, punctuality etc. are continuously developed to support infrastructure managers (IMs) to identify performance killers and in making more efficient and effective decisions, but they are often ad-hoc and seldom standardised. Measuring entails data collection, but since raw data does not give any information by itself, these must be analysed, validated and converted to information in the right format for decision making. This consumes resources, especially, if wrong parameters are measured. However, a good performance measurement system does not necessarily require a high level of precision [4]. It is more important to know whether the trend is up or down and how the current value compares to historical measures. Consistency is therefore especially important in order to capture long term trends, predict future development and take the appropriate corrective actions at an early stage. Thus, if the methods for measuring or analysing are changed, the old information or analysis method should be kept for some time to safeguard the trend tracking. Moreover, performance measurement is also important for feasibility of railway certifications [5]. It is crucial to thoroughly analyse what to measure, as large costs and equally large savings are associated with measuring. Thus, there exists a need to study the railway PIs used by different IMs, to find out which ones are the most important, which are required and which are not required.

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

Increased interoperability and building of a trans-European railway network is another goal of the European Union. The required harmonisation and standardisation of the management of railways have led to increased use of European standards. The identified PIs have therefore been compared to the European standard; Maintenance Key Performance Indicators (KPIs), EN 15341, in order to find indicators in common [6].

Several projects on indicators and benchmarks for railway transport operations have been carried out, see reviews by [7, 8, 9], but similar works on the maintenance aspect are few, which can be seen in [10, 11].

In this paper, maintenance performance indicators for railway infrastructure have been mapped and compared with indicators of EN 15341 [6]. The listed indicators form a basis for constructing a maintenance performance measurement system (MPM-system) for railway infrastructure.

This paper is based upon Stenström et al. [12], but the current paper includes the following additional research: grouping of indicators revised, revised text and figures, besides extended literature review. More precisely, Figures 1 and 2, as well as Tables A.1 to A.5, have been revised.

2 Maintenance performance indicators for railway infrastructure

Phrases like "what gets measured gets managed" are often used to justify indicators. What gets measured gets managed is not a promise [13]. Rather, measuring is a management tool which facilitates and supports effective decision making. In and of itself, it does not determine performance, but it can facilitate good management.

2.1 Indicators for managing performance

Organisations use indicators to measure their performance in some form or another. The most common ones are financial; many of these are mandatory by law. Other indicators are technical, organisational, HSE (health safety and environment), etc. There are few agreements on how to categorise indicators. It is up to each organisation to decide which standards or frameworks to use. The best known standards for maintenance KPIs are the European standard EN 15341 and SMRP Best Practice Metrics [6, 14]. Use of standardised indicators or metrics, such as the indicators from the standard EN 15341 or the SMRP metrics has the following advantages [15]:

- Maintenance managers can rely on a single set of standardised indicators supported by a glossary of terms and definitions

- The use of standardised indicators makes it easier to compare maintenance and reliability performance across borders

- When a company wants to construct a set of company indicators or scorecard, the development process based on standardised indicators is simplified

- The standardised indicators can be incorporated in various enterprise resource planning (ERP) systems and reports

- The standardised indicators can be adopted and/or modified to fit the companys or the branchs special specific requirements

- The need for discussion and debate on indicator definitions is not required and uncertainties are thus eliminated

Organisations maintenance performance measurement (MPM) system often grows from the need to measure different processes. The number of databases and indicators in organisations often grows over time. Some indicators stay while others disappear, but at some point, the amount of information is too large and becomes uncontrollable. The MPM system must then be organised or reorganised, databases and indicators must be documented, regulations set, gaps must be identified, the MPM-system must be aligned to the business goals and the owners of databases and indicators must be clear. See Figure 1 for high level requirements (HLRs) for organising a measurement system. Supportive

guidelines for asset management in railways can be found in a work by International Union of Railways (UIC), as a seven-step procedure based on the following standards and manuals: PAS 55, the asset management standard by British Standards Institute; the International Infrastructure Management Manual (IIMM) by New Zealand Asset Management Steering (NAMS) Group; and the Asset Management Overview by the US Highway Agency [16, 17, 18, 19, 20].
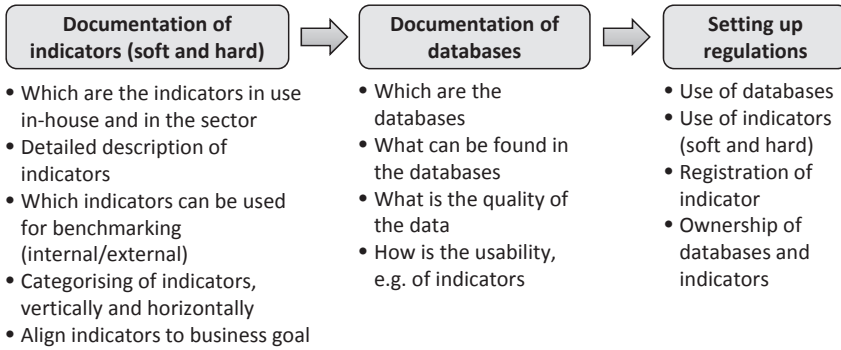
Figure 1: High level requirements (HLRs) for organising or reorganising a performance measurement system, e.g. MPM-system.

According to Gillet, Woodhouse found that a human cannot control and monitor more than four to eight indicators at the same time [21]. Data aggregation is therefore necessary [22]; see Figure 2. As an example in railways, capacity and availability goals can be broken down to system and component performance requirements at the infrastructure level. The outcome is then aggregated and compared to the set objectives by use of indicators.

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

It is not possible to measure everything with only quantitative or only qualitative methods. Rather a combination of both methods must be used to create a measurement system that is as complete as possible. Qualitat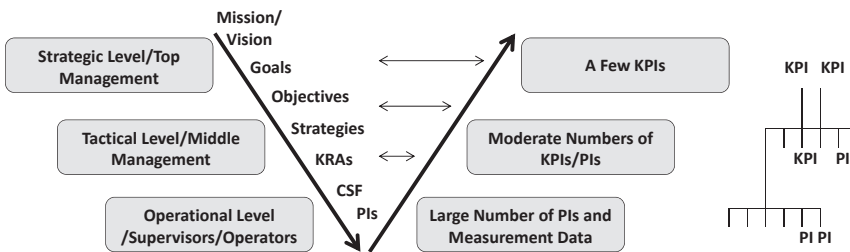ive measurement methods are good for measuring soft values like employee satisfaction and for checking conformity with quantitative indicators. Galar et al. have merged qualitative measures with quantitative ones and developed an audit that shows the relation between trends in questionnaires and indicators, validating the correlation or highlighting the divergence [23, 24].

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

2.2   Railway maintenance performance indicators

A study was undertaken to review the maintenance PIs used by researchers and the professionals in the field of railway infrastructure maintenance, as well as reviewing project reports, policy documents, handbooks, etc. of European IMs. Interviews of the Swedish IM were also carried out. In order to manage the large number of indicators, they have been grouped into two overall groups; managerial and infrastructure condition indicators. The managerial indicators are extracted from different computer systems, e.g. enterprise resource planning (ERP), computerised maintenance management system (CMMS), etc., excluding condition monitoring (CdM) 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 CdM data that are at a subsystem or component level. See work by Stenström et al. [25] for further discussion on terminology of performance indicators.

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

This section presents the four groups of managerial indicators and the six groups of the CdM indicators.

Managerial indicators

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

Technical indicators are closely related to reliability, availability and maintainability (RAM); see Tables A.1 and A.2. The research is extensive, see [26, 27, 28, 29, 30] for work on failure frequencies and delays, see [26, 31] for maintainability, see [10] for mapping of
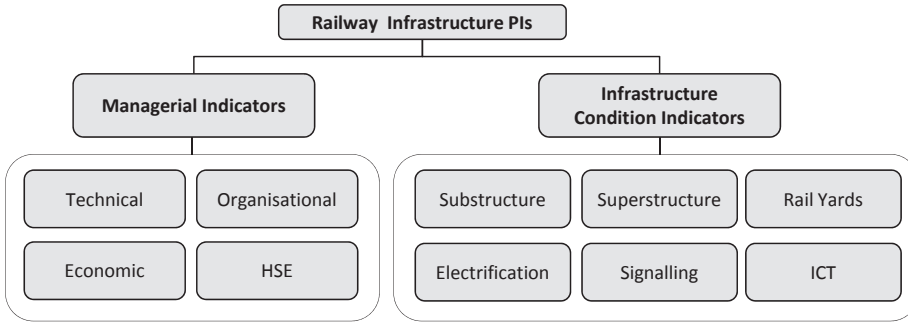
Figure 3: Structure of railway infrastructure PIs.

maintenance PIs, see [32] for capacity, and [33, 34, 35] for overall equipment effectiveness (OEE) and data envelopment analysis (DEA).

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

Many overall financial indicators are regulated by the ministry of the IM and are therefore easy to find; see Table A.4. Besides annual reports, those indicators are also often used in high-level benchmarking, e.g. [22, 23]. Similar cost indicators at operational level, i.e. per item, are scarcer, but research is carried out, e.g. on switches and crossings by [24, 25, 26].

Maintenance staffs are exposed to hazards and suffer from bad ergonomics due to unstandardized or non-routine work, lowered barriers, leakage, pressure, electricity, etc. [24]. As in all forms of rail transportation, the safety is a critical factor. Thus, HSE has a special importance in the management of railway infrastructure maintenance. General HSE indicators are easy to find and often required by law, but specific ones for maintenance are scarcer. Both types have been considered in Table A.5.

Condition monitoring indicators

The railway condition monitoring (CdM) indicators have been divided into six groups; substructure, superstructure, rail yards, electrification, signalling, and information and communication technology (ICT), Figure 3. Condition monitoring of these assets has been mapped by studying various inspection methods, mainly in [36, 37, 38]; see Tables A.6 and A.7. Ocular inspections and manual inspections using gauges have been left out due to their large number of routines. Bridges and tunnels condition monitoring have

not been considered either; they are out of the scope of this paper. Wayside detectors are monitoring trains; only the infrastructure is considered in this paper. Nevertheless, the rolling stock is as important as the infrastructure since it will be in similar condition [39]. See work by Bracciali [40] for a state-of-the-art review on wayside detectors.

2.3   Constructing a railway maintenance scorecard

A scorecard, scorebook or scoresheet in business is a statistical record used to measure achievement or progress towards a particular goal [41].

For a successful MPM-system, it needs to be able to provide the right information at the right time, to the right people, in the right quantity and format [42]. According to Gillet, Woodhouse found that a human cannot control and monitor more than four to eight indicators at the same time [21]. For these reasons, it is essential to find the right indicators for the different organisational levels, indicators that match the objectives and strategy of the business. With use of a scorecard the top management can oversee the indicators for each responsibility, e.g. operations, financial, HR, etc. The indicators and parameters in Tables A.1-7 have been brought together into a scorecard; see Table 1.

Table 1: Railway infrastructure maintenance scorecard.

Perspective	Aspect	Indicators [no.]	
Perspective	**Aspect**	**System**	**Subsystem**
Managerial		**System**	**Subsystem**
Technical	Availability	8	8
	Maintainability	1	1
	Capacity consumption	1	5
	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	7	-
	Safety - Maintenance	4	-
	Environment	4	-
Condition monitoring		**Subsystem**	**Component**
Technical	Substructure	6	16
	Superstructure	10	32
	Rail yard	-	-
	Electrification	-	-
	Signalling	1	4
	Information communication tech.	-	-

3   Linking railway indicators to EN 15341

The indicators of EN 15341 consist of 71 key performance indicators (KPIs) categorised into three groups and three levels [6]. The groups are economic, technical and organisational indicators, and the levels are going from general indicators to more specific ones. The KPIs have been constructed by taking the ratio of two or more factors, or PIs. The railway KPIs have therefore been compared both with the factors and the KPIs of level one to three. See Tables 2 and 3. Indicators at the same row are considered to be closely related to each other.

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

Railway PIs		EN 15341 PIs	
#	Name/Description	#	Name/Description
E3 = E1/T19	Maint. cost / Train-km	E3	Total maint. cost / Quantity of output
T1/E1	Track availability / Maint. cost	E6	Availability related to maint. / Total maint. cost
E2/E1	Maint. mgmt cost / Maint. cost	E13	Cost for indirect maintenance personnel / Total maint. cost
E4/E1	Maint. contractor cost / Maint. cost	E10	Total contractor cost / Total maint. cost
E1/H16	Maint. cost / Energy consumption per area	E14	Total maint. cost / Total energy used
E5/E1	Corrective maint. cost / Maint. cost	E15	Corrective maint. cost / Total maint. cost
E6/E1	Preventive maint. cost / Maint cost	E16	Preventive maint. cost / Total maint. cost
T1	Track availability	T1	Availability related to maint.
H11/ Time	Maint. accidents and incidents / Time	T5	Injuries for people due to maint. / Working time
H12/T4	Failure accidents and incidents / Failures in total	T11	Failures causing injury to people / No. of failures
		T12	Failures causing pot. injury to people / No. of failures
O2+T18	Mean waiting time (MWT) + Mean time to repair (MTTR)	T21	Total time to restoration / No. of failures
O3	Maintenance backlog	O22	Work orders performed as scheduled / Scheduled work orders

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

Railway PIs		EN 15341 PIs	
#	Name/Description	#	Name/Description
E1	Maint. cost	E1.1	Total maint. cost
T19	Traffic volume (train-km)	E3.2	Quantity of output
T1	Track availability	E6.1	Availability related to maintenance
E2	Maint. mgmt cost	E13.1	Cost for indirect maintenance personnel
E4	Maint. contractor cost	E10.1	Total contractor cost
H16	Energy consumption per area	E14.2	Total energy used
E5	Corrective maint. cost	E15.1	Corrective maint. cost
E6	Preventive maint. cost	E16.1	Preventive maint. cost
H11	Maint. accidents and incidents	T5.1	Injuries for people due to maint.
T4	Failures in total	T11.2	Total number of failures
H12	Failure accidents and incidents	T11.1	Failures causing injury to people
		T12.1	Failures causing pot. injury to people

4 Conclusions

Maintenance performance indicators for railway infrastructure have been identified and listed in Tables A.1-7. Similar indicators have been considered as one indicator. Some indicators have been added, since they are considered as general ones, e.g. maintenance personnel absenteeism. The listed indicators form a basis for constructing a maintenance performance measurement system (MPM-system) for railway infrastructure.

The identified indicators have been compared to EN 15341 [6] in Tables 2 and 3. It was found that 13 PIs are similar. Further work on harmonisation is possible. A number of the indicators in the European standard are general for any maintenance functions. But, at the same time, it has to be kept in mind that the standard is mainly for manufacturing businesses and not for linear assets. Thus, some key railway indicators cannot be found in the standard.

Besides mapping and harmonisation of railway indicators, further research on the interlinkage of the indicators is needed for better understanding, e.g. linkage and effect of failures, preventive maintenance and cost.

This paper provides a number of indictors used in the management of railway infrastructure and compares them to European standard EN 15341 [6].

Acknowledgements

A Tables

Table A.1: Technical railway infrastructure indicators.

Technical indicators			
Category	**Indicators** (Comments) [Unit]	**Reference**	**#**
Availability	**System level**		
	Track availability (or Network availability) [%]	[36, 43]	T1
	Arrival punctuality [no. or %]	[44, 45, 46]	T2
	Train regularity [no. or %]	[45, 47]	T3
	Failures in total [no.]	[26, 28, 29, 30, 48, 49, 50]	T4
	Train delay [time]		T5
	Delay per owner (Operation centrals, Secondary delays, Infrastructure, Train operators, Accidents and incidents, etc.) [%/owner]		T6
	Faults interfering with traffic [no. or %]	[51, 52]	T7
	Temporary speed restrictions (TSRs) [no.]	[36]	T8
	Sub-system level		
	Availability per line, line class or area [%/line, class or area]	[36]	T9
	Punctuality per line, line class or area [no. or %/line, class or area]	[44, 45]	T10
	Regularity per line, line class or area [no. or %/line, class or area]	[47]	T11
	Failures per item [no./item]	[26, 28, 29, 30, 49, 50]	T12
	Failures per track-km, line, line class or area [no./track-km, line, class or area]		T13
	Delay per item [time/item]		T14
	Delay per line, line class or area [time/line, class or area]		T15
	Temporary speed restrictions (TSRs) per line, line class or area [no./line, class or area]	[36]	T16
Maintainability	**System level**		
	Mean time to repair (MTTR) (or Mean time to maintain (MTTM), or Maintainability)	[31, 48, 51]	T17
	Sub-system level		
	Mean time to repair (MTTR) per item (or Maintainability)	[26, 31, 51]	T18

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

Technical indicators			
Category	**Indicators** (Comments) [Unit]	**Reference**	**#**
Capacity consumption	**System level**		
	Traffic volume [train-km]	[10, 45]	T19
	Sub-system level		
	Traffic volume per line, line class or area [train-km/line, class or area]	[10, 45]	T20
	Train-km per track-m and line class [train-km/track-m]	[45, 50]	T21
	Tonne-km per track-m and line class [tonne-km/track-m]		T22
	Capacity consumption (or Capacity utilisation) (24h and 2h) [%]	[10, 32, 45]	T23
	Harmonised capacity consumption (double track counted twice) [train-km/track-metre]	[51]	T24
Riding comfort	**Sub-system level**		
	Track quality index (TQI) (e.g. K-/Q-value) [index]	[36, 50, 51, 53]	T25
OEE and DEA	**Sub-system level**		
	OEE per line, line class or area [%/line, class or area]	[34]	T26
	Data envelopment analysis (DEA) [-]	[33, 35]	T27
Age	**Sub-system level**		
	Mean age of assets (rail, S&C, OCS, ballast, etc.) [time]	[44, 49, 50, 54]	T28

Table A.3: Organisational railway infrastructure indicators.

Organisational indicators			
Category	**Indicators** (Comments) [Unit]	**Reference**	**#**
Maintenance management	**System level**		
	Preventive maint. share (or Corrective maint. share) [%]	[51, 55]	O1
	Mean waiting time (MWT) (or Maint. supportability, or Org. readiness, or Reaction time, or Arrival time) [time]	[31, 51]	O2
	Maintenance backlog [no. or time]	[36]	O3
	Maintenance possession overrun [time or no.]	[27]	O4
	Sub-system level		
	Preventive maint. share (or corrective maint. share) per line, line class, area or item [%/line, class, area or item]	[51]	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 %]	[50, 51]	O7
	Sub-system level		
	Faults in infrastructure with unknown cause per line, line class, area or item [no. or %/line, class, area or item]	[51]	O8

Table A.4: Economic railway infrastructure indicators.

Economic indicators			
Category	**Indicators** (Comments) [Unit]	**Reference**	**#**
Allocation of cost	**System level**		
	Maintenance cost (incl. or excl. management cost) [monetary]	[36, 45, 52, 54]	E1
	Maintenance management cost (or Indirect maintenance cost) [monetary]	[45, 54]	E2
	Maintenance cost per train-km, track-km, fkm or gross-ton-km [monetary/train-km, track-km or fkm]	[36, 45, 50, 51, 56, 57]	E3
	Maintenance contractor cost [monetary]	[54]	E4
	Corrective maintenance cost [monetary]	[58]	E5
	Preventive maintenance cost [monetary]		E6
	Sub-system level		
	Maintenance cost per line, line class, area or per item [monetary/line, class, area or item]	[59, 60, 61]	E7

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

HSE indicators			
Category	**Indicators** (Comments) [Unit]	**Reference**	**#**
Health	Maintenance personnel absenteeism [time or no.]	General	H1
	Maintenance employee turnover [no.]		H2
	Maintenance employee talks [no.]		H3
Safety - General	Urgent and one-week inspection remarks [no.]	[51]	H4
	Harmonised inspection remarks		H5
	Deaths and injuries (or Casualties and accidents) [no.]	[36, 44, 54, 62, 63]	H6
	Vehicle damages [no.]	[44]	H7
	Accidents at level crossings [no.]	[10, 36]	H8
	Accidents involving railway vehicles [no.]	[10]	H9
	Incidents (or Mishaps, or Potential injuries) [no.]	[54]	H10
HSE indicators			
Category	**Indicators** (Comments) [Unit]	**Reference**	**#**
Safety - Maintenance	Maint. accidents and incidents (occurred and potential) [no.]	[62]	H11
	Failure accidents and incidents (occurred and potential) [no.]		H12
	Derailments [no.]	[36, 54, 64]	H13
	Bucklings (or Sun kinks) [no.]	[36, 65]	H14
Environment	Envir. accidents and incidents due to failure [no.]	General	H15
	Energy consumption per area [J/area]	[10]	H16
	Use of envir. hazardous mtrls [-]		H17
	Use of non-renewable mtrls [-]		H18

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

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

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

Features	Method	Parameters (component level)	PIs (Sub-system level)
Superstructure - Switches and crossings (S&C)			
Geometry and integrity	Geometry car	Track deflection at switches	Deduced: S&C deflection inspection remarks [No. or No./S&C]
	Continuous monitoring using sensors	Contact area between blade and rail, Switch flangeway (open distance), Operational force, Power and current usage, Residual stress (retaining force), Detector rods pos.	Deduced: Malfunctions per switch type [No. or %] (in open, in closed, residual stress, detector rods, power or current consumption)
		Impacts on frog (wear)	Deduced: Axis passing [No.]
		Frog fastening force	-
		Rail temp, Long. forces	
	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]
Superstructure - Overhead contact system (OCS)			
Position and Condition	Optical sys.	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 sys.	Condition of catenary wire, droppers, clamps and contact wire	

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Link and Effect Model for Performance Improvement of Railway Infrastructure

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Link and Effect Model for Performance Improvement of Railway Infrastructure

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Abstract

Railway traffic has increased over the last decade due to greater energy costs and the need to reduce emissions. To manage railway infrastructure assets effectively against agreed and set objectives, the infrastructure performance needs to be measured and monitored. Different systems are used to collect and store data of traffic, failures, inspections, track quality, etc., for the analysis and exchange of performance indicators. However, these tools are often used in an ad hoc manner, partly because of the weaknesses of traditional performance measurement systems. The link and effect model emphasizes the underlying performance drivers and killers, rather than the thresholds as in traditional performance measurement systems. This model provides information on performance killers and drivers and how railway systems are interlinked, thereby facilitating proactive decision making. In this paper, the system and methodology are applied to a case study of a railway section in Sweden. The performance drivers and killers in terms of failures, train delays and repair times are identified and linked to potential savings.

1 Introduction

Railway traffic has increased over the last decade and is likely to further increase with the shifting of transportation from road to rail due to increasing energy costs, road and sky congestion, and the demand to reduce emissions [1]. The key goals of the White Paper 2011 for the European transport system include a 50 % shift of medium distance intercity passenger and freight journeys from road to rail and waterborne transport, and a 60 % cut in transport CO_2 emissions by 2050. The available capacity of the railways has to be enhanced and become greener if these demands are to be met.

Efficient and effective maintenance is required to assure maximum dependability and capacity of the existing railway infrastructure. To manage maintenance successfully within the scope of set objectives, the infrastructure performance needs to be measured and monitored. Performance indicators (PIs) of reliability, capacity, punctuality, etc. are extensively used by infrastructure managers (IMs) in decision making. However, they are often used in an ad hoc manner and seldom standardised. Performance measurement can lead to savings and bring business safety by more proactive management. As additional costs are associated with measuring, it is important to thoroughly analyse what, where, when and how to measure [2]. The efficiency and effectiveness of railway infrastructure can be improved if an appropriate performance measurement (PM) system is selected,

one which links the various objectives of the stakeholders. In traditional PM systems, PIs are given threshold values, indicating when an action needs to be taken, i.e. they can be reactive if used wrong. The underlying factors responsible for the performance are not thought of before a threshold has been passed, which, in effect, turns PIs into black boxes. But in the link and effect (LE) model, PIs are analysed for the underlying performance drivers and killers, providing a blueprint for improved PIs.

This paper studies the performance measurement of railway infrastructure using a link and effect model. The model employs a top-down and bottom-up approach, breaking down overall strategic goals into operational objectives, followed by measuring and studying the outcomes in terms of performance killers and drivers. The model is tested in a case study in Sweden. The strategic planning of transportation is reviewed with emphasis on European and Swedish national perspectives to identify goals and objectives. Thereafter, statistical analysis of operation and maintenance data is carried out to study performance outcomes in terms of performance killers and cost drivers, i.e. the underlying factors of the performance. In brief, the link and effect model forms a performance measurement system based on drivers and killers for railway infrastructure, utilising a top-down and bottom-up approach and continuous improvement (kaizen).

2 Performance improvement under a link and effect model

With increasing competition, internationalisation and HSE (health, safety and environmental) legislation, traditional accounting using only financial measures is insufficient for assessing business performance [3, 4]. Accordingly, new performance measurement methods, scorecards and frameworks have been developed considering measures of non-financial perspectives [5, 6, 7]. For example, the maintenance function, a key element in the business success of many organisations [8, 9, 10], now employs more holistic and balanced performance measurement systems. Performance measurement systems have shown to increase the performance and competiveness of organisations through their use of more balanced metrics (e.g. see [7, 11]), but there are some implementation issues. In a literature review, Bourne et al. [12] list the issues noted by researchers in the implementation of performance measurement initiatives, including the following:

- Time and expense

- Lack of leadership and resistance to change

- Vision and mission may not be actionable if there are difficulties evaluating the relative importance of measures and problems identifying true drivers

- Goals may be negotiated rather than based on stakeholder requirements

- Striving for perfection can undermine success

- Strategy may not be linked to department, team and individual goals

- A large number of measures dilutes the overall impact

- Metrics can be poorly defined

- A highly developed information system is required and data may be hard to access

- Consequences of measurement

Kaplan and Norton [13] list several of the issues recorded by Bourne [12] and stress the problem of overlooking the strategy planning and instead introducing a rigorous data collecting computer system. Davenport et al. [14] carried out interviews with 20 companies and found that a major concern in the information age is that companies are not turning data into knowledge and results. Karim et al. [15] make similar observations in maintenance data processing, saying the gap between data processing and knowledge management is too large. In traditional PM systems, PIs give quantitative numbers of something and omit the underlying factors responsible for the performance of the PIs. The link and effect model aims at providing the user with knowledge of the underlying performance drivers and killers.

Concerning the problem of 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 of measures on a scorecard, thereby confusing detail with accuracy [16]. The number of strategic level indicators depends on the number of senior managers, but identification of the most important indicators and data aggregation is needed since there can be several hundreds of indicators at the operational level. Aggregation of data is a weakness of traditional performance measurement systems; the link and effect model tries to solve this by replacing thresholds with a performance measurement of underlying factors.

Infrastructure managers (IMs) have grown with the expansion of railways; thus, operation and maintenance practices have grown with respect to the specific needs of each IM. However, harmonisation and increased use of standards have come with the globalisation, especially in the EU, considering increasing interoperability and building of a trans European railway network [17]. 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 a computerised maintenance management system (CMMS) within an organisation can alter the performance measurement practices and monitoring of historical asset condition data. Organisational changes can also affect the success of measuring performance. 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, e.g. maintenance procedures and ERP

- Organisational changes

- Evolving regulations, e.g. health, safety, security and environment

- Stakeholder requirements

- Fluctuations in economy, i.e. the business cycle

Strategic planning and performance measurement need to be integrated because of the many stakeholders; at the same time, they must be simple to be understood so that they can be adjusted to meet new requirements (see Figure 1).
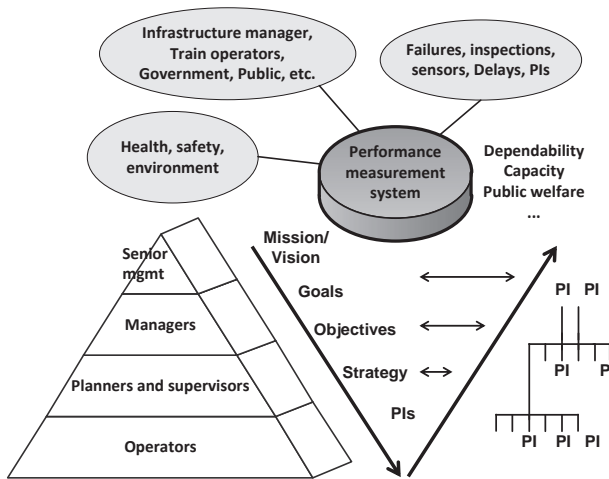

Figure 1: Illustration of integrating strategic planning with performance measurement in a link and effect model for the railway business.

The link and effect model aims to solve some of the problems of traditional performance measurement systems. More specifically, it omits thresholds and replaces them with the underlying factors responsible for the performance, i.e. the performance drivers and killers. Indicators with thresholds need attention only when some limit has been passed, which in some indicators can lead to reactive management. In contrast, the link and effect model gives knowledge of the underlying drivers and killers, providing a basis for improvements, i.e. a white box approach. It is more dynamic and proactive since improvements are carried out continuously instead of at some threshold. Finally, as PIs are often aggregated measures, there is a risk in more traditional models of losing the perception of the underlying factors if they are hidden behind a number. See Figure 2.
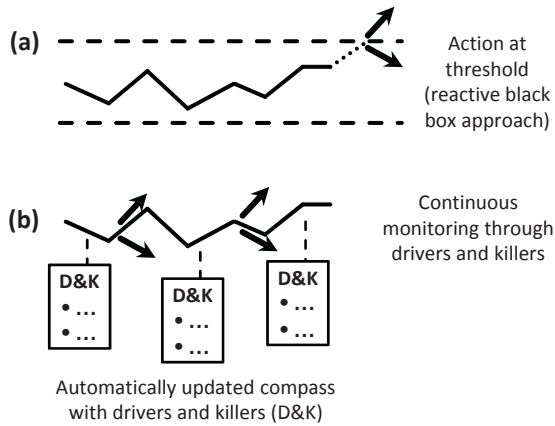
Figure 2: (a) Traditional performance measurement system with thresholds. (b) Link and effect model with performance compass.

3   The link and effect model

The link and effect model has two main components: a top-down and bottom-up approach, Figure 1, and a four-step continuous improvement process, Figure 3. Its methodology starts by breaking down the objectives, followed by updating the measurement system accordingly, analysis of data and finally identification and implementation of improvements. The link and effect model is related to reengineering in its structure, but it considers both physical assets and business processes as part of reengineering.

The first step of the link and effect model, the break-down of objectives, concentrates on gathering stakeholders objectives and assembling them into a common framework. For railways in the EU, aligning and harmonisation start at the European level and are broken down to national governmental and infrastructure manager levels, i.e. from strategic to operational planning.

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.

IMs are collecting a vast amount of data, but analysis is required to determine what data are required and what data are superfluous. Accordingly, Step 3 identifies the important data for developing indicators and for identifying performance drivers and killers.

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, reengineering physical assets and processes, implementing prognostic techniques and further defining indicators and databases.
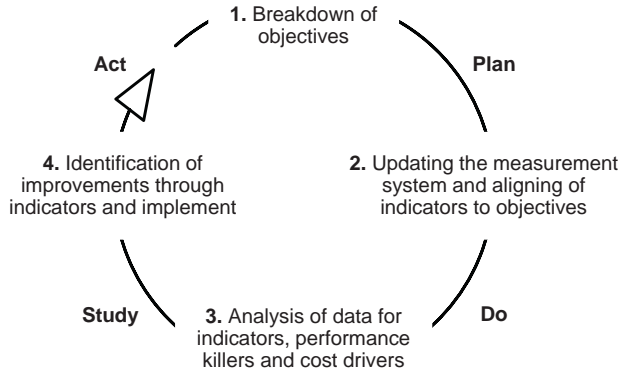

Figure 3: Steps added to the link and effect model for performance improvement of railway infrastructure utilising continuous improvement (kaizen).

4   Case study

The selected case study of a Swedish railway demonstrates and validates the link and effect model. The model begins by breaking down goals of transportation at the European level, followed by analysis at the national level of Sweden and the Swedish infrastructure manager, Trafikverket (Swedish Transport Administration).

4.1   Step 1: Break-down 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 components and putting them into the same terminology; secondly, translating the high-level initiatives and goals, which can be conceptual, into specific operational tasks. For a review of the railway infrastructure management in Sweden, see work by [18, 19].

At the European level, the White Paper on the European transport system of 2011 identifies the relevant components [1]:

- Vision: a competitive and 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

Key components 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 [20]

- Objectives: Railway operation and maintenance related objectives can be found in Trafikverkets quality of service (QoS) scorecard [21]

By studying the QoS scorecard, we find two indicators that 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 perspectives to operational measures. By studying the objectives, we find 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; see Figure 4 [22].
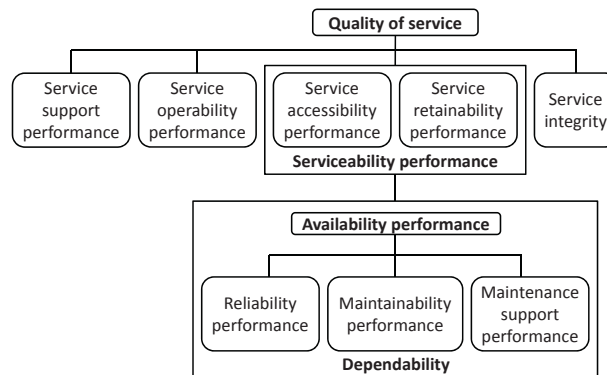

Figure 4: Quality of service. Adapted from [22].

As can be seen in Figure 4, availability is a vital component of service quality. The focus in this case study is on availability, more specifically, on failures and down time in railway infrastructure; see Figure 5.
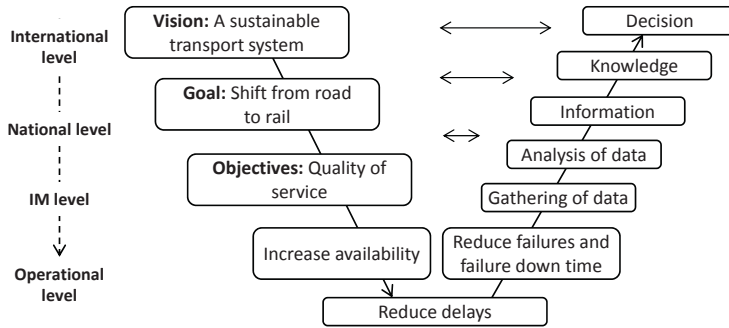
Figure 5: Break-down of strategy into failures and down time. Based on [1].

4.2 Step 2: Updating the measurement system and aligning indictors

Next, indicators need to be set up and aligned to measure the results. Indicators related to failures and down time specific to railways [23, 19, 24] include:

- 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 Trafikverkets 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, the objective of the link and effect model is to present an indicator along with its underlying factors, not just as an aggregated measure.

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

Operation and maintenance data of Swedish railway section 111 have been collected, validated and analysed. Section 111 is a 128 km 30 tonne mixed traffic heavy haul line stretching from the border of Norway, Riksgränsen, to Kiruna city (Figure 6). 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.

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

The corrective maintenance work order data consist of urgent inspection remarks reported by the maintenance contractor, as well as failure events and failure symptoms identified outside the inspections, commonly reported by the train driver, but occasionally reported by the public. The work order failure reports include the three categories of RAM (reliability, availability and maintainability) failure as identified by the European Standards 50126 [25]; see Figure 7. Failures identified outside inspections include the following:

- Accidents with animals

- Inspections after wheel impact

- Actions after failure in railway safety equipment

- Actions after alarms

- Actions after report from operators or others

- Actions after suspecting failure

- Lowering failed pantographs

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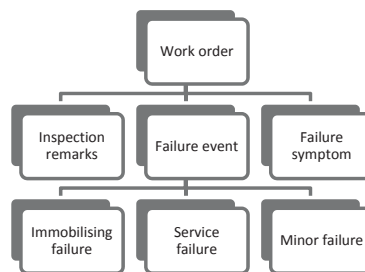

Figure 7: Work order description. The three RAM (reliability, availability, maintainability) categories are: immobilising failure, service failure and minor failure.

Matlab software is used to integrate work orders with train delay data, to carry out basic control of data quality and to perform data analysis. Starting at the system level of the railway infrastructure, work orders and delays are plotted in a probability-consequence diagram in Figure 8. The whole data set of 1 966 WOs is used on the left hand side of the figure, while data up to the 98th percentile, with respect to delays, can be seen on the right hand side. The two percent longest delays are considered as outliers on the right hand side. Outliers are preferably analysed before decision-making, but this is beyond the scope of this research. All further analysis is based on WOs with delays up to the 98th percentile. In terms of WOs, 1 926 out of 1 966 WOs are considered; in terms of delay, this is 112 616 minutes out of 166 693 minutes.

The hypotenuse in the probability-consequence diagram (Figure 8) can be used for risk ranking [26]. The figure shows that the poorest performing systems are the switches and crossings (S&C) and the track, together causing 45 470 minutes delay out of the 112 616 minutes, i.e. 40 % (Figure 8b). These two systems are further analysed in Figure 9.
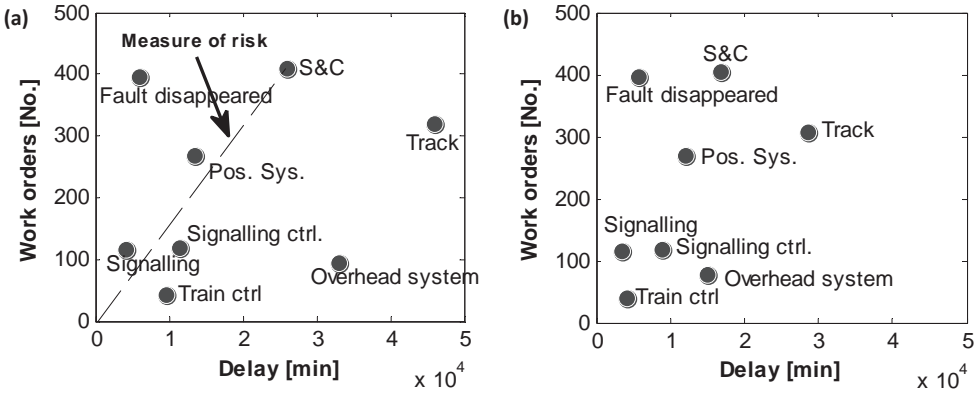

Figure 8: Probability-consequence diagram at system level, displaying work orders and corresponding train delays. (a) Complete data set and (b) data up to the 98th percentile for delays.

Figure 9a 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 with respect to WOs and delays. 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.
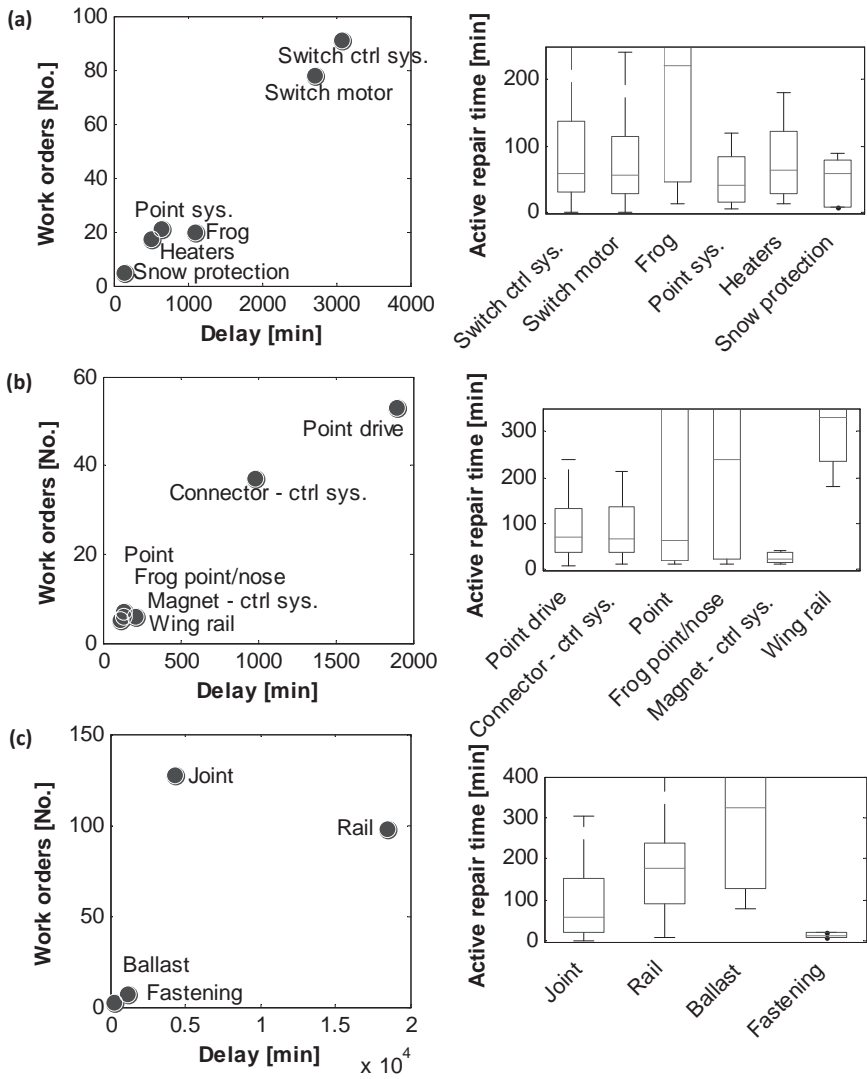
Figure 9: Analysis of the: (a) subsystems of S&C, (b) components of S&C and (c) subsystems of the track. Delay data up to the 98th percentile are used.
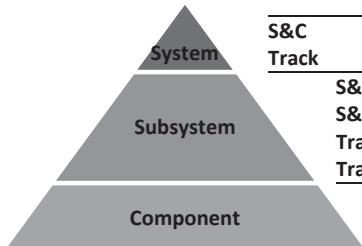
The subsystems of the S&C are further broken down to the component level in Figure 9b. Connectors and point drives, which are part of the switch control system and switch motor, are found to have a high risk ranking. In addition, the frog point and wing rail of the frog have high active repair times.

Lastly, analysis of the track subsystems appears in Figure 9c. The figure shows that joints and rails are the subsystems responsible for the poor performance of the track. Interestingly, joints cause many WOs, but few delays. In contrast, the rail causes many delays but fewer WOs. The boxplot indicates that rail WOs takes three times longer to repair; a possible reason for the high delays. Joints consist of insulation pads and insulation rings causing short circuits, the main reason for WOs, while the main reason for rail WOs is breakage.

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

Large savings would be obtained if the performance killers could be improved to meet the performance drivers. Table 1 lists work orders, train delays and risk ranking of performance killers to indicate potential savings. The risk ranks equal the length of the hypotenuse after normalising the x-values to the y-values by dividing the delays by 100.

Table 1: Work orders (WOs) and train delays of performance killers.

		WOs [No.]	Delay [Min]	Risk rank
System	**S&C**	404 (21%)	16880 (15%)	**438**
	Track	308 (16%)	28590 (25%)	**420**
Subsystem	**S&C: Ctrl sys.**	91 (4,7%)	3069 (2,7%)	**96**
	S&C: Motor sys.	78 (4,0%)	2724 (2,4%)	**83**
	Track: Joints	127 (6,6%)	4325 (3,8%)	**134**
	Track: Rail	98 (5,1%)	18470 (16%)	**209**
Component	**S&C: Connector**	37 (1,9%)	989 (0,9%)	**38**
	S&C: Point drive	53 (2,8%)	1898 (1,7%)	**56**

Table 1 gives figures of potential savings; however, aggregating data over nine years does not necessarily give accurate information of the present state. The main 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. In Figure 10 below, the data of railway section 111 (up to the 98th percentile) are used to calculate yearly risk ranking. As in the probability-consequence diagram, the risk is given by the hypotenuse [26]. The top three systems appear for each year. Letter D stands for fault disappeared, which is the term used when the repair team could not find the fault. It can be seen that the fault disappeared (letter D) risk ranking is high from

2005 and onward, while risk related to the track (letter B) goes down. The performance compass can be expanded with other underlying factors, e.g. various maintenance times.
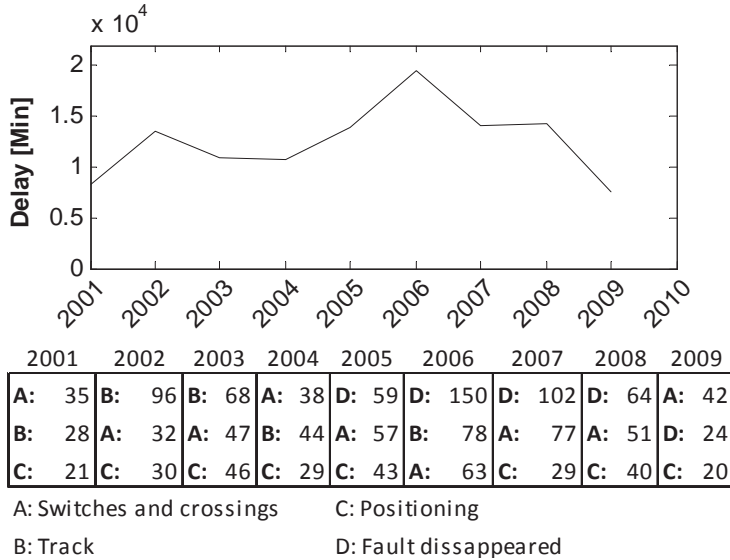

2001		2002		2003		2004		2005		2006		2007		2008		2009	
A:	35	B:	96	B:	68	A:	38	D:	59	D:	150	D:	102	D:	64	A:	42
B:	28	A:	32	A:	47	B:	44	A:	57	B:	78	A:	77	A:	51	D:	24
C:	21	C:	30	C:	46	C:	29	C:	43	A:	63	C:	29	C:	40	C:	20

A: Switches and crossings   C: Positioning

B: Track   D: Fault dissappeared

Figure 10: Indicator of delay with performance compass of each year showing the three underlying systems with highest risk ranking.

4.4   Step 4: Identification of improvements through indicators and implement

The previous section shows how indicators, performance killers and cost drivers can be identified. Performance drivers and killers on section 111 are identified in Figures 8-10 and Table 1. By redesigning or applying preventive maintenance to the identified performance killers, the overall delay can be reduced in the most efficient way, directly impacting the indicators listed in Step 2. However, it is preferable to simulate improvements before moving to action. Figure 11 provides 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 power outage faults in the railway reduces most.
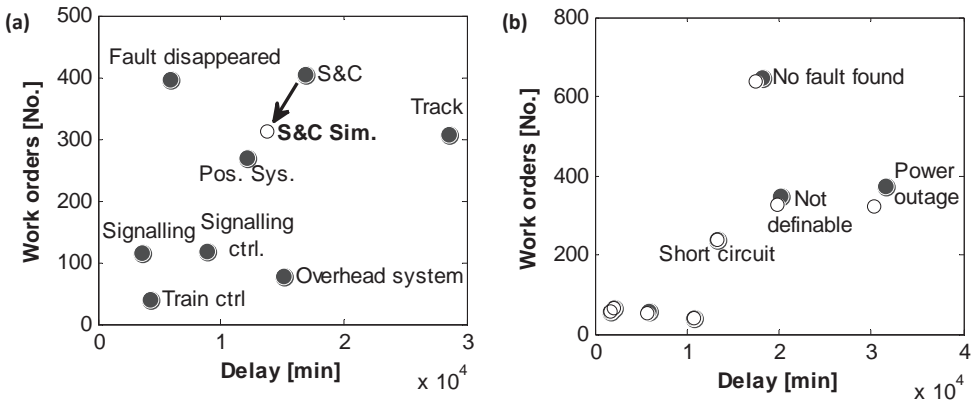
Figure 11: Simulation at system level of the railway section. (a) Impact on the S&C when all the WOs of the switch controller system are removed from the dataset. (b) All WOs sorted according to the registered actual fault. The black circles show the result when all the WOs of the switch controller system are removed from the dataset.

5 Discussion and conclusions

In traditional performance measurement systems, PIs are given threshold values, indicating when an action needs to be taken, i.e. they can be reactive if used wrong. Since the PIs depend on historical data, the underlying factors responsible for performance are not considered before a threshold has been passed, making some PIs intangible and possibly black boxes. This is an issue since PIs are often aggregated measures of several indicators, e.g. production delays or overall equipment effectiveness. In short, aggregated PIs in traditional performance measurement systems can be reactive and fail to provide in-depth knowledge.

The link and effect model was designed to analyse performance drivers and killers, rather than thresholds as in traditional performance measurement systems. While traditional performance measurement systems aggregate information in a bottom-up manner, the link and effect model starts at the top and breaks down objectives into indicators and underlying performance killers and drivers. In this approach, the problems of reactive thresholds and aggregated black box measures are avoided, making the performance measure more dynamic. The main purpose of the study was to present indicators along with their underlying factors, thereby solving some of the problems in measures with only thresholds (Figure 10).

In the application of the model to the case study (Swedish railway section 111), we found that the key components of strategic planning in the railway business are used differently and to varying extents by the various stakeholders; this means that an experienced person is required to align strategic, tactical and operational planning under

the same terminology and top-down basis.

Data analysis was carried out in two parts. The first part calculated performance drivers and killers of railway infrastructure systems for nine years (Table I). The second part performed a similar analysis for each of the nine years (Figure 10). It is found that aggregating data over nine years does not necessarily give accurate information of the present state.

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

Further research could consider data quality in more detail. WOs require a number of fields to be completed before closure; therefore, detailed analysis of practice and requirements for WO closure can enhance the understanding of WO morphology and data quality.

Acknowledgment

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