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LICENTIATE THESIS

A Study of Maintenance Performance Indicators for the Swedish Railroad System

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The thesis is designed as a state of the art regarding the use of maintenance performance indicators from a railway infrastructure perspective. During the research are one research report, three conference proceedings, and two technical reports delivered.

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Thomas Åhrén
Luleå, August 2005

ABSTRACT

The Swedish railway authorities have a long tradition of using performance indicators to follow up their performance. Already in 1915 when they decided to electrify the iron ore line between Kiruna and Riksgränsen, they introduced some indicators to measure and follow up expected benefits of upgrading the transportation system, e.g. total amount and costs per transported iron ore tonnage, employee safety training, and accidents or near-accidents related to the new power source of electricity.

Today, one of the requirements on the infrastructure management is to achieve cost-effective maintenance activities and a punctual and cost-effective railroad transportation system. For this, cost-effective maintenance processes are necessary to achieve budget targets, while punctual railroad system is required by different stakeholders. One key issue for Banverket is to verify that undertaken maintenance activities have given expected results, measured in terms of technical, economically, and organizational indicators.

The purpose of this thesis is to identify and develop a set of performance indicators that supports the maintenance decision-making process in proportion to punctuality, safety, environmental impact and profitability; i.e. establishing a link and effect model. The main aim is to clarify how different maintenance performance indicators can be used to make optimal decisions in the maintenance process; show and illustrate present status of the infrastructure as well as predict the future condition based upon today's maintenance decisions.

The analysis of existing and potential maintenance performance indicators resulted in a useful set of indicators applicable for railway infrastructure assets management, classified into different classes and subgroups appropriate to match a modified link and effect model originally developed for the offshore industry. A link and effect model adjusted to management of railway infrastructure assets is also presented.

In order to successfully implement performance indicators it is important to start with the definition of the business goals and overall objectives that later on must be broken down to maintenance objectives. With clear objectives regarding punctuality, safety, environmental impact, and profitability, is it possible to develop and implement indicators, especially performance driver indicators, for a maintenance department or maintenance contract.

SAMMANFATTNING

Svensk järnvägsförvaltning har lång tradition av att använda sig utav indikatorer vid verksamhetsuppföljning. Redan 1915 då det beslutades att malmbanan mellan Kiruna och Narvik skulle elektrifieras, introducerades ett antal indikatorer för att följa upp att förväntade fördelar också inträffade. Det implementerades också några indikatorer för att följa upp utbildningsinsatser med anledning av att en ny kraftkälla introducerades.

Idag är kraven på infrastrukturförvaltningen att den ska leda till både ett kostnadseffektivt underhåll som klarar att hålla sig inom givna budgetramar och ett kundkrav om ett punktligt och kostnadseffektivt järnvägssystem. Det är viktigt för Banverket att verifiera att underhållet leder till förväntade resultat i tekniska, ekonomiska och organisatoriska termer.

Syftet med detta forskningsprojekt är att identifiera och utveckla indikatorer som kan användas som stöd för underhållsbeslut som rör punklighet, säkerhet, miljö och lönsamhet. Målet är att beskriva hur indikatorer kan användas för bättre underhållsbeslut samt beskriva hur indikatorer kan användas för att visa nuvarande anläggningsstatus och förutspå framtida status baserat på dagens underhållsbeslut.

Analysen av existerande och potentiella indikatorer resulterar i ett antal indikatorer som är lämpliga att använda för järnvägsinfrastrukturförvaltning. Dessa är klassificerade och grupperade för att passa en modifierad länk och effektmodell som ursprungligen utvecklats för Offshoreindustrin. En länk och effektmodell för järnvägsinfrastrukturförvaltning presenteras också.

För att få en lyckad implementering av indikatorer är det viktigt att först identifiera övergripande mål och strategier, som därefter bryts ned i lämpliga underhållsmål och strategier. Finns klara mål för punktlighet, säkerhet, miljö och ekonomi är det möjligt att utveckla och införa indikatorer, och då speciellt förutspående indikatorer, för underhållsverksamheten.

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1 INTRODUCTION AND BACKGROUND

This chapter gives the reader a brief introduction to the background and research problem area.

1.1 Evolution for Swedish railway network

The history of the Swedish railway network goes back more than 150 years (Banverket, 2005). From the beginning, both private and government initiatives were undertaken to build the rail network. In 1939 was the entire network nationalized, and Swedish State Railways (SJ) was established. The Swedish National Rail Administration (Banverket) was formed in 1988 when the infrastructure ownership was separated from SJ who now became a pure traffic operator. In 1998 was Banverket divided into an infrastructure owner organization and result units such as operation, maintenance, and consultancy units, i.e. one purchasing organization and several contractor organizations.

The Swedish railway authorities have a long tradition of working with and use performance indicators to follow up their performance. Already in 1915 when they decided to electrify the iron ore line between Kiruna and Riksgränsen, they also introduced some indicators to measure and follow up calculated benefits of upgrading the transportation system (Wiklund, 2005). Two of the introduced indicators reflected the transportation process, e.g. costs per transported iron ore tonnage and total amount of transported iron ore tonnage, and some health, safety and environmental (HSE) related indicators as employee safety training and accidents or near-accidents related to the new power source of electricity.

The national railroad system is used for freight and passenger transportation, where political and social considerations has to be taken in to account; e.g. safety and environmental impact as well as public demands of safe, reliable and cost-effective transportations. The railroad is therefore strictly governed by regulations and government legislations; containing technical limitations and financial targets, many of these are used as performance indicators (Ministry of Industry, 2002).

Today, the railroad is a complex system, where an unexpected event or disruption will affect different stakeholders, e.g. passengers, operators and contractors. An obvious example of this, were all extensive train delays due to bad weather conditions with heavy snowfalls during the winter 2001/2002 (Banverket, 2002a). It is therefore necessary to identify, classify, and analyze all disruptions in the railroad transportation process, so that they can be minimized through effective and efficient maintenance activities. Maintenance decisions should be taken on rational foundations, based on a carefully prepared and a well defined maintenance strategy developed by the infrastructure owner, taking different stakeholder requirements into account. In order to do so, maintenance decisions must be based on reliable data reflecting the status and condition of the railway infrastructure system.

Banverket is the responsible authority for rail traffic in Sweden. They follows and conducts development in the railway sector, assisting parliament and the government on issues related to railway besides the operation and management of state track installations, co-ordinate the local, regional and inter-regional railway services, and provide support for research and development. Banverket's operations are therefore divided into sectoral duties, track provision and production. The responsibility for track provision, i.e. the infrastructure asset management is imposed on five different track regions with support from the head office. Since 2001 maintenance is outsourced to different in- or out-house contractors.

1.2 Problem discussion

When Banverket was established, it took over a railway infrastructure in need of scale renewals. Therefore, during the 1990s Banverket have made large investments and re-investments to upgrade and meet increased requirements for the railroad system, e.g. increased axel loads, higher speed, and increased transportation volumes, see Figure 1 (Banverket, 2002b). As a consequence, this has led to increased demands on Banverket to have a more effective and efficient track maintenance.

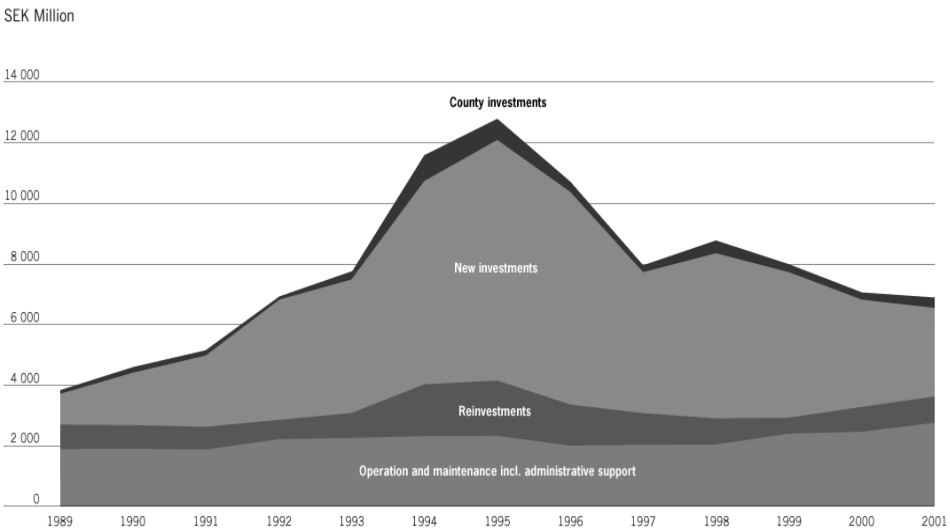

Figure 1. Operating volume for track provision 1989–2001 (Banverket, 2002b)

The requirements from the infrastructure management perspective, in order to achieve cost-effective maintenance activities and a punctual and cost-effective railroad transportation system, are an ongoing development process in the area of railway maintenance engineering. Cost-effective maintenance processes are necessary to achieve budget targets, while punctual railroad system is required by different stakeholders. If this is done properly, Banverket is able to keep existing infrastructure as well as rolling stock in good shape. Thereby, it is possible to prolong the expected life for such assets.

One key issue for Banverket is to verify that undertaken maintenance activities have given expected results. One way of doing that is to compare railway asset condition before and after maintenance activities have been carried out. These measures in terms of technical, economically, and organizational indicators can, for example, relate to:

- Maintenance planning
- Working time for different types of maintenance activities
- Maintenance costs
- Asset condition and reliability

Efficient and effective maintenance is also expected to give environmental benefits, reduced number of train disruptions, increased safety, etc. Together this gives competitive and cost effective transportation solutions for both passengers and industry.

In an organization like Banverket managing large complex railway assets, asset management and asset condition monitoring requires a lot of different asset condition data and measures. The decision maker is dependent of knowing present asset condition, as well as asset degradation patterns; knowing asset condition degradation trends to predict the future. The decision making process can be supported by different decision support system, provided that these system are supported by the right type of necessary data and measures. In the end, this indicates a more effective and systematic decision making process. For Banverket, with a total maintenance budget on approximately 2 billion SEK, every percentage of reduced maintenance costs is worth 20 million SEK per year.

As mentioned before, the use of indicators within Banverket is not something new. It was already in use in 1915 when the iron ore line between Kiruna and Narvik was built. A quick glimpse to other industries shows that the evolution and use of performance measurements started as early as in 1880s in USA (Segovia and Thornton, 1990). The evolution of management accounting and management accounting systems (MAS) reach its peak in the early 1920s. The different management accounting techniques developed during this time period is still in use. The purpose then as it is today, is to provide the management with relevant, accurate, and timely information regarding an organization's internal activities.

From the beginning, the use of MAS could be looked upon as an engineers approach to ensure good resource allocation and utilization, i.e. focus on management decisions rather than focus on reported profit (Segovia and Thornton, 1990). From the 1920s the use of MAS declined due to ever-increasing costs just to keep the MAS in function when the firm growth, i.e. more and more diverse product lines due to the market forces as well as manufacturing and technical developments. At the same time the influence of public accountants was increasing, leading to more focus on reported profit than management decisions, i.e. the auditors approach.

During the late 1960s, once again the need of complementary engineering management decision parameters increased, e.g. engineering approached management parameters used in the maintenance departments (Husband, 1976). Since the early 1990s the use of performance indicators for different purposes are quite common in the whole society, both public and industry.

1.3 Purpose

The purpose of this thesis is to identify and develop a set of Performance Indicators that supports the maintenance decision-making process; study and analyze the effect of maintenance activities in proportion to punctuality, safety, environmental impact and profitability, i.e. establishing a link and effect model.

The main aim is to clarify how different maintenance performance indicators can be used to facilitate effective and efficient decision making for the management of the maintenance process. The indicators will also make it easier to show and illustrate present status of the infrastructure, as well as predict the future condition based upon today's maintenance decisions.

1.4 Research Questions

The purpose of the study has been transferred in to the following research questions:

1. How can performance indicators support the maintenance decision-making process in proportion to punctuality, safety, environmental impact, and profitability?

2. How can a maintenance performance indicator frame work be designed?

3. How can a maintenance link and effect model with respect to punctuality, safety, environmental impact, and profitability be designed?

1.5 Scope and Limitations

This thesis focuses on maintenance and maintenance related activities from an infrastructure owner point of view, limited to the area of maintenance performance indicators. It is important that findings and results can be implemented in Banverket's prevalent organization, i.e. no suggestions needing organizational change that requiring new regulations or standards can be made.

1.6 Structure of the Thesis

The thesis structure is as follows.

The first chapter - *Introduction and Background* – introduces the reader to the background and research problem area. It also describes the purpose, research questions, and scope and limitations.

The second chapter - *Theoretical frame of reference* – presents the theoretical framework for this thesis.

In the third chapter - *Research Methodology* – is the research methodology presented. It also discuss the chosen research approach for this thesis

The fourth chapter - *Maintenance Performance Measurement* – presents the maintenance process for Banverket and maintenance performance indicators (MPI) in use. It also describes how some similar railway authorities abroad use MPI.

The fifth chapter - *Analysis and Results* – presents analyses and results for this study.

Finally, the sixth chapter - *Discussion and Conclusion* – discusses the findings in this thesis and some suggestions for future research.

2 THEORETICAL FRAME OF REFERENCE

This chapter consists of the theoretical frame of reference for this thesis, and important areas are described.

2.1 Maintenance

The purpose of maintenance and maintenance management is to maximize the production system availability at minimum costs, by reducing the probability of equipment or system breakdowns (Husband, 1976). The management of the maintenance process can from a holistic view be described as management of available maintenance resources, i.e. competence, capital, material, and information, to ensure a desired output in terms of high physical asset integrity, see Figure 2 (Liyanage and Kumar, 2002a). It also includes management of unexpected inputs as well as undesirable outputs in terms of equipment or plant anomalies or unwanted events.

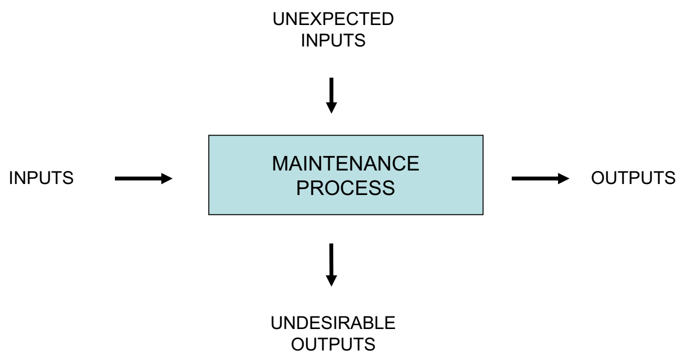

Figure 2. The holistic view of the maintenance process (Liyanage and Kumar, 2002a)

The evolution of maintenance and maintenance management starts with the time period up until the Second World War, when the dominating maintenance policy was run to failure (Kelly, 1989). This period is called The First Generation of Maintenance (Moubray, 1991).

During the time period up until the 1960s safety matters became more important as well as improvement in labour efficiency, and a more preventive maintenance strategy emerged; also called The Second Generation of Maintenance (Moubray, 1991). This change of strategy made it not only possible to plan maintenance activities; it also made it possible to start controlling maintenance performance, costs and production assets availability (White, 1973).

The third Generation of Maintenance (Moubray, 1991), emerged during the 1970s and the preventive maintenance strategy was developed further due to technological advances and requirements from maintenance managers to predict future amount of maintenance; a condition based maintenance strategy evolved (Kelly, 1989).

The evolution of maintenance has today reached the fourth generation of Maintenance, where maintenance is looked upon from a more holistic point of view (Dunn, 2003); an integration of production asset management and maintenance management (Peterson, 1999, Woodhouse, 1997). Maintenance is not longer viewed upon as a cost-profit centre, it creates value to the business process (Liyanage and Kumar, 2003, Liyanage and Kumar, 2002b).

Maintenance is basically needed due to lack of reliability and quality losses. According to standards, maintenance is a "combination of all technical, administrative and managerial actions during the life cycle of an item intended to retain it in, or restore it to, a state in which it can perform the required function" (SIS, 2001). Maintenance is often looked upon as a process including following: establishment of goal and strategy, program establishment, planning, execution, and analysis and continuous improvement, see Figure 3.

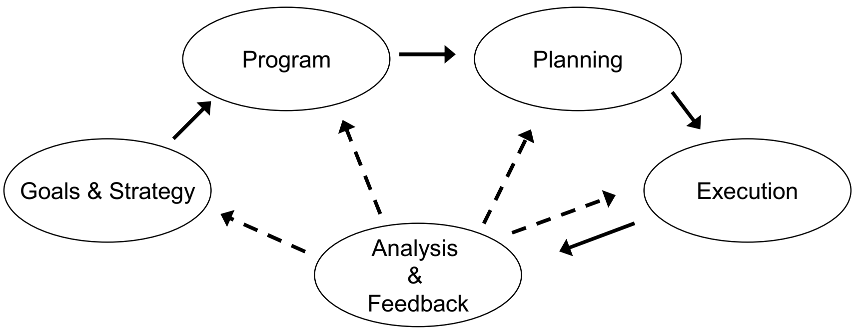

Figure 3. Maintenance Process (Ellingsen et al., 1999)

Maintenance is performed either as corrective after a disturbing equipment failure has occurred, or preventive to reduce the probability of future breakdowns (Swanson, 2001), see Figure 4. Traditionally, preventive maintenance is performed on a distance or timely basis. Today, often a predictive maintenance approach is used when it is possible to monitor the equipment condition, giving the opportunity to do maintenance only when there is a need for it. The benefits of this strategy are prolonged maintenance intervals and reduced maintenance costs (Swanson, 2001). Sometimes, it is however more cost-effective to have a run-to-failure strategy for cheap and easy failure detectable equipments that have no effect on the production process, i.e. no health, safety or environmental impacts.

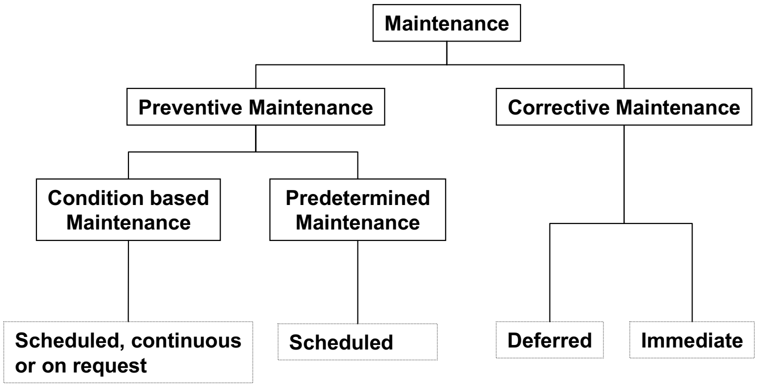

Figure 4. Maintenance overview (SIS, 2001)

In order to follow up and evaluate short and long term effectiveness and efficiency of the maintenance management and undertaken maintenance activities, as well as assessing that the maintenance process is supporting the overall corporate business objectives, is the use of maintenance performance measurement systems generating useful performance indicators a requisite (Wireman, 1998). Back in the 1960s was the main focus related to economy, equipment, and organizational issues (Husband, 1976), but today is also health, safety, and environmental issues equally important (Liyanage and Kumar, 2003).

2.2 Performance Indicators

A search through different databases and literature in order to find a definition of performance indicators indicates a mix of both different definitions as well as related types of indices and measures. It must be mentioned that no definition of maintenance performance indicators could be found. The following chapter summarize therefore the state of the art regarding performance indicators and related indices.

2.2.1 Indicators

A search through different data bases in order to give a definition of an indicator, results in five major types of definitions as follows:

- The technical definition, describing an indicator as a device showing how the pressure and volume inside a piston engine is changing (Nationalencyklopedin, 2002a).
- The chemistry definition, describing a substance showing the concentration of a specific substance (Nationalencyklopedin, 2002b).
- The ecological definition, saying that one organism through its existence is showing certain existing conditions (Nationalencyklopedin, 2002c).
- The anatomic definition, telling that an indicator is the muscle that stretches the index finger (Oxford English Dictionary, 2003).
- The economical definition, defining an indicator as a statistical useful measure, that in combination with other indicators are used to determine the general condition of the economy (Encyclopedia Britannica, 2003). Useful indicators for this purpose is inflation, interest, labor market, and business (InvestorWords.com, 2003). These indicators are sometimes even called index, key variables, comparative figures, and ratios.

2.2.2 Performance Indicators

An indicator can be defined as a number that describes the prevalent performance for a specific activity or occurrence (Allander, 1997). The number is normally related to a fixed measurement scale, e.g. the thermometer showing -17° C or the speedometer's 75 km/h. If the indicators are extended to measure the performance of working life related issues, they are called performance indicators; classified in to seven horizontal main groups, i.e. efficiency, effectiveness, productivity, budget/profit, quality of working life, innovation, and quality (Allander, 1997), see Figure 5. The indicators can later on be aggregated to a performance index.

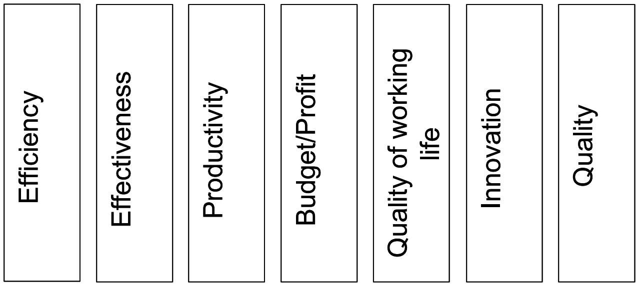

Figure 5. Allander's classification of Performance Indicators (Allander, 1997)

Performance indicators can also be defined as a comparison between present environmental condition and the desired one, i.e. the distance left to reach the goal (European Environment Agency, 2002), and as a measure capable of generating a quantified value to indicate the level of performance taking into account single or multiple aspects (Liyanage et al., 2001).

There exist more definitions of performance indicators, where one is "the key measures of the performance of a company, which are monitored and assessed to ensure its long-term success and helps to pinpoint the company's strengths and weaknesses" (A Dictionary of Business, 2002). According to this definition, the different indicators are often divided into following horizontal main groups:

- Strategic
- Operational
- Specific
- Behavioral
- Confidence
- Ethical

Broadly, performance indicators can be classified as leading or lagging indicators (Stricoff, 2000). Leading, lead, or prospective indicators is a performance driver, i.e. a measure which drives the performance of the outcome measure. The outcome measure itself is simply the lagging, lag, or retrospective indicator. Typical lagging indicators are different financial measurements. In economical contexts are often one additional indicator used, so called coincident indicators, (Encyclopedia Britannica, 2003). This indicator changes its value at the same time as the specific object, target, or event of interest is changing. They are beneficial to use when the measure of interest is more or less impossible to measure. An example of typical coincident indicators, are those who indicates changes in the overall economy, see Figure 6.

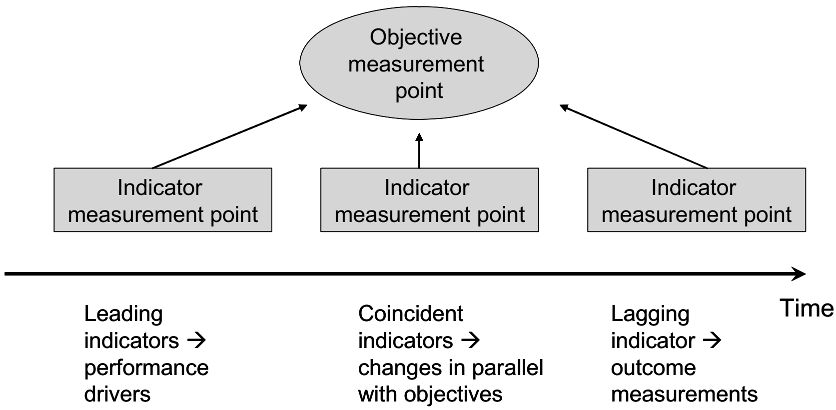

Figure 6. Leading, coincident or lagging indicators

2.2.3 Key Performance Indicators

Key Performance Indicators (KPI) is defined as "a performance indicator with a strategic significance, which is perceived as critical under given business circumstances and preferably selected from a pool of performance indicators", (Liyanage et al., 2001). Indicators can also be defined as a collection of one or more measures focusing on a predefined situation, and if several indicators are used at the same time and combined to each other whit the purpose to get objective information the resulting measure is now also called KPI (Smith, 2003). These measures can be used to assess critical parameters or processes. From maintenance point of view the developed KPI must yield objective information regarding maintenance, e.g. preventive maintenance, spare parts logistics, planning and follow up. In order to compare and evaluate the different KPI, they must reflect the outcomes in monetary terms or other comparable measures such as reliability of plant assets.

There are two important aspects that must be taken into consideration when KPI are used, (Smith, 2003). The first aspect is that input data can be inappropriate, giving wrong KPI outputs and wrong decisions based on the KPI. The other aspect is that managers must be aware that planned changes in for instance the production line probably will generate new and changed KPI measures, though everything is in order.

In order to use KPI as a decision support tool for business management, leading KPI should be used (Smith, 2003). In Table 1, 18 suitable KPI are listed and divided into seven horizontal main groups.

Table 1. Key Performance Indicators (Smith, 2003)

Main group	Key Performance Indicators
Reliability/Maintainability	▫ MTBF (mean time between failures) per total operation, area, or equipment ▫ MTTR (mean time to repair) per unit ▫ MTBR (mean time between repairs) per unit ▫ OEE (overall equipment effectiveness)
Preventive maintenance	▫ Preventive labor hours per emergency labor hours ▫ Preventive work orders per corrective or planned/scheduled work orders as a result of inspections
Planning and Scheduling	▫ Planned per schedule compliance ▫ Planned work per scheduled work
Materials management	▫ Stores service level ▫ Inventory accuracy
Skills training	▫ MTBF ▫ Parts usage
Maintenance supervision	▫ Maintenance control (unplanned hours per total hours) ▫ Crew efficiency (work hours completed on schedule per estimated time) ▫ Work order discipline (share of labor work accounted on work orders)
Work process productivity	▫ Maintenance costs per net asset value ▫ Total cost per unit produced ▫ Overtime hours per total labor hours

Since performance indicators is just an indicator of performance, KPI are nothing else than a more strategic and important indicator of performance (Wireman, 1998). The main purpose is to pinpoint possible areas for improvement within an organization. If common used and defined KPI are chosen, benchmarks between different organizations can be done. However, KPI can always be used to make internal benchmarks.

When developing and implementing the use of indicators within an organization in a more systematic way, they are often put together in a vertical indicator system similar to a traditional hierarchical organization structure, see Figure 7 (Wireman, 1998).

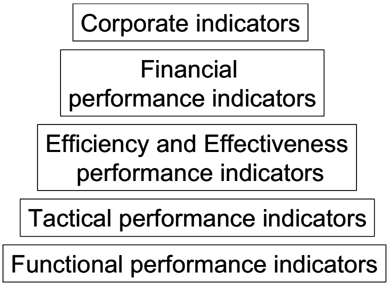

Figure 7. Wiremans's indicator structure (Wireman, 1998).

The indicator structure is developed from a top-down perspective, where the indicators at the highest indicator level must support the company overall objectives while indicators at the bottom of the indicator structure supports sub-processes or single equipment objectives (Wireman, 1998). The result is an indicator system where all indicators at different levels support organizational long term objectives. This indicator development method corresponds to the development process for balanced scorecards, see Figure 8 (Kaplan and Norton, 2001a, Kaplan and Norton, 2001b).

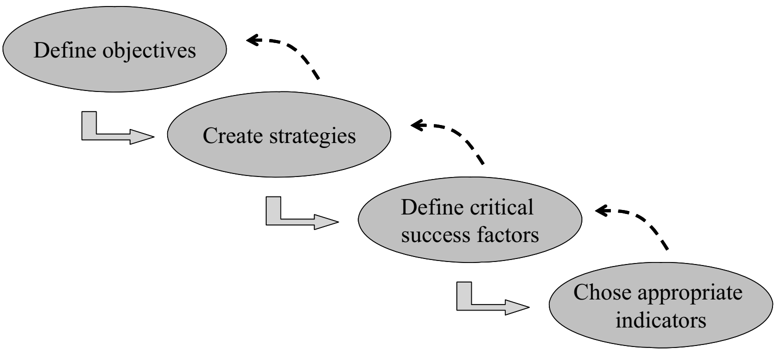

Figure 8. Indicator development process

While the development process for indicators follows a top-down structure, the indicator system reporting structure follows a bottom-up perspective (Wireman, 1998). The KPI on a top management corporate level is therefore built up of aggregated underlying indicator levels; i.e. several indicators on an operational level is aggregated up to a tactical level, and afterwards aggregated to the top management level. The indicator system is therefore normally provided with data on an operational level (Andersen and Fagerhaug, 2002, Engelkemeyer and Voss, 2000).

One example of an indicator system is presented in Figure 9 (Wireman, 1998). The different indicators are grouped in a vertical pyramid structure, linked to corporate asset management. The basic idea for development and implementation of the indicator system is to start with the bottom line in the pyramid; i.e. when the preventive maintenance related indicators are implemented and the managers have control over that process they start to implement the next level of different indicators. In order to make a successful indicator implementation, the different groups must be supported of belonging programs and processes (Wireman, 1998). As an example, development and successful implementation of reliability centered maintenance indicators need an implemented program for the same process, as well as underlying processes. The connection between the different indicator groups is not that strong, since the different indicators are collecting necessary data from the different programs.

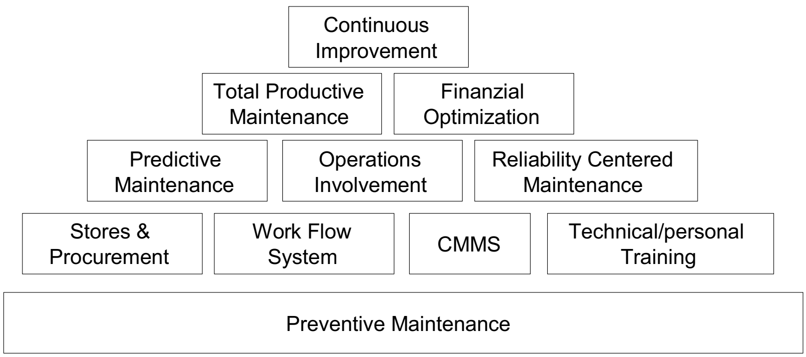

Figure 9. Wireman's maintenance asset management structure (Wireman, 1998).

International Atomic Energy Agency uses a different nomenclature to describe different types of indicators and their reciprocal relationship regarding nuclear power plant security (IAEA, 2000). The different indicators are grouped at three different levels in a vertical pyramid structure; overall indicators on a top management level which are broken down to strategic indicators and further on to specific indicators on a plant specific equipment level. It is the specific indicators that can be measured in the plant or in the organization, see Figure 10 (IAEA, 2000). In practice, this means that a large number of indicators on an operational level will be aggregated to a strategic level, and finally being aggregated to a small number of indicators on an overall level.

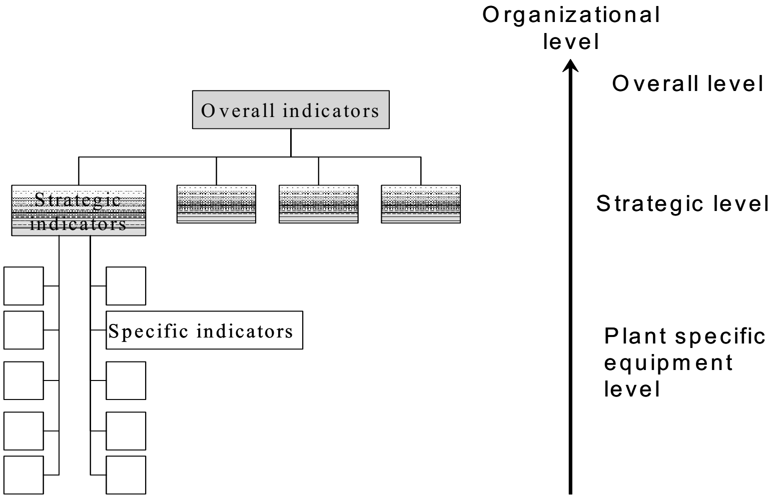

Figure 10. Relationship between overall indicators, strategic indicators and specific indicators (IAEA, 2000).

2.2.4 Key Variables

Key Variables can be defined as compressed information given by one single number (Mossberg, 1977). The word compressed indicates essentialness, as well as that the single number gives summarized information. The use of key variables indicates therefore that the user has limited ability to receive and use given information; often the case when the amount of information in reports etc. are to large compared to available reading time (Mossberg, 1977). Today, with the extensive use of different information and communication technologies, this is a known problem called data overload (Parida et al., 2003).

The overall purpose to use key variables is management and control. This purpose can be broken down to a planning or proactive purpose and a follow up or reactive one (Mossberg, 1977). The latter one can further be broken down into alarm and diagnostic purpose, see Figure 11. Key variables used for planning are normally numbers used to express the plan in a compressed form.

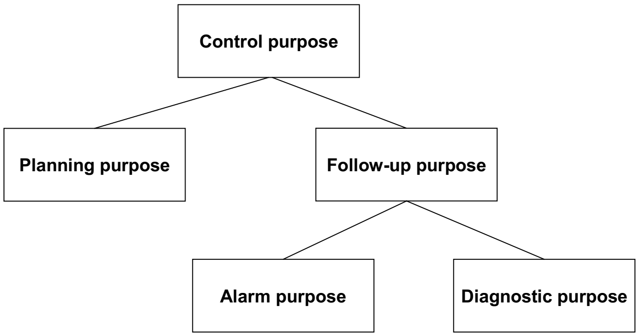

Figure 11. Purpose of Key Variable (Mossberg, 1977)

The follow-up process aims to find out if there is a need for some kind of necessary action decisions (Mossberg, 1977). The first step is therefore to identify if there is a need for action, i.e. alarm decision. Next step is to identify what type of actions that are required, i.e. diagnostic decision. The involved key variables in this process must therefore act as a signal or indicator that something is happening and give a hint of the characteristics of necessary decisions. To do so, the key variable must be described in three terms, to make it easier to understand it (Mossberg, 1977). These are:

- Description of the meaning of the key variable signal
- Description of the characteristics of the decision the signal pointing at
- Description on the connection between the signal and the decision characteristics

As described earlier, key variable is the same as compressed information. The key variable itself can be seen as replacement of undelivered uncompressed information, or as complement to delivered uncompressed information (Mossberg, 1977). Since all compression of information leads to some degree of losses of information, it is important to follow up and if possible, verify how much the information can be compressed; investigate how many key variables that are required to deliver the desired amount of information. In order to get better and more precise key variables over time, it is important to gather experience from practical use and build up experience and competence(Mossberg, 1977).

There is often an interest to study the relation between different key variables, since one key variable's degree of benefit can be dependent of other presence key variables (Mossberg, 1977). The relation between different key variables can be studied from three different perspectives, namely:

- Relationship through signals and decision characteristics
- Relationship through signals only
- Relationship through decision characteristics only.

When the key variable relation study is carried out, they can be put together in key variable groups or models giving new aggregated key variables (Mossberg, 1977). The different groups are logically arranged while the models can be seen as vertically hierarchical alignments. Two examples of key variable models are Return on Investments (ROI) more known as the Du Pont Model, and Overall Equipment Effectiveness (OEE).

2.2.5 Strategy and efficiency indicators

Maintenance related indicators can also be defined as strategy and efficiency indicators (Cummings, 1993). Strategy indicators refer to indicators intended to follow up the maintenance strategy and objectives. They compare present status against the planned one. The purpose is to focus on continuous maintenance improvement for the organization. They are normally divided into following (Cummings, 1993):

- Planning indices
- Workload indices
- Preventive/predictive maintenance indices
- Skills improvement indices
- Scheduling indices
- Material indices

Efficiency indicators refer to the concrete measures quantifying the processes the strategy indicators are supposed to follow up (Cummings, 1993). As an example, a company objective can be to reduce the amount of immediate corrective maintenance, i.e. strategic indicator. The concrete measures, i.e. efficiency indicators, that the company has to measure can be in terms of costs, workload, number of failures, etc. Exactly which measures one company chooses to use, is up to them to decide.

2.2.6 *Safety related indicators*

It is generally recommended that indicators are developed from a top-down perspective. However, this is not applicable for safety related indicators, since safety, health and environmental issues are not dependent on written corporate objectives (Stricoff, 2000). They are instead directly driven by activities and actions performed on the plant floor as well as plant equipment. Therefore, they should be developed from a bottom-up perspective, and also be reported the same way.

The corporate interest of implementing safety related indicators is to identify and focus on existing safety related risks (Stricoff, 2000). With this knowledge, the company can asses if this is acceptable or not. The judgements will largely be affected of the present public opinion and prevalent regulations. Later on, if necessary, the company can revise their objectives and strategies; safety related objectives and strategies are partly driven by external factors.

Since safety management itself basically is to prevent things from going wrong, i.e. prevent accidents and illness, the management must be proactive. For this purpose, it is important that indicators in use also provide the safety managers with preventive information, i.e. leading indicators must be used (Toellner, 2001). The use of leading safety indicators helps to set the focus on preventive actions and putting resources on accident prevention processes.

2.2.7 *Asset condition index*

In the middle of the 1990's, Scandinavian offshore industry pinpointed out the need for an overall asset condition index, describing an assets long term condition and degradation patterns not only from a pure technical point of view. A research project was initiated and resulted in the development of an asset condition index. The index is defined as an aggregated measure taking technical, financial, and statistical parameters into consideration, describing an asset's degradation compared with its original design state (NFR-PROSMAT 2000, 1999). The index aggregation structure is designed as a vertical pyramid structure and can be implemented into existing computer software.

2.2.8 Environmental biodiversity indicators

Human disturbance on different ecosystem varies from one place to another. Sometimes this impact can be relatively severe in certain areas. In order to manage these ecosystems in a long term view it is necessary to monitor and assess the ecosystem health (Lyons et al., 2000). For that purpose is environmental biodiversity indicator system developed, so called index of biotic integrity (IBI).

The IBI-system itself is a vertical indicator system, where the IBI-index is an aggregated parameter of different environmental biodiversity indicators (Lyons et al., 2000). The indicators themselves are measures reflecting the condition of different species in the actual ecosystem, i.e. assessing the specific species degradation level compared to its original state before the human disturbance on the ecosystem occurred. This degradation level is normally divided into three levels of degradation, namely good, fair, and poor (Lyons et al., 2000) or undisturbed, moderately disturbed, and severe disturbed (Kimberling et al., 2001). When aggregating these indicators to an IBI-index it is also easy to calculate the IBI-index's numerical value and its degradation level in the same way as for the different environmental biodiversity indicators.

2.2.9 Indicator design and characteristics

Today, maintenance is identified as a critical and strategic process within many organizations. Therefore is it necessary to manage maintenance in line with business objectives. When designing maintenance performance indicators it is important to relate them to both process inputs and outputs. If this is done properly maintenance performance indicators can provide and identify (Kumar and Ellingsen, 2000):

- Resource allocation and control
- Problem areas
- Maintenance contribution to business objectives
- Maintenance benchmarking and performance trends
- Maintenance personnel performance and contribution to maintenance and overall business objectives

In order to make it easier to develop and implement fruitful indicators, there are some basic questions that have to be taken into consideration to avoid future unpleasant surprises (The Local Government Management Board, 1995), namely:

- What is the purpose of the indicator

- What is the indicator supposed to measure
- How to implement the indicator
- Who owns the indicator
- Who is supposed to use the indicator

When the basic questions above are answered, more indicator specific characteristics have to be taken into consideration. In the development and implementation process of safety indicators and indicator system, it is important that the chosen indicators fulfil the following characteristics as far as possible in order to get reliable indicators and indicator system (IAEA, 2000). The different characteristics for the indicators are:

- Direct relationship between the indicator and safety
- Necessary data are available or capable of being generated
- Expressed in quantitative terms
- Unambiguous and meaningful
- Significance is understood
- Not susceptible to manipulation
- Are a manageable set and integrated into normal operation activities
- Can be validated
- Linked to the cause of malfunction
- Accuracy of data can be subjected to quality control and verification
- Actions can be taken on the basis of the indicators

When developing and designing environmental indicators is it important that the chosen indicators are scalable (Failing and Gregory, 2003). This means that the indicator must be able to be used locally at the same time as it is possible to aggregate it to be valid on a regional level and a national or international level or vice versa, i.e. it can be downscaled from a national level to a local one.

Experiences from different indicator users point out some other important characteristics to have in mind when indicators are to be developed and implemented, i.e. contradictory indicator characteristics. The most common ones besides of the term "leading or lagging indicators" are:

- Off the shelf or tailor made indicators: important if the indicators are supposed to be used in benchmarks (Wireman, 2004)
- Long or short term indicators: important when deciding how long time indicator measures have to be stored (IAEA, 2000)
- Slow or fast changing rate indicators: important for trend calculations or to decide if slower/faster redundant indicators must be used or developed,

often the case for environmental issues (Miljövårdsberedningen, 1998, Kimberling et al., 2001)

In the area of environmental issues it is recognized one problematic type of indicators, so called trade-of indicators. Trade-of indicators are a set of indicators representing different organizational objectives when put together the objectives are showing a contradictory behaviour (Failing and Gregory, 2003). Often one of the contradictory objectives is concerning financial issues, i.e. necessary actions are identified but no one is willing to pay for it. It is now up to the decision-makers to decide which way to chose, i.e. which one of the contradictory objectives is most important for the moment.

In the development and implementation process of environmental indicators, is it identified ten common mistakes that have been done quite often (Failing and Gregory, 2003). The mistakes are:

- Failing to define endpoints; i.e. different endpoints need different strategies and thereby different indicators
- Mixing means and ends; i.e. ends are the objectives while the strategies to achieve them are means
- Ignoring the management context; i.e. neglecting stakeholder requirements
- Making lists instead of indicators; i.e. indicators must pinpoint out information upon which management decisions can be made
- Avoiding importance weights for individual indicators; i.e. decision makers must know the relative importance of individual indicators
- Avoiding summary indicators or indices because they are considered overly simple; i.e. simple summary indicators are often useful in long term assessment
- Failure to link indicators to decisions; i.e. what type of decisions do these indicators facilitate
- Confusing value judgement with technical judgement; i.e. the meaning of an indicator parameter is a technical judgement, while deciding what to do about it is a value judgement
- Substituting data collection for critical thinking; i.e. indicator development first then data collection, not vice versa
- Ignoring spatial and temporal trade-offs; i.e. do not use indicators reflecting temporal conditions in long term assessment

2.2.10 Indicator visualization and presentation

When indicators and indicator system are implemented in an organization is it helpful if indicators in use can be presented and visualized to the user in a user friendly interface. Today, it is possible to both track and present the indicators with modern technique and sophisticated computer software. However, irrespective of modern technique, indicators are often visualized in diagrams showing both indicator history and trends (NFR-PROSMAT 2000, 1999, IAEA, 2000, Ellingsen et al., 2001). It is also common that the indicators are visualized with help of different colors depending on the actual indicator value in relation to a desired target or goal, so called traffic lights, see Figure 12.

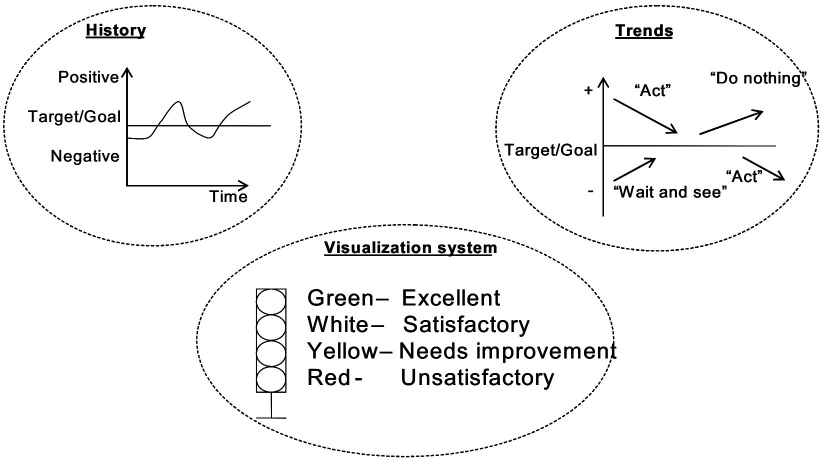

Figure 12. Examples of indicator visualization techniques

2.2.11 Definition summary

As shown in previous sections the names and definitions of different indicators and performance indices vary. They are summarized and presented in Table 2 and Table 3.

Table 2. Definitions of different types of performance indicators

Type of indicator	**Definition**
Indicators	▫ Describing the condition of an event from a technical, chemistry, ecological, or economical perspective ▫ A number that describes the prevalent performance for a specific activity or occurrence (Allander, 1997)
Performance indicators	▫ Simply an indicator of performance (Wireman, 1998) ▫ Measurement of the performance of working life related issues; classified into efficiency, effectiveness, productivity, budget/profit, quality of working life, innovation, and quality (Allander, 1997) ▫ Comparison between present environmental condition and the desired one, i.e. the distance left to reach the goal (European Environment Agency, 2002) ▫ The key measures of the performance of a company, which are monitored and assessed to ensure its long-term success and helps to pinpoint the company's strengths and weaknesses (A Dictionary of Business, 2002) ▫ A measure capable of generating a quantified value to indicate the level of performance taking into account single or multiple aspects (Liyanage et al., 2001)
Key performance indicators	▫ A performance indicator with a strategic significance, which is perceived as critical under given business circumstances and preferably selected from a pool of performance indicators (Liyanage et al., 2001) ▫ The resulting measure of a collection of one or more measures focusing on a predefined situation, whit the purpose to get objective information (Smith, 2003) ▫ A more strategic and important indicator of performance (Wireman, 1998)

Table 3. Definition of different types of performance indices

Type of indicator	Definition
Key variable	▫ Compressed information given by one single number; i.e. essential summarized information given by single or aggregated key variables (Mossberg, 1977)
Strategy indicators	▫ Indicators intended to follow up the maintenance strategy and objectives, comparing present status against the planned one with focus on continuous maintenance improvement for the organization (Cummings, 1993)
Efficiency indicators	▫ The concrete measures quantifying the processes the strategy indicators are supposed to follow up (Cummings, 1993)
Asset condition index	▫ An aggregated measure taking technical, financial, and statistical parameters into consideration, describing an asset's degradation compared with its original design state (NFR-PROSMAT 2000, 1999)
Environmental biodiversity indicators	▫ Measures reflecting the condition of different species in an ecosystem, i.e. assessing the specific species degradation level compared to its original state before the human disturbance on the ecosystem occurred, where the degradation level is normally divided into three levels of degradation, namely good, fair, and poor or undisturbed, moderately disturbed, and severe disturbed (Kimberling et al., 2001)
Index of Biotical Integrity (IBI)	▫ Aggregated index of environmental biodiversity index, where the calculated numerical value and its degradation level is presented in the same way as for the different environmental biodiversity indicators (Lyons et al., 2000)
Safety related indicators	*No definition*

2.3 Balanced Scorecard

The balanced scorecard concept was introduced in 1992 (Kaplan and Norton, 1992). The basic idea was to find a way of managing and measuring the company performance from a more holistic view, apart from financial performances. The old traditional way of measuring a company's performance, based on financial results alone, were found to be inadequate and inefficient, since all measures only reflect outcome results. In practice, the company was managed by looking into the mirror.

The balanced scorecard concept introduced three more strategic perspectives in addition to the financial one, which were seen as critical to a company performance, reflecting not only the company's financial history but also its present and future performance; namely customers' perspective and internal business perspective reflecting the present performance, and finally learning and growth perspective reflecting what the company has to do to prepare them selves for the upcoming future i.e. innovations, see Figure 13 (Kaplan and Norton, 1992). The advantage of such a scorecard is that it is possible to manage and balance different activities within a company, even if the different activities can't be directly measured into economical terms.

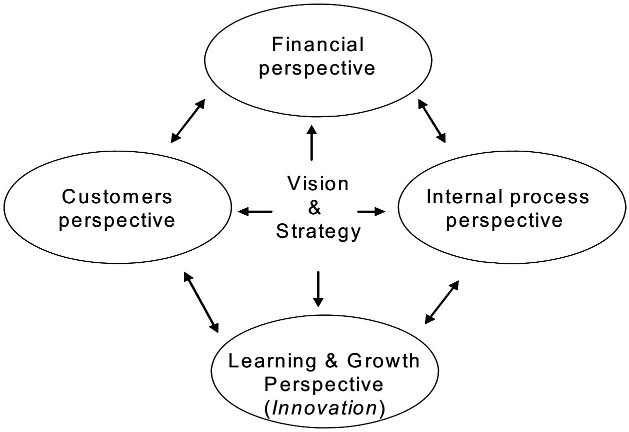

Figure 13. Balanced Scorecard (Kaplan and Norton, 1992)

In order to develop and implement the scorecard into an existing company it will incorporate more than the top management, but to make sure that the overall objectives permeate all scorecard perspectives in the process, a top-down approach is necessary as well as the top management support (Kaplan and Norton, 1992). If necessary, the balanced scorecard can be broken down, further down into the organisation.

One fundamental idea with the balanced scorecard is that important values cannot always be related to financial measures. The balanced scorecard model is therefore suitable for long term non-business activities where profit is not the main purpose (Olve et al., 1999). This is especially the case for the public sector where long term public demands have to be taken into consideration e.g. public services as for example healthcare, education, environmental issues and transportation. The use of the balanced scorecard concept also gives the opportunity to highlight what will happen in the long term with different financial assumptions, i.e. how to act in the long term.

2.4 Link and Effect Model

Another perspective is to study a so-called link-and-effect model. For an example introducing any performance measurement system which is meant to fulfil the needs of operations and maintenance processes in a company or a business unit, it is important that it focuses on critical-strategic areas determined by the nature of the specific business, business concerns and public requirements and regulations (Liyanage and Selmer, 1999). The critical-strategic areas varies from business to business, but normally include areas as financial, health safety and environment, internal processes, plant technical status, competencies, and finally, internal and external relationships. When developing the performance measurement system it is important that it supports overall objectives for the company or the business unit, signifying a top-down approach. The direct link between overall objectives and the measures for operations and maintenance is in terms of return on investments (ROI) and health, safety and environment (HSE) (Liyanage and Selmer, 1999). The main performance driver for ROI and HSE is the integrity of the plant. The foundation for plant integrity is laid by adequate competencies, functional internal processes and good internal and external relationships see Figure 14.

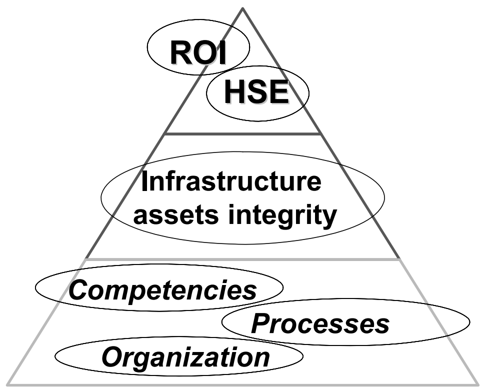

Figure 14. Link and effect model (Liyanage and Selmer, 1999)

Therefore, when deriving the different performance indicators for each critical-strategic area to trace the maintenance performance, it is also necessary to classify the degree of effect for every single indicator towards linked areas, i.e. create a logical cause-and-effect structure, to pinpoint those measures that are the key performance indicators (Liyanage and Selmer, 1999). The final output from this is a link-and-effect model, showing how the operations and maintenance processes contributes to overall objectives for the company or the business unit. The same approach can be used to analyze an existing operations and maintenance performance measurement system.

3 RESEARCH METHODOLOGY

This chapter briefly describes the research process and discusses the chosen research approach.

3.1 Research Purpose

All research activities start with a problem that need to be explained and understood. If the research aims to solve more practical related problems is the research called applied research. On the other hand, if the aim is to gain and widen knowledge for future use is the research called fundamental research (Patel and Davidson, 1994).

Research can be divided into three different ways of doing research, depending on how much knowledge there is about a certain problem or problem area (Patel and Davidson, 1994), namely:

- The exploratory research; used when the knowledge level is low and there are known knowledge gaps in the field of interest; i.e. aims to explore and gain more knowledge about a specific problem by using many different techniques to gather information.
- The descriptive research; used when the knowledge level is moderate and it is possible to categorize existing knowledge into models etc; i.e. aims to describe a few aspects one by one or together in the area of interest by using more or less only one technique.
- Hypothesis testing; used when the knowledge level is considered as high and there exist developed theories in the area of interest; i.e. aims to verify theories experimentally by hypothesis testing by using techniques that gives as precise information as possible.

Research may also be divided into quantitative and qualitative studies (Patel and Davidson, 1994). Quantitative research studies aim to study and analyze the problem with statistical methods, i.e. using numbers. The qualitative research aims to study and analyze problems with verbal analysis methods.

In order to describe the chosen research approach for this thesis is it important to recapitulate the research purpose, aims, and limitations, namely:

- The purpose of this thesis is to identify and develop a set of railway maintenance performance indicators, i.e. study and analyze the effect of maintenance activities in proportion to punctuality, safety, environmental impact, and profitability.

- The main aim is to clarify how different maintenance performance indicators can be used to achieve more suitable decisions in the maintenance process.
- This thesis is limited to focuses on maintenance and maintenance related activities from an infrastructure owner point of view. It is important that findings and results can be implemented in Banverket's prevalent organization.

Based on the research purpose, aims, and limitations the chosen research approach for this thesis can be described as follows:
- Applied research approach; results are supposed to be used for the railway infrastructure owner.
- Exploratory/Descriptive research approach; understand the nature of indicators and describe how it can be applied on maintenance.

3.2 Research Approach and Strategy

The research approach can be divided into three different methods, namely (Alvesson and Sköldberg, 1994):
- The deductive approach; characterized by using theories and general rules to explain a specific case
- The inductive approach; using empirical data from many cases to explain and develop theories and general rules
- The abduction approach; can be seen as a combination of deduction and induction, e.g. a research study can start with a deductive approach based on a theoretical framework to do an empirical collection and later on develop new theories based on the empirical collected data.

The research strategy can be divided into five different strategies, e.g. experiment, survey, archival analysis, history, and case study (Yin, 1994). When to use each strategy is based upon three conditions, i.e. the type of posed research question, the extent of control over actual behavioral events, and the degree of focus on contemporary versus historical events, see Table 4.

Table 4. Relevant situations for different research strategies (Yin, 1994)

Strategy	Research question form	Behavioral events control	Contemporary events focus
Experiment	How, why	Yes	Yes
Survey	Who, what, where, how many, how much	No	Yes
Archival analysis	Who, what, where, how many, how much	No	Yes/No
History	How, why	No	No
Case study	How, why	No	Yes

In this study are an abduction research approach used; literature theory studies and collection of empirical data to develop a general framework. The research strategy is a case study; research questions focusing on "how" and no researcher control of behaviour events at the same time as contemporary events must be taken into consideration.

3.3 Data Collection and Analysis

In order to solve research problems there is a need of information in terms of different data. Necessary information sources can be divided in to four categories (Patel and Davidson, 1994), namely:

- Documents
- Interviews
- Observations
- Experimental measurement

The next step after necessary data is collected from different information sources in a research study is to process the data to useful information, i.e. examine, categorize, arrange, and rearrange and recombine the data (Patel and Davidson, 1994). This can be done with a quantitative approach using statistical methods or with a qualitative approach using verbal analysis methods.

In this study is the data collected through the literature study in different databases and scientific journals, e.g. LIBRIS, Compendex, Raildok, Emerald, Elsevier Science Direct, Kluwer, and Tris Online. Different related keywords were formulated and used in different combinations, e.g. indicator, indices, index, variable, link and effect, maintenance, and performance. The data reduction is done by comparing headlines and abstracts against the purpose of the study.

The empirical data collection is done through railway infrastructure owner's documents and interviews. The data analysis is made by a qualitative approach using verbal analysis. The data classification is made by using a link and effect model identified through the literature study.

3.4 Reliability and Validity

Whenever research is conducted, it is crucial that presented findings and conclusions can be held as through, i.e. reflect the reality of the studied cases. In order to do so, it is important that both research processes and the outcomes of it can be evaluated, and if it is necessary, also can be done again. Reliability reflects to which extent an experiment or procedure yields the same results when it is repeated, while validity reflects to which extent a measure reflects what it is supposed to measure (Carmines and Zeller, 1979).

In this study is the empirical data examined against other sources of information whenever it has been possible due to reliability and validity issues.

4 MAINTENANCE PERFORMANCE MEASUREMENT

This chapter describes Banverket's track management and maintenance process as well as identified indicators of various sorts. It also presents identified maintenance related indicators within other railway authorities abroad.

4.1 Banverket Track Management Process

Banverket is the responsible authority for rail traffic in Sweden, and their operations are divided into sectoral duties, track provision, and production. In 1999 Banverket took a decision to run their business from a process and customer oriented management perspective, and in 2001 was the entire organization ready to adopt the new management approach (Banverket, 2002c). After two more years of process management evaluation could the final process map be presented, see Figure 15. Banverket's main processes are divided in to three different processes; train traffic process resulting in available train positions for the train traffic operators, track management process resulting in a safe and reliable track network, and exercise of authority processes taking care of the sectoral duties (Banverket, 2002c). The business long term management and control is taking care of in the business management process, and necessary administrative and technical support is defined as support processes.

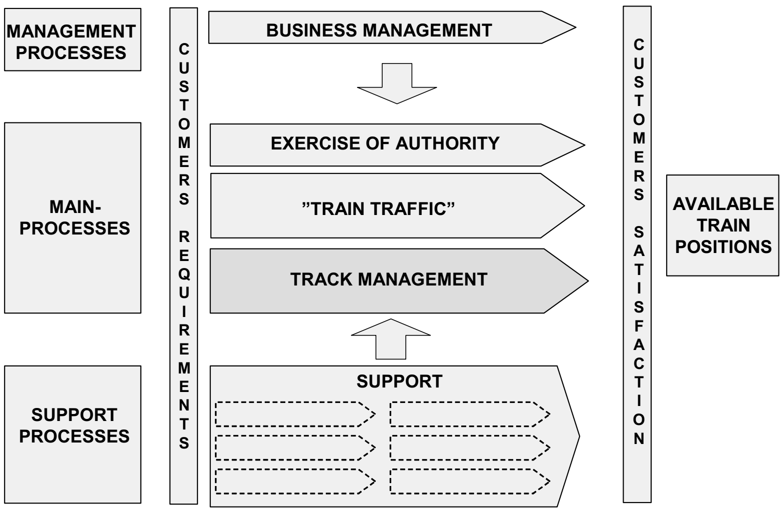

Figure 15. Banverket's process map (Banverket, 2002c)

The track management main process is divided into seven different sub-processes (Banverket, 2002c). The two first sub-processes named condition assessment and requirement analysis are assessing the rail network condition and analyzing future requirements accompanied by proposals of prioritized suitable actions. The five remaining sub-processes are reflecting the different ways of managing the rail network, i.e. how to operate, maintain, upgrade, and incorporate or close down track lines, see Figure 16.

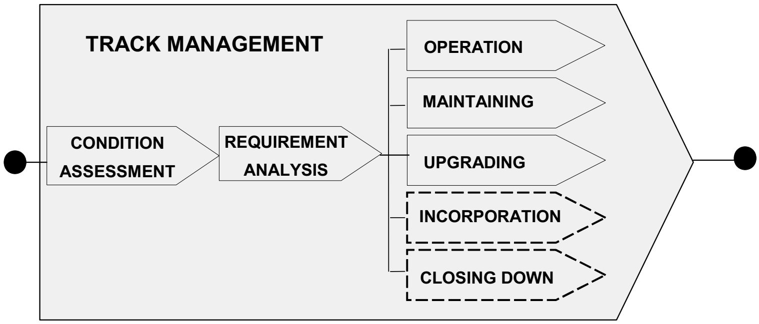

Figure 16. Banverket's track management process (Banverket, 2002c)

4.2 Banverket Maintenance Process

Banverket has chosen to use the Swedish maintenance standard (SIS, 2001) for definition and description of maintenance (Espling, 2004). It has later on been translated to support Banverket's own maintenance requirements, and the output is a track network maintaining structure where a distinction between maintenance and renewal is done due to financial and regulatory aspects, as shown in Figure 17 (Banverket, 2001a).

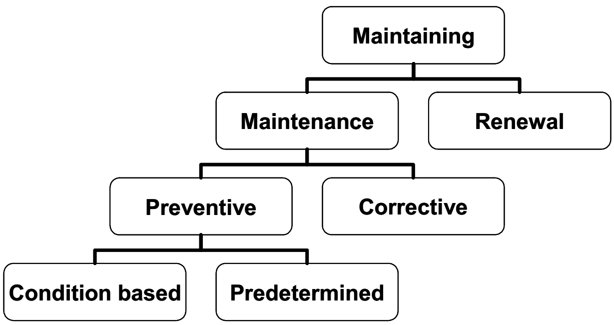

Figure 17. Banverket maintaining structure (Banverket, 2001a)

The process of maintaining the track network is called nothing else than just maintaining and is divided into three different sub-processes, i.e. corrective maintenance, preventive maintenance, and renewal, sees Figure 18 (Banverket, 2002c).

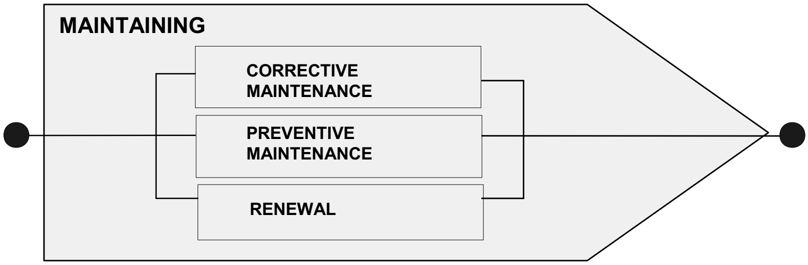

Figure 18. Banverket's maintaining process (Banverket, 2002c)

In Banverket is corrective maintenance done when a failure is detected that requires immediate repair with the purpose to restore an item to such a condition that it can perform its required function (Banverket, 2001a). Corrective maintenance is divided into three different types of work, i.e. immediate failure repairs, damage repairs, and correction of immediate inspection remarks. Figure 19 shows the corrective maintenance sub-process.

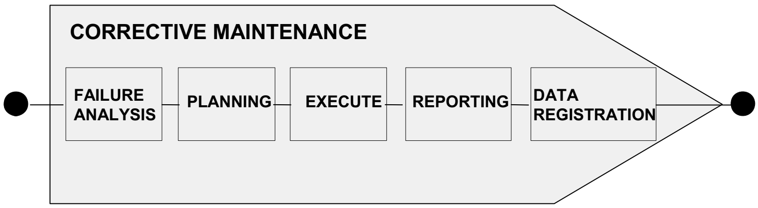

Figure 19. The corrective maintenance sub-process (Banverket, 2002c)

The preventive maintenance sub-process is shown in Figure 20. Since the inherent process steps are the same for both condition based maintenance and predetermined maintenance is not the preventive maintenance sub-process broken down any further (Banverket, 2001a). However, when it comes to the realization of different preventive maintenance activities in Banverket, is it important to notice the difference between conditions based maintenance and predetermined maintenance (Banverket, 2003). Most of the preventive maintenance tasks done at Banverket can be counted as condition based maintenance tasks (Espling, 2004), e.g.:

- Safety and maintenance inspections
- Correction of minor inspection remarks
- Condition control
- Track maintenance
- Subgrade maintenance
- Revisions

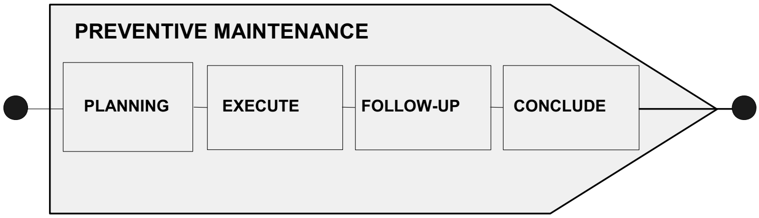

Figure 20. The preventive maintenance sub-process (Banverket, 2002c)

Predetermined maintenance tasks periodicity is synchronized against different inspections classes, which are based on the traffic volume and train speed for the specific track line (Banverket, 2003). The different intervals vary from every second week up to every third year and can be summarized as:

- Cleaning, adjustment, and lubrication
- Exchange of different types of bulbs and batteries
- Testing and control of different safety system

The third sub-process in the maintaining process is renewal, see Figure 21. When a maintaining task should be determined as a renewal project and not as a condition based maintenance activity, is defined in Banverket's regulations as well as in public laws (Banverket, 2001a). The purpose of renewal projects is always to restore the railway infrastructure to its designed state.

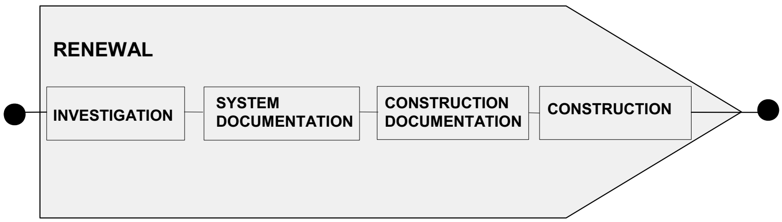

Figure 21. The renewal sub-process (Banverket, 2002c)

However, it is important to notice that since it was decided back in 1998 that Banverket should be divided into an infrastructure owner and different production units, the consequence for Banverket led to a need of internal or external outsourcing of all production activities such as maintenance and track renewals. Irrespective of chosen type of contract, maintenance executive parts in the maintenance process is taking care of by the contractor.

4.3 Banverket Maintenance Performance Indicators

Today, there exist a number of different measures and asset condition parameters in Banverket that are used or planned to be in use for follow up purpose regarding maintenance activities. Presented parameters in the first subsection are found and identified through databases and documents, and can therefore be looked upon as national public indicators within Banverket. Identified parameters in the second and third subsection represent indicators of a more regional but still public nature.

4.3.1 Identified indicators on a national level

Following chapter describes identified metrics or condition parameters in use on a national level at Banverket that can be related to maintenance and railway asset management. In Banverket handbook BVH 824.10 are following indicators described (Banverket, 2000):

- Rail head top wear - % of track distance
- Rail head side wear - % of track distance
- Rifles and waves - % of track distance
- Rail defects – number of defects per track kilometre and year
- Rail defects - % of track distance renewal
- Fastening – fastening clip force mean value
- Sleeper - % of sleeper inspection remarks
- Ballast depth – ballast depth mean value
- Ballast contamination - % of contaminated ballast
- Track quality Q-number
- Track quality c-error - % of track distance
- Track gauge c-limit - % of track distance
- Technical status – weighting of all indicators above according to a pre-defined analysis model

In a report from Banverket regarding the present state of the governmental owned track infrastructure is several indicators described. The description contains definition, measurement unit, and data source location (Banverket, 2001b):

- Number of functional disruptions per track kilometre and year
- Number of functional disruptions per track kilometre and year leading to train disruption
- Number of train delay minutes per track kilometre and year
- Number of train delay minutes per train
- K-number (track quality)
- Q-number (track quality)
- Number of emergency and weekly inspection remarks per track kilometre and year

In the Government appropriation letter for fiscal year 2003 concerning Banverket, are national objectives for Banverket defined (Ministry of Industry, 2002). According to the appropriation letter is the overall objective for Banverket defined as “a transportation system for the general public and industry throughout Sweden that is both socio-economically efficient and sustainable in the long term”. The overall objective is broken down into six first level sub-goals, specifying the level of ambition in the long term. The six sub-goals are further broken down into seventeen different second level sub-goals which are supported by almost 70 specified indicators; out of these 70 indicators can 15 indicators can be identified as maintenance performance indicators together with two additional ones identified through interviews, see Table 5 (Åhrén and Kumar, 2004).

During the interviews where also two indicators that are too much aggregated identified, namely traffic volume and maintenance costs (Åhrén and Kumar, 2004). The problem regarding the first one is that it reflects the traffic volume for the track region; not scalable down to different track lines. The problem with the second indicator is that it reflects the maintenance costs only by type of infrastructure asset or maintenance activity but nor for both together, i.e. for instance not possible to trace corrective maintenance per rail maintained.

Table 5. Identified maintenance performance indicators within the hierarchical goal structure at Banverket fiscal year 2003 and identified through interviews (Åhrén and Kumar, 2004).

First level sub-goals	**Second level sub-goals**	**Maintenance performance indicators**
An accessible transport system	Improve the use of state infrastructure	▫ Capacity utilization ▫ Capacity restrictions
A high quality of transport	Decreased train delays	▫ Train delays due to infrastructure
	Decreased freight traffic disruptions	▫ Hours of freight train delays due to infrastructure ▫ Number of delayed freight trains due to infrastructure
	Increased rail network maintenance efficiency	▫ Number of train disruptions due to infrastructure ▫ Q-factor (Degree of track standard) ▫ Markdowns in current standard ▫ Maintenance cost per track-kilometer ▫ Traffic volume
Safe traffic	Reduced number of killed and injured persons	▫ Number of accidents involving railway vehicles ▫ Number of accidents at level crossings
A sound environment	Reduced energy consumption	▫ Energy consumption per area
	Effective natural resource consumption	▫ Use of environmental hazardous material ▫ Use of non-renewable materials
Identified through interviews		▫ Total number of functional disruptions ▫ Total number of urgent inspection remarks

In the State of the art description for the Swedish state railroad assets, can following presumptive maintenance performance indicators be identified (Banverket, 2001b):

- Share of track lines in different K-quality measure class; i.e. graphical presentation in different layers such as 0-50%, 50-70%, 70-80%, 80-90% and >90%.
- Share of track line in different Q-quality measure class; graphical presentation is missing but a similar one as used for the K-measure can be used.
- Share of train delays for different track line quality classes per track kilometre and year; presented in classes of 0-5 minutes, 5-50 minutes and >50 minutes.
- Share of track lines for different train delays classes; presented in classes of 0-0,1 minutes per train, 0,1-1,0 minutes per train and >1,0 minutes per train.

- Share of track lines in different train traffic capacity classes; i.e. severe or minor lack of capacity or capacity in balance.

4.3.2 Established/planned maintenance performance indicators in use at working group TURSAM

TURSAM (Tillämpat UndeRhåll i SAMverkan, in English: applied maintenance in co-operation) is a collaborative railway industry working group active in the northern part of Sweden. The overall purpose with TURSAM is to create good co-operations between different actors in the railway industry, including Banverket, contractors, operators, and universities. TURSAM has developed and partially introduced a number of maintenance performance indicators, i.e. so called thumb-marks, see Table 6 (Espling and Olsson, 2003):

Table 6. Established or planned maintenance thumb-marks in TURSAM (Espling and Olsson, 2003)

Type of thumb-marks	**Indicators**
Established thumb-marks	▫ Number of reported failures ▫ Total hours of train delays ▫ Total number of train delays due to infra structure
Partially Established thumb-marks	▫ Share of unplanned maintenance
Planned thumb-marks	▫ Number of infra structure inspection remarks ▫ Number of broken and parked railroad cars ▫ Number of inspections due to wheel flats ▫ Derailments ▫ Number of natural disasters ▫ Speed restrictions ▫ Track quality ▫ Changes in traffic

4.3.3 Maintenance performance indicators in use at Banverket Northern Track Region

Banverket Northern Track Region decided in 2003 to follow up its maintenance process and its performance outcomes by using a regional developed and introduced balanced scorecard. In order to meet stakeholder requirement, they have modified Kaplan and Norton's balanced scorecard by splitting the learning and growth perspective into two different perspectives and renamed them to co-operator perspective and development perspective. They have also renamed the financial perspective to commission perspective.

Since the use of a regionally balanced scorecard is still in its infancy, it is set under continuous evaluation and further improvements. It is important to notice that the scorecard does not present any metrics related to the railway assets technical status. It is also important to notice that there are maintenance parameters that are followed up beside the introduced balanced scorecard. A selected pool of maintenance parameters is also reported into the Banverket head office. The chosen maintenance performance indicators in the first scorecard used in 2003 as well as other parameters is presented in Table 7 (Åhrén, 2004).

Table 7. Maintenance performance indicators in use 2003 at Banverket Northern Track Region (Åhrén, 2004).

Maintenance performance indicators in use 2003 at Banverket Northen Track Region	**Included in the balanced scorecard**	**Scorecard perspective**	**Reported to Banverket Head office**
Budget deviation		Commission	Yes
Contractor outcome		Commission	
Total train delays	Yes	Customer	Yes
Train delays due to infrastructure failures	Yes	Customer	Yes
Customer dialogue	Yes	Customer	
Urgent inspection remarks		Customer	Yes
Top-10 failure statistics	Yes	Customer	
Top-50 most important switches	Yes	Customer	
Defect sleepers		Customer	Yes
Partnering contracts		Customer	
Accidents and near-accidents	Yes	Process	Yes
STRIX-measurements		Process	Yes
Reduced stress	Yes	Co-operator	Yes
		Development	

4.4 Railway Maintenance Indicators abroad

The following chapter give some examples of how other railway authorities outside Sweden works with maintenance performance indicators.

4.4.1 Rete Ferroviaria Italiana (RFI, Italian Railway Network)

In order to improve and, if possible, optimize undertaken maintenance activities, Italian Railway Network (RFI) have decided that all 15 track regions must plan the maintenance two years ahead (Bianchi and Saccardi, 2003). To succeed they have prepared a maintenance simulation software tool, based on Monte Carlo simulation techniques. The simulation tool uses a what-if perspective, and requires track information in terms of failure rate, repair time, delays due to failures, purchase price, repair costs, and preventive maintenance costs.

The simulation results in a well worked-out Reliability Availability Maintainability Life Cycle Cost (RAM-LCC) model for every object on a specific track line during the next upcoming 15 years (Bianchi and Saccardi, 2003). Using the simulation tool, different maintenance strategies can be tested against each other, finding the optimum one from a minimum cost perspective. In addition, eight different RAM-indicators are presented to validate and follow up the simulated results for the coming years. These are:

- Availability
- Number of expected failures
- Number of preventive maintenance actions
- Number of inspections
- Number of corrective maintenance actions
- Downtime due to preventive maintenance
- Downtime due to inspections
- Downtime due to corrective maintenance

4.4.2 Queensland Rail, Australia

In Queensland, Australia, are the railway network managed in a similar way as in Sweden. The railway infrastructure is owned and governed by the public organization Queensland Rail, having the final responsibility for the entire railway system. The track maintenance is done by in- or out-house contactors. In order to render more effective track maintenance, as well as opportunities for internal benchmarking, Queensland Rail started a project in 1998 where implementation of key performance indicators (KPI) should help to evaluate the track maintenance (Plunkett, 2003).

The work started with an investigation to find out what the above-rail customers required in terms of railway asset performance, i.e. condition, reliability and safety

(Plunkett, 2003). Afterwards was an in-depth study performed regarding maintenance and reinvestment costs. The result pointed out a number of important areas, beside economical, that requires continuous follow-ups, so called key result areas, see Table 8. Another result from the same study showed that the economical accounting didn't match assets physical structure, leading to wrong maintenance prioritizations (Plunkett, 2003). To respective key result area were also a number of KPI developed and implemented to make it possible to:

- Establish new performance targets
- Follow up single managers performance
- Assess train delays for specific trains
- Use selected KPI in a balanced scorecard, connected to contractor bonus and penalty calculations

As mentioned above, Queensland Rail uses the balanced scorecard concept (BSC) to follow up internal and external contractor performance, where maintenance contracts are linked to BSC and six chosen KPI (Plunkett, 2003). The KPI targets are established in negotiation with the contractors, and afterwards linked to bonus and penalty calculations. If the contractor performs a better result than stipulated a bonus will be disbursed, while performance worse than stipulated will imply contractor penalties. The outcome will be followed up every month and fixed once a year. The KPI weighting and assessment interval is listed in Table 9.

In order to make the evaluation process easier and faster the KPI are presented in bar charts, showing the KPI history, expected KPI targets, and calculated KPI trends (Queensland Rail, 2003).

Table 8. Key Result Area and Key Performance Indicators for Queensland Rail (Queensland Rail, 2003).

Key Result Area	Key Performance Indicators
Safety	▫ Injury down time rate ▫ Lost time frequency rate ▫ Lost time injuries ▫ Public trespass accidents ▫ Public level crossing accidents ▫ Wildfires
Asset Reliability (Condition Indicators)	▫ Track and structures transit time delays ▫ Trackside transit time delays ▫ Running move derailments caused by infrastructure ▫ Buckles, pull-aparts ▫ Rail defects – number per 10 kilometres ▫ Wayside faults reported ▫ RIFOT – red signal in front of train ▫ SPAD - Signals passed at danger ▫ Dewirements ▫ Transformers ▫ Non-resetable trips per electric kilometre ▫ Wayside equipment mean time between faults ▫ Wayside equipment mean time to repair
Maintenance Performance	▫ Fault response time for traction power ▫ Fault response time wayside ▫ Completed trackside isolations ▫ Re-sleepering against programme ▫ Resurfacing against programme ▫ Rail grinding against programme ▫ Ballast undercutting against programme ▫ Track recording against programme ▫ Trackside percentage of routine maintenance completed
Cost Control	▫ Inventory value

Table 9. BSC-linked KPI, assessment interval, and weighting (Plunkett, 2003).

KPI	Assessment interval	Weighting
Lost Time Frequency Rate (LTFR)	Yearly	10 – 15 %
Derailments	Yearly	10 – 15 %
Budget	Yearly	50 %
Track Train Delays (TTD)	Monthly	10 %
Trackside System Delays (TSD)	Monthly	0 – 10 %
Overall Track Condition Indice (OTCI)	Monthly	10 %

4.4.3 Network Rail, UK

The railway network in United Kingdom is owned and managed by the Network Rail Limited (Network Rail, 2003). It is a company limited by guarantee and it is run under commercial lines and any profit will be reinvested in the railway. The business focus for Network Rail is clear; operations, maintenance, and renewals. The railway infrastructure is managed more or less in the same way as in Sweden; one purchasing organization and different contractors. However, Network Rail has taken back the responsibility for deciding what and when maintenance has to be done. They have also taken back the responsibility to ensure that maintenance is done when it is supposed to be done.

In order to follow up that undertaken maintenance activities are giving the expected results is Network Rail using different key performance indicators, see Table 10 (Network Rail, 2004).

Table 10. Network Rail Key Performance Indicators (Network Rail, 2004)

Area of interest	Key Performance Indicators
Improved safety	▫ Public safety index
Higher performance	▫ Public performance index ▫ Train delay minutes
Increased system capability	▫ Passenger capability ▫ Freight capability
Improved customer & stakeholder relationship	▫ Passenger complaints
Improved financial control	▫ Financial efficiency index
Improved business performance	▫ Employee engagement
Supplementary indicators	▫ Delays minutes per 100 train kilometres ▫ Number of broken rails ▫ Level 2 exceedence ▫ Number of signalling failures > 10 minutes delay ▫ Number of temporary speed restrictions ▫ Traction power supply failures ▫ Track geometry ▫ Points and circuit failures

4.5 Non-written Experiences of Indicator usage

One experience is from Banverket[1] when dealing with the usage of so called traffic lights when presenting indicators. The problem is that you don't know how far away the indicator value is from reaching a changing point, e.g. change colour from green to reed. As long as an indicator is green everything is in order, but when it turns into red then it has became a problem, i.e. per definition someone has to do something about the red indicator. When the indicator later on is examined it is often the case that the indicator value is more ore less unchanged, i.e. the indicator value is balancing on the edge between the two colours.

One experience is from Queensland Rail[2] and is dealing with the common accepted expression "what's getting measured is getting done". The problem is arising when the focus is on "wrong" measures. This is especially the case when using wrong or bad performance indicators. Another experience they have is dealing with the potential problem with indicators that in some way are using the same background data. The problem arise if two different indicators uses the same data, and one of the indicators is showing a positive trend if the indicator value is increasing but the other indicator is getting more and more positive if the indicator value is decreasing. What will happen is that the indicator will show an unstable behaviour, i.e. no matter how much attention you pay to the indicator it will still be unstable due to the fact that there is someone else that is trying to stabilize the indicator in the other direction.

[1] Pelle Corshammar, Banverket Southern Region
[2] Chris Wicks, Queensland Rail

5 ANALYSIS AND RESULTS

This chapter presents the analysis and the results from the findings of the thesis work.

5.1 Maintenance Performance Indicators Framework

5.1.1 Definition

During the literature survey no definition of maintenance performance indicators was found. However, the following analysis will address that it is not necessary to develop a new definition.

The definitions of the different types of indicators and other indices can be summarized to reflect the following areas:

- Expressed in a single number
- Delivering information of physical condition and/or processes
- Delivering information reflecting ends and/or means, i.e. goals and/or strategies
- Delivering measures reflecting single item/task and/or multiple items/tasks information, i.e. non-aggregated and/or aggregated information

The different types of indicators and indices and their definitions as well as what type of information they are supposed to deliver can be summarized in Table 11. When doing such a comparison between the different indicators and indices, there are three types of them that can fulfill to deliver information reflecting all areas, namely performance indicators, key performance indicators and key variables. It is important to notice that there is no difference between the covered areas according to the definition for performance indicators and key performance indicators. The only visible difference is that the phrase "key" is used to highlight the more important and critical performance indicators, i.e. give a hint on which one to focus on in a trade-of situation.

Table 11. Type of delivered information from different types of indicators and indices

Type of indicator	Express physical condition	Express process condition	Goals related	Strategy related	Non-aggregated	Aggregated
Indicators	x	x			x	
Performance indicators	x	x	x	x	x	x
Key performance indicators	x	x	x	x	x	x
Strategy indicators	x	x	x	x		x
Efficiency indicators	x	x			x	
Key variable	x	x	x	x	x	x
Asset condition index	x		x			x
Environmental biodiversity indicators	x		x		x	
Index of Biotical Integrity (IBI)	x		x			x

It can always be discussed if one more additional definition will increase the definition's value of performance indicators, key performance indicators, and key variables. Since there are existing definitions that cover all aspects, it is suitable to choose one of them and not spending time to develop yet another one. Therefore, the type of indicators that are able to reflect and express the physical or process conditions, are goals or strategy related, and express aggregated or non-aggregated measures are performance indicators and the chosen definition for these performance indicators is the one reflecting the different aspects in a clear way, namely:

- *Performance indicator is a measure capable of generating a quantified value to indicate the level of performance taking into account single or multiple aspects (Liyanage et al., 2001)*

The use of different prefix before the term "performance indicators", can not be seen as anything else than an information to different users and stakeholders what type of measures they reflect. Some examples of used prefixes are key, maintenance, business, and environmental.

5.1.2 Characteristics

The use of key variables and performance indicators is about management and control of physical assets and processes on different levels inside an organization (Mossberg, 1977). If this is done properly maintenance performance indicators can provide and identify (Kumar and Ellingsen, 2000):

- Resource allocation and control
- Problem areas
- Maintenance contribution to business objectives
- Maintenance benchmarking and performance trends
- Maintenance personnel performance and contribution to maintenance and overall business objectives

The performance indicators themselves can broadly be classified as:

- Leading or lagging indicators; leading indicators are the performance drivers and the outcome measures are the lagging indicators (Stricoff, 2000)
- Off the shelf or tailor made indicators; important if the indicators are supposed to be used in benchmarks (Wireman, 2004)
- Long or short term indicators; important when deciding how long time indicator measures have to be stored (IAEA, 2000)
- Slow or fast changing rate indicators; important for trend calculations or to decide if slower/faster redundant indicators must be used or developed, often the case for environmental issues (Miljövårdsberedningen, 1998, Kimberling et al., 2001)

Management and control of the outcome measures is the same as a follow up of the same measures, requiring both alarm signals when something in the outcome measures differs from the expected value. After knowing that something is wrong, it is necessary to diagnose why it is wrong in order to do something about it (Mossberg, 1977). Management and control of performance drivers can therefore be looked upon as forecasting and prediction of the outcome measures. Once again it is important to be able to get early warnings when things are not going in the desired direction as well as it is important to be able to diagnose why it is happening, see Figure 22.

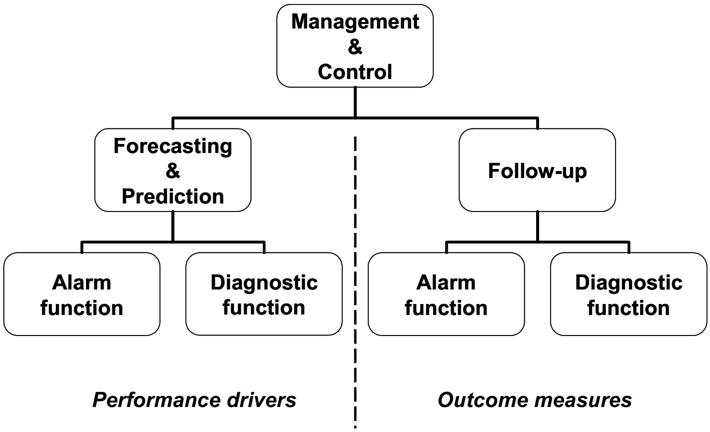

Figure 22. Performance indicator functions

In order to use performance indicators for alarm and diagnostic purposes they should be described in three terms to express and understand how they work (Mossberg, 1977), namely:

- Description of the meaning of the performance indicator signal
- Description of the characteristics of the decision the signal pointing at
- Description on the connection between the signal and the decision characteristics

When an asset or process is to be managed and controlled there is often a need to use more performance indicators to get a more complete picture and a broader and deeper understanding of how and why things are like they are. In order to choose "the right" performance indicators amongst a set of possible ones the relation between different performance indicators can be studied from three different perspectives (Mossberg, 1977), namely:

- Relationship through signals and decision characteristics
- Relationship through signals only
- Relationship through decision characteristics only.

To illustrate the relationship between signals and decisions an example of car driving can be used, see Figure 23. Think of the two different decisions making situations where the first one is resulting in a need of immediate stop, and the other one resulting in a need for planning a stop at next gas station, i.e. a relationship of signals due to decision characteristics similarity. Causes that lead to an immediate stop can be danger and obstacle ahead, a flat tire, or loss of engine oil pressure. Causes leading to a planed stop can be tiredness, a generator fault, or a need for more gas. A relationship due to signal similarity only can be identified amongst car condition signals. It is important to notice that a signal similarity not necessary lead to decision similarity, as well as a decision similarity can be based of signals showing no signal similarity to each other.

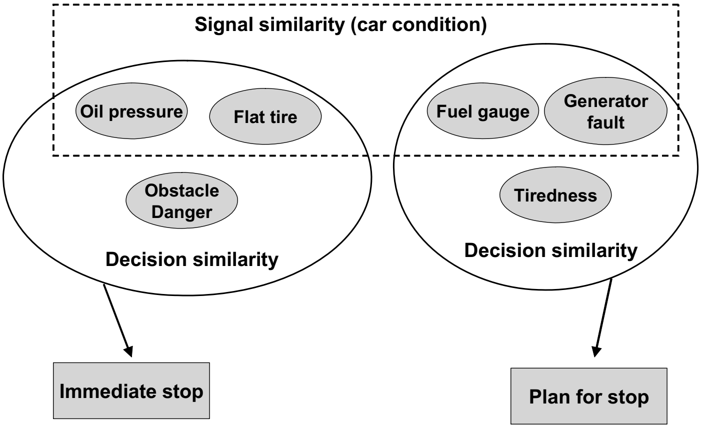

Figure 23. Example of signal and decision relationship for car driving

After a performance indicator relationship study is carried out, the different performance indicators in use can be put together in groups or models (Mossberg, 1977). The different groups are logically arranged (Allander, 1997, Cummings, 1993) while the models can be seen as vertically hierarchical alignments (IAEA, 2000). Two examples of performance indicator models are the monetary Return on Investments (ROI) more known as the Du Pont Model, and the non-monetary Overall Equipment Effectiveness (OEE).

5.1.3 Visualization and presentation

Today, there are two dominating techniques to present and visualize performance indicators. The first one is to use so called traffic lights and the other one is to use bar or line charts containing performance indicator history, expected targets, and calculated trends. Experiences from Banverket has pinpointed out one problem in connection with the use of traffic lights and what to do when the traffic light is changing colour; i.e. how far away from the limit are the value and what to do about it.

When taking Banverket's experiences in to consideration, it is obvious that the information delivered by a changing traffic light is not sufficient to make managerial decisions. In order to take decisions it is also necessary to have access to the information that can be delivered by a bar or line chart. However, using traffic lights can be an easy way to pinpoint out potential problem areas.

5.1.4 Link and effect model

During the 1960s safety matters and improvements in labour efficiency became more important and a more preventive maintenance strategy emerged (Moubray, 1991). This change of strategy made it not only possible to plan maintenance activities, it also made it possible to start controlling maintenance performance, costs and production assets availability (White, 1973); i.e. maintenance management in terms of organisation, economy, and assets (Husband, 1976).

In 1992 was the balanced scorecard introduced as a concept of managing and measuring the company performance from a more holistic view, apart from financial performances (Kaplan and Norton, 1992). The traditional way of measuring a company's performance, based on financial results alone, were found to be inadequate and inefficient. The balanced scorecard concept introduced three more strategic perspectives in addition to the financial one; namely customers' perspective, internal business perspective, and finally learning and growth perspective. To make sure that the overall objectives permeate all scorecard perspectives, a top-down approach is necessary. It is however important to notice that the scorecard is not explicitly reflecting the aspects of asset management.

In the late 1990s is so an operation and maintenance link and effect model presented, taking into consideration the specific needs of the offshore industry performance measurement systems (Liyanage and Selmer, 1999). The model focuses on critical-strategic areas determined by the nature of the specific business; normally including areas as financial, health safety and environment, internal processes, plant technical status, competencies, and internal and external relationships. When developing the performance measurement system it is important that it supports overall objectives for the company or the business unit, signifying a top-down approach. The link and effect model can be looked upon as an extended balanced scorecard, including the same perspectives and two additional ones; asset management perspective and health, safety and environment perspective.

In the link and effect model is the direct link between overall objectives and the measures for operations and maintenance in terms of return on investments (ROI) and health, safety and environment (HSE) (Liyanage and Selmer, 1999). The main performance driver for ROI and HSE is the integrity of the plant. The foundation for plant integrity is laid by adequate competencies, functional internal processes, and good internal and external relationships.

Since the link and effect model is taking critical-strategic areas in consideration that can be applied to other industries than the offshore industry, it can also be used to manage and maintain railway infrastructures. The long term vision and goals for Banverket regarding their railway infrastructure management can be summarized into:

- High transport quality; i.e. railway infrastructure quality and punctuality
- Health, safety, and environmental issues

When applying the link and effect model on Banverket, the model must be added with one more critical-strategic area, namely punctuality. Since punctuality can be expected to be dependent on the railway infrastructure condition, it must be taken care of in the same way as for instance health, safety and environmental issues. It is also suitable to change the term return on investments (ROI) to return on maintenance investments (ROMI) since it reflects in a better way the actual activities undertaken by Banverket to manage and maintain the railway infrastructure assets (Parida et al., 2004). It is also convenient to change into the term railway infrastructure assets integrity instead of just infrastructure assets integrity, see Figure 24.

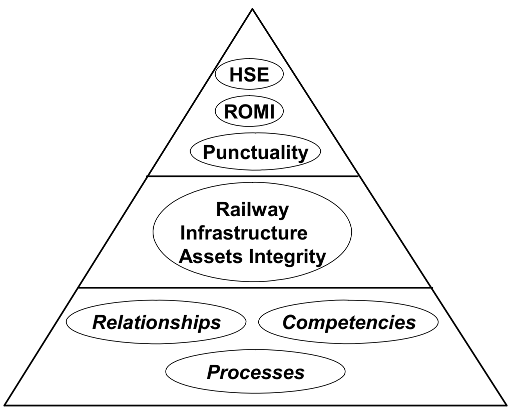

Figure 24. Railway infrastructure management link and effect model

5.2 Banverket Maintenance Performance Indicators

The analysis made in this chapter is done to identify maintenance performance indicators (MPI) that are in use or can be suitable to use at Banverket in the process of maintaining their railway infrastructure assets. The analysis criteria are as follows:

- MPI must be reflected by a single number or being able to covert into a single number.
- MPI signal should be able to act as an alarm signal or be able to point out the characteristics of necessary decisions.
- For MPI reflecting the same thing, but expressed in different units is only one of them chosen, i.e. eliminating redundancy indicators. An example of typical redundancy units are "total number" and "total number per track kilometre".
- MPI must reflect performance drivers and outcomes that can be tied to the railway infrastructure and its maintenance, i.e. excluding indicators where a part of the indicator value can be tied to others such as traffic operators or train traffic control. An example is total train delays.
- MPI must be scalable in order to be valid both locally and nationally, i.e. excluding indicators that are not comparable between different track regions. An example is the K-quality measure which is not comparable between track lines with different speed classes.

The maintenance performance indicators identified during the analysis will be classified to reflect the different critical-strategic areas that where presented in the railway infrastructure management link and effect model. They will also be gathered into smaller groups to better reflect what type of indicator they are. The presentation of the identified indicators shows from where they are collected. Indicators found in several sources will also be presented in that way. The different sources where the indicators are identified are:

- National used performance indicators (Åhrén and Kumar, 2004)
- Banverket Northern Track Region (Åhrén, 2004)
- TURSAM (Espling and Olsson, 2003)
- State of the art description for track lines (Banverket, 2001b)

Initially where 55 different presumptive performance indicators identified at Banverket, see Chapter 4. During the analysis process are the numbers of indicators reduced by approximately 50 %. How they are distributed is shown in Table 12 to Table 16.

Table 12. Indicators representing ROMI in the railway infrastructure management link and effect model

ROMI Link/effect model perspectives	National used performance indicators	Banverket Northern Track Region Performance indicators	TURSAM	State of the art description for track lines
Maintenance costs	Maintenance cost per track-kilometre			
		Budget deviation		
		Contractor outcome		

Table 13. Indicators representing HSE in the railway infrastructure management link and effect model

HSE Link/effect model perspectives	National used performance indicators	Banverket Northern Track Region Performance indicators	TURSAM	State of the art description for track lines
Health		Reduced stress		
Safety	Number of accidents involving railway vehicles			
	Number of accidents at level crossings			
			Derailments	
Environment	Energy consumption per area			
	Use of environmental hazardous material			
	Use of non-renewable materials			

Table 14. Indicators representing PUNCTUALITY in the railway infrastructure management link and effect model

<u>**Punctuality**</u> **Link/effect model perspectives**	**National used performance indicators**	**Banverket Northern Track Region Performance indicators**	**TURSAM**	**State of the art description for track lines**
Train delays	Train delays due to infrastructure	Train delays due to infrastructure failures	Total number of train delays due to infra structure	
	Hours of freight train delays due to infrastructure			
	Number of delayed freight trains due to infrastructure			
	Number of train disruptions due to infrastructure			

Table 15. Indicators representing PROCESSES and RELATIONSHIPS in the railway infrastructure management link and effect model

Link/effect model perspectives	**National used performance indicators**	**Banverket Northern Track Region Performance indicators**	**TURSAM**	**State of the art description for track lines**
Processes (Maintenance)			Share of unplanned maintenance	
Relationships		Partnering contracts		
		Customer dialogue		

Table 16. Indicators representing RAILWAY INFRASTRUCTURE ASSETS INTEGRITY in the railway infrastructure management link and effect model

Infrastructure Link/effect model perspectives	**National used performance indicators**	**Banverket Northern Track Region Performance indicators**	**TURSAM**	**State of the art description for track lines**
Capacity	Capacity utilization			
	Capacity restrictions			
Speed restriction	Markdowns in current standard		Speed restrictions	
Traffic volume	Traffic volume		Changes in traffic	
Functional disruptions	Total number of functional disruptions		Number of reported failures	
				Number of functional disruptions per track kilometre and year leading to train disruption
Inspection remarks	Total number of urgent inspection remarks	Urgent inspection remarks	Number of infra structure inspection remarks	
			Number of inspections due to wheel flats	
Track quality		Defect sleepers		
	Q-factor (Degree of track standard)			Q-number (track quality)
		Track quality (Degree of physical degradation)	Track quality	

5.3 Railway Link and Effect Model Framework

In this thesis are both existing as well as potential maintenance performance indicators for Banverket identified. The analysis outcome in the previous section resulted in a set of performance indicators suitable to use for management of the railway maintenance process. The identified indicators where also classified and categorized into different critical-strategic areas and sub-groups in order to match a possible link and effect model that can be used to link maintenance activities to maintenance goal and strategies and further on to overall objectives for the railway infrastructure management. In this section is so an attempt made to put the different indicators into the link and effect model, based on previous analysis results.

The suggested link and effect model is build up by smaller indicator models. The indicator models themselves are so build up in the same way as the indicators where classified in the analysis. Existing indicators are highlighted in the model by being colored. Uncolored indicators in the model symbolize non-existing indicators but necessary ones to finish and complete the different models so they can be put into the final link and effect model. The non-existing indicators will now on be called indices, just to separate them from existing indicators.

The first indicator model is the one classified as the ROMI-model reflecting return on maintenance investments, see Figure 25. It is build up by the three existing indicators named as:

- *Budget deviation*
- *Maintenance costs per kilometer*
- *Contractor outcome*

The maintenance per kilometer indicator can further be broken down into corrective, predetermined, and condition based maintenance costs. Every one of these can also reflect the different parts of the railway infrastructure assets, namely substructure, superstructure, wayside equipments, and catenary.

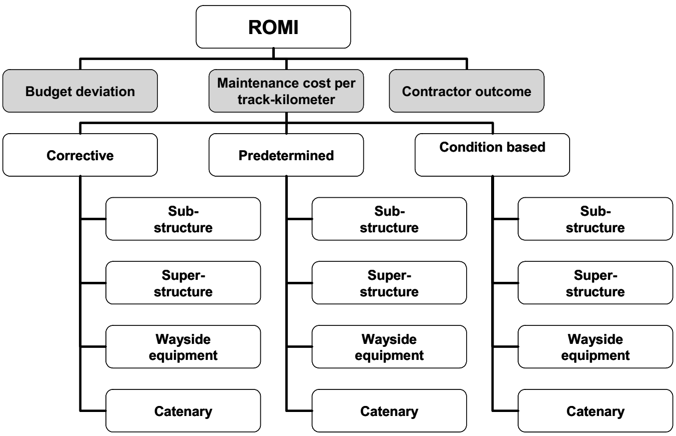

Figure 25. The ROMI-model in the link and effect model

The second indicator model is the HSE-model reflecting health, safety, and environmental issues, see Figure 26. This model is build up by the three non-existing indices health, safety, and environment. However, health is so far the same as the *reduced stress indicator*. Safety is build up by the *number of accidents at level crossings* indicator and the *number of accidents involving railway vehicle indicator* which is further broken down into the *share of derailments indicator*.

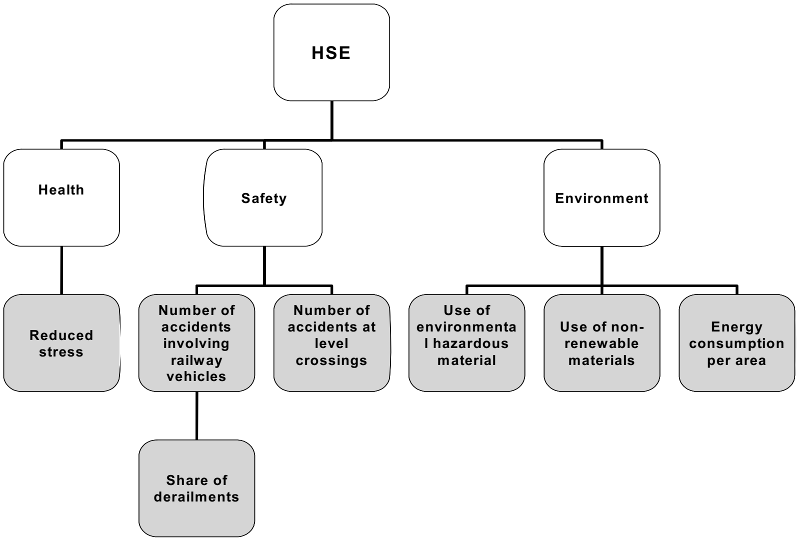

Figure 26. The HSE-model in the link and effect model

The third indicator model is the Train delay index-model reflecting punctuality, see Figure 27. The model is build up by the following existing indicators:

- *Train delays due to infrastructure*
- *Hours of freight train delays due to infrastructure*
- *Number of delayed freight trains due to infrastructure*
- *Number of train disruptions due to infrastructure*

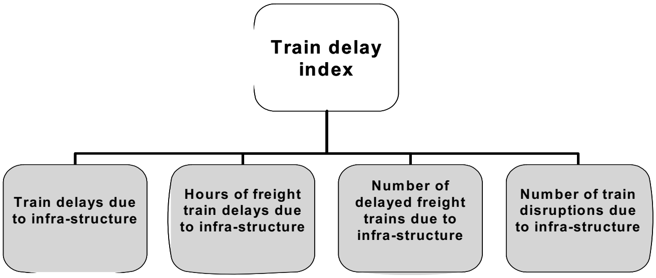

Figure 27. The Train delay index-model in the link and effect model

The fourth indicator model is the Railway infrastructure assets integrity-model reflecting the general condition of the railway infrastructure, see Figure 28. The model is build up by three non-existing indices, namely track quality, reliability index, and availability index. Track quality is build up by the *Q-factor indicator, Track Quality indicator,* and the *defect sleeper indicator*. Reliability index is build up by the *total number of urgent inspection remarks indicator* including the *share of inspections due to wheel flats* and the *total number of functional disruptions indicator* including the *share of functional disruptions leading to train disruptions indicator.*

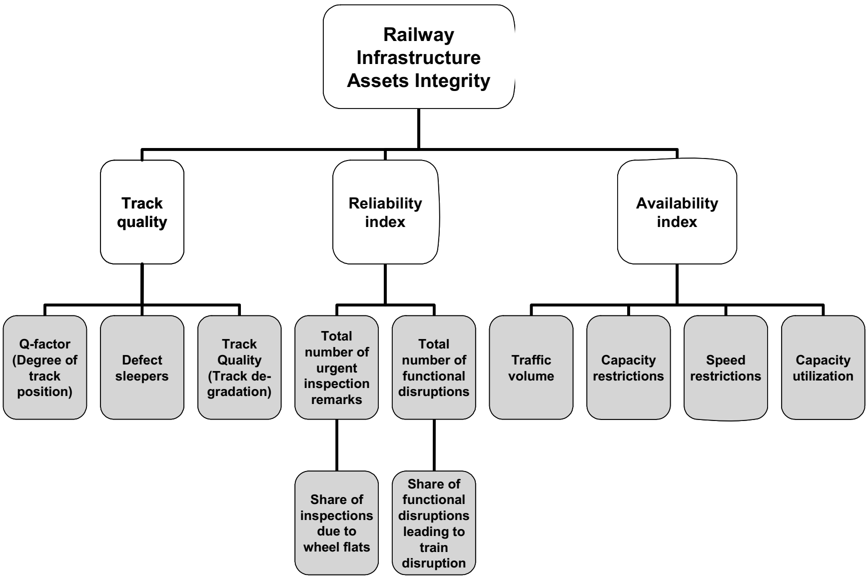

Figure 28. The Railway infrastructure assets integrity-model in the link and effect model

The fifth indicator model is the Process-model reflecting the processes in the involved organizations, i.e. involved maintenance organizations, see Figure 29. The model is build up by the *share of unplanned maintenance indicator* and two additional non-existing indices, namely share of condition based maintenance indices and share of predetermined maintenance indices.

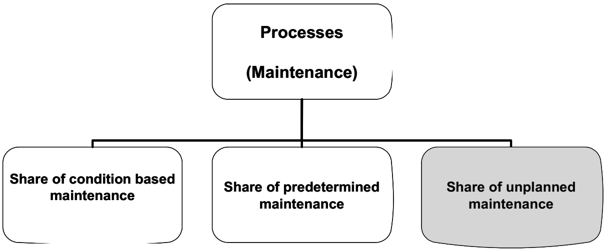

Figure 29. The Process-model in the link and effect model

Finally, the sixth indicator model is the Relationship-model reflecting internal and external relationships inside and outside the maintenance organization, sees Figure 30. The model is build up by the *partnering contracts indicator* and the *customer dialogue indicator.*

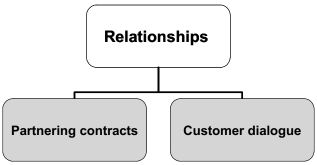

Figure 30. The Relationship-model in the link and effect model

6 CONCLUSION AND DISCUSSION

This chapter summarizes the findings in this thesis. It will also discuss some observations made during the thesis. Finally, it and discusses future research.

6.1 Conclusions

The purpose of this thesis was to identify and develop a set of performance indicators that supports the maintenance decision-making process; resulting in the main aim formulated to clarify how different maintenance performance indicators can be used to achieve more suitable decisions in the maintenance process. The purpose and aims of the study was then transferred in to the following research questions:

1. How can a maintenance performance indicator frame work be designed?

2. How can performance indicators support the maintenance decision-making process in proportion to punctuality, safety, environmental impact, and profitability?

3. How can a maintenance link and effect model with respect to punctuality, safety, environmental impact, and profitability be designed?

6.1.1 Findings regarding research question 1

The foundation for a maintenance performance indicator framework is identified in the literature study, e.g. different types of indicators, indicator design and characteristics, and indicator visualization and presentation, see section 2.2. In the analysis phase in section 5.1 are the different indicator definitions compared to each other and also one definition of performance indicators chosen, namely:

- *Performance indicator is a measure capable of generating a quantified value to indicate the level of performance taking into account single or multiple aspects (Liyanage et al., 2001)*

In the analysis are also some important questions regarding indicators presented as well as general indicator characteristics. A possible link and effect model and its critical strategic areas is identified in the literature study and adjusted to railway maintenance conditions during the analysis, see Figure 24.

During indicator development, implementation, and usage are some critical questions identified from a railway infrastructure perspective, namely:

- What is the meaning of the indicator signal and what type of decisions should be taken based on the signal, i.e. the indicator must reflect actions that are in line with maintenance objectives and chosen maintenance strategies
- Who is supposed to act on a changed indicator signal
- How should the indicator signal be visualized to the user to initiate the expected type of decisions

6.1.2 Findings regarding research question 2

The analysis of identified maintenance performance indicators in use at Banverket address that they can be tied to and reflect the different strategic areas identified for the modified link and effect model adjusted to railway infrastructure maintenance management, see section 5.2. By using the link and effect model's inherent design regarding under which conditions different sets of indicators are supposed to act as leading or lagging indicators, can the support of different sets of performance indicators in the decision making process in proportion to punctuality, safety, environmental impact, and profitability be assessed.

The design of the railway link and effect model is that the performance drivers for return on maintenance investments; health, safety, and environment; and punctuality is railway infrastructure assets integrity. The foundation for the infrastructure integrity is laid by good relationships, processes, and competencies. According to the design of the railway link and effect model must, as an example, desired improvements for the punctuality be made through improvements for the railway assets integrity as well as for instance process improvements.

The total set of identified performance indicators covers at least on the paper all critical strategic areas in the railway link and effect model. During this thesis work is however no assessment of the individual indicators performed in order to evaluate how well the different indicators are reflecting what they are supposed to reflect.

6.1.3 Findings regarding research question 3

The analysis of existing and potential maintenance performance indicators resulted in a useful set of indicators applicable for railway infrastructure assets management, classified into different classes and subgroups appropriate to match a modified link and effect model originally developed for the offshore industry. A link and effect model adjusted to management of railway infrastructure assets is presented in section 5.3 - Railway Link and Effect Model Framework. However, the suggested link and effect model shows that there are some more indicators that has to be developed before the link and effect model can be assessed and validated, and finally be tested in under true conditions. The missing indicators can be classified into two different indicator types, namely:

- Aggregated indicators such as a aggregated health, safety, and environmental indicator, aggregated train delay indicator, or aggregated railway infrastructure asset integrity indicator
- Broken down indicators such as maintenance costs per different types of railway assets and type of maintenance activities

Before a true condition test of the railway link and effect model can be undertaken is it also necessary to prioritize the different indicators amongst each others, i.e. define the relative impact of the indicators in order to make it possible to do the right decisions in a trade-of situation.

6.2 Discussion

The need of management on one hand and control on the other one is not a new phenomenon for the industry. Already back in the 1880s, the industry evolution and growth of the business themselves had led to demands of diverse production lines, resulting in that complex system that no one could manage and control them alone. The birth of an engineering driven management and control system was a fact.

From maintenance perspective became the need of such a management and control system a reality during the 1960s when the management of maintenance opened up for more maintenance alternatives than repair when broken. Today, the maintenance themselves is like an industry with extensive use of the latest technology. The opportunities to monitor and control in practice all kind of assets is today's reality but also a source of data overload for the managers. When it is time for decision making the manager is still not able to take into consideration more than just a few parameters. The question is therefore, which parameters or indicators should the maintenance decisions be based on?

The literature study shows that the choice of possible indicators can be counted into many hundreds at the same time as many of them are more or less tailor made for specific conditions; experiences expressed in the literature point at that direction. However, what all indicator practitioners can agree upon is that the use of indicators must be tied to and reflect the business overall objectives. They can also agree upon that it is important to find the ones that drives the future business performance; i.e. management by using proactive performance drivers instead of reactive performance outcomes. This may be done if the company has full control over all processes, which is not the case for Banverket and their maintenance processes. It is contracted out on the open market.

Depending on the chosen strategy for maintenance outsourcing and how the purchased maintenance contracts are written, it can vary a lot how much of the maintenance process that Banverket actually can manage without a need of negotiation with the maintenance contractor. Since Banverket is the core owner of the maintenance process though it is contracted out it is their responsibility to define overall maintenance goals and strategies. It is also Banverket that has to do the final assessment of the maintenance outcomes and compare it with their own overall goals and strategies as the railway infrastructure owner. Based on this can a comparison between the standard maintenance process map and the actual maintenance process map that can be viewed from Banverket's horizon be done, see Figure 31.

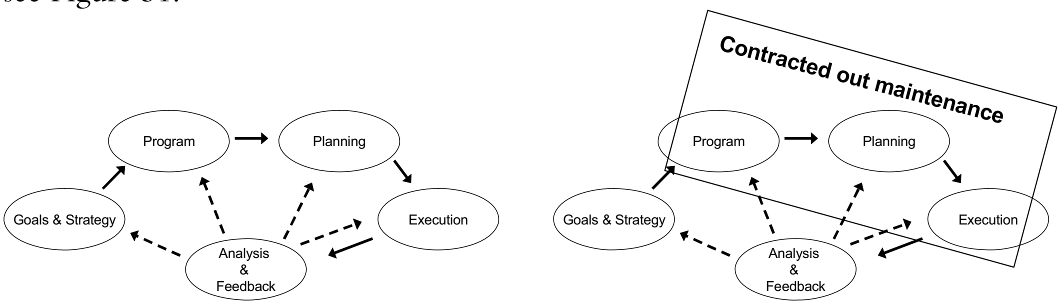

Figure 31. Standard maintenance process map and the maintenance process map viewed from Banverket's horizon

When developing and implementing new maintenance performance indicators into the maintenance process, it is important to be aware of how much of the maintenance process that are managed by Banverket and how much that are in practice managed by the different contractors. Since outsourcing is done primary to reduce costs it is important that the different contractors are allowed to do their tasks in different ways; that's how the contractors compete in an open market. However, during the last years has Banverket started to use the partnering concept as a tool to create a win-win situation together with different contractors; i.e. establishment of a win-win situation for all involved in the management of the maintenance process.

Two other important considerations to have in mind when developing and implementing new maintenance performance indicators for the Swedish railway network, is that the railway management is strictly regulated by different regulations and strong safety attitudes. The other one is that management of railway assets is a question of maintaining infrastructure assets with an expected lifetime up to more than hundred years, i.e. there is no room for gambling.

A comparison between Sweden, and for instance Queensland Rail in Australia and Network Rail in the UK, indicates that the use of maintenance performance indicators is more or less the same within the different railway administrations. In both Australia and UK is there a larger focus to present information on certain assets such as signals and power supply. In Australia is there also paid attention to openly express and follow up the fault response time. Queensland Rail is therefore the only railway administration that openly collects and presents information from the more executive parts in the maintenance process. However, this type of information is collected through different information systems at Banverket, such as the fault reporting system "0felia". 0felia can be translated into zero faults in the assets. Since this type of system is in use in Sweden, it also probably exist similar ones in the UK. Therefore, one conclusion from this thesis work is that the use of maintenance performance indicators is quite similar between Sweden, Australia, and UK. The existing differences are more a question of addressing different focuses inside the different railway administrations.

6.3 Future research

During the work with this thesis to identify maintenance performance indicators for railroad systems, are there also identified areas where future research should be undertaken in order to improve both the indicators themselves but also to develop new and more precise indicators. One research area is to continue the research started in this project in order to tune up and adjust the indicators in use.

Another research area is to develop fruitful indicators to manage and understand the maintenance process when it is outsourced into the open market, i.e. which indicators can be used to manage the interface between the purchaser and the contractor.

It is also important to undertake future research for further development of the link and effect model for railroad system in order to identify and understand which are the most critical-strategic railway areas from a maintenance perspective, as well as to identify and understand the links between them and based on that find proper indicators.

Finally, one research area of interest is to develop a model for monitoring and evaluation of the railroad system overall efficiency, a so called overall equipment efficiency model. This model is looked upon as a powerful management tool for many industries such as process and manufacturing industries.

7 REFERENCES

A Dictionary of Business (2002) IN Pallister, J. & Isaacs, A. (Eds.), Oxford University Press.

Allander, H. (1997) Objectives Matrix provides information balance. *Water Engineering & Management,* 144**,** 30-31.

Alvesson, M. & Sköldberg, K. (1994) *Tolkning och reflektion: vetenskapsfilosofi och kvalitativ metod,* Lund, Studentlitteratur.

Andersen, B. & Fagerhaug, T. (2002) Eight steps to a new performance measurement system. *Quality Progress,* 35**,** 112.

Banverket (2000) BVH 824.10: Tillståndsbeskrivning av banöverbyggnaden.

Banverket (2001a) Definition av begrepp inom banhållningsprocessen, BVF 826.

Banverket (2001b) Nulägesbeskrivning av statens spåranläggningar.

Banverket (2002a) Vinterutredning: Åtgärdsprogram inom järnvägssektorn. GD 02-111/OR40 (In Swedish).

Banverket (2002b) Annual Report 2001.

Banverket (2002c) Slutrapport: Kartläggning av banhållningsprocessen.

Banverket (2003) Förutbestämt underhåll, BVF 817.

Banverket (2005) Järnvägens historia, http://www.banverket.se/templates/StandardTtH____2642.asp, 2005-04-05.

Bianchi, M. & Saccardi, D. (2003) An integrated approach to railway asset management optimisation. *Conference proceeding of WCRR 2003, World Congress Railway Research.* Edinburgh, Scotland.

Carmines, E. G. & Zeller, R. A. (1979) *Reliability and Validity Assessment,* Newbury Park, Sage Publications.

Cummings, G. (1993) Beyond most modern-day maintenance strategies: Strategy indicators. *Industrial Engineer,* 25**,** 22.

Dunn, S. (2003) The Fourth Generation of Maintenance. *Conference proceedings of International Conference of Maintenance Societies (ICOM 2003).* Perth, Australia.

Ellingsen, H. P., Kumar, U., Liyanage, J. P., Hamre, R., Drangeid, S. O., Fuglseth, H., Honerud, B. M., Waldeland, R., Viland, L., Folstad, R., Bringedal, N., Aasland, A. T. & Nedrebø, R. (1999) The maintenance management process. Centre for maintenance and asset management, Stavanger University College.

Ellingsen, H. P., Kumar, U., Liyanage, J. P., Tönnesen, N., Hamre, R., Nilsen, N. M., Waldeland, R., Nerhus, O. & Espeland, Ö. (2001) Guidance for usage and implementation of operation & maintenance performance indicators. Centre for maintenance and asset management, Stavanger University College.

Encyclopedia Britannica (2003) http://search.eb.com/eb/articla/?eu_32476, 2003-09-20.

Engelkemeyer, S. & Voss, R. (2000) Bearing the Gift of Royal Performance Indicators. *Quality Progress,* 33**,** 35-39.

Espling, U. (2004) Ramverk för en drift- och underhållsstrategi ur ett regelstyrt infrastrukturperspektiv. *Järnvägstekniskt Centrum.* Luleå, Luleå tekniska universitet.

Espling, U. & Olsson, U. (2003) Delrapport 1 ”Arbetsgrupp TURSAM”. Intern rapport, JvtC.

European Environment Agency (2002) http://www.neb-one.gc.ca/safety/spi/sirformword_e.doc+definition+performance+indicator&hl=sv&ie=UTF8, 2002-09-20.

Failing, L. & Gregory, R. (2003) Ten common mistakes in designing biodiversity indicators for forest policy. *Journal of Environmental Management,* 68**,** 121-132.

Husband, T. M. (1976) *Maintenance, management and terotechnology*, Saxon House.

IAEA (2000) Operational safety performance indicators for nuclear power plants, IAEA-TECDOC-1141. International Atomic Energy Agency.

InvestorWords.com (2003) http://www.investorwords.com/cgi-bin/getword.cgi?2435&indicator, 2003-09-10.

Kaplan, R. & Norton, D. (1992) The Balanced Scorecard - Measures That Drive Performance. *Harvard Business Review,* 70**,** 71-79.

Kaplan, R. & Norton, D. (2001a) Transforming the Balanced Scorecard from Performance Measurement to Strategic Management: Part 1. *Accounting Horizons,* 15**,** 87-104.

Kaplan, R. & Norton, D. (2001b) Transforming the Balanced Scorecard from Performance Measurement to Strategic Management: Part 2. *Accounting Horizons,* 15**,** 147-160.

Kelly, A. (1989) *Maintenance and its management,* Monks Hill, Conference Communication.

Kimberling, D. N., Karr, J. R. & Fore, L. S. (2001) Measuring human disturbance using terrestrial invertebrates in the shrub-steppe of eastern Washington (USA). *Ecological Indicators,* 1**,** 63-81.

Kumar, U. & Ellingsen, H. P. (2000) Development and implementation of maintenance performance indicators for the Norwegian oil and gas industry. *Conference proceedings of 15th European Maintenance Conference (Euromaintenance 2000).* Gothenburg, Sweden.

Liyanage, J. P., Ellingsen, H. P., Folstad, R. & Bringedal, N. H. (2001) Terminology. Centre for Maintenance and Asset Management, Stavanger University College.

Liyanage, J. P. & Kumar, U. (2002a) Process of Maintenance Performance Management and Its Imperatives Within the Offshore Petroleum Industry (Part II): Value Based Maintenance Performance Management (VBMPM). *SMRP Solutions,* 2002:2.

Liyanage, J. P. & Kumar, U. (2002b) Process of Maintenance Performance Management and Its Imperatives Within the Offshore Petroleum Industry (Part III): Integration of Maintenance Performance to Corporate Value Process. *SMRP Solutions,* 2002:3.

Liyanage, J. P. & Kumar, U. (2003) Towards a value-based view on operations and maintenance performance management. *Journal of Quality in Maintenance Engineering,* 9**,** 333-350.

Liyanage, J. P. & Selmer, C. (1999) Establishment of an engineering methodology and a structure for a measurement system within the operation and maintenance process. Centre for maintenance and asset management, Stavanger University College.

Lyons, J., Gutiérrez-Hernández, A., Díaz-Pardo, E., Soto-Galera, E., Medina-Nava, M. & Pineda-López, R. (2000) Development of a preliminary index of biotic integrity (IBI) based on fish assemblages to assess ecosystem condition in the lakes of central Mexico. *Hydrobiologia,* 418**,** 57-72.

Miljövårdsberedningen (1998) Gröna nyckeltal: indikatorer för ett ekologiskt hållbart samhälle: betänkande. *Statens offentliga utredningar, 1998:15.* Stockholm, Fritzes offentliga publikationer.

Ministry of Industry, E. a. C. (2002) Government appropriation letter for fiscal year 2003 concerning Banverket etc. within the expenditure area 22 Communications. N2002/11974/IR (In Swedish).

Mossberg, T. (1977) *Utveckling av nyckeltal,* Stockholm, CEBE Grafiska.

Moubray, J. (1991) *Reliability-centred maintenance,* Oxford, Butterworth-Heinemann.

Nationalencyklopedin (2002a) http://www.ne.se /jsp/search/article.jsp?i_art_id=211062, 2002-09-20.

Nationalencyklopedin (2002b) http://www.ne.se /jsp/search/article.jsp?i_art_id=211063, 2002-09-20.

Nationalencyklopedin (2002c) http://www.ne.se /jsp/search/article.jsp?i_art_id=211065, 2002-09-20.

Network Rail (2003) Annual Report and Accounts. Network Rail Infrastructure Ltd.

Network Rail (2004) Business Plan Summary 2004. Network Rail,UK.

NFR-PROSMAT 2000 (1999) Bruk av Teknisk Tilstandsindeks som måltall for overordnet styring av teknisk tilstand. IN Sörli, A. (Ed.).

Olve, N. G., Roy, J. & Wetter, M. (1999) *Performance drivers: a practical guide to using the balanced scorecard,* Chichester, Wiley cop.

Oxford English Dictionary (2003) http://dictionary.oed.com/cgi/entry/00115274?query_type=word&queryword=indicator, 2003-09-02.

Parida, A., Phanse, K. & Kumar, U. (2004) An Integrated Approach to Design and Development of e-Maintenance System. *ACSIM 2004.* New Delhi.

Parida, A., Åhren, T. & Kumar, U. (2003) Integrating maintenance performance with corporate balanced scorecard. *Conference proceeding of the 16th. International Congress of COMADEM.* Växjö, Sweden.

Patel, R. & Davidson, B. (1994) *Forskningsmetodikens grunder: att planera, genomföra och rapportera en undersökning,* Lund, Studentlitteratur.

Peterson, S. B. (1999) Defining Asset Management. *Maintenance Technology,* 12**,** 13-17.

Plunkett, C. (2003) Measuring Maintenance Performance to Reduce Costs and Improve Efficiency. *Conference Proceeding of IHHA 2003, International Heavy Haul Association.* Dallas, USA.

Queensland Rail (2003) ISG Key Performance Indicators, Internal Report.

Segovia, J. J. & Thornton, D. B. (1990) Relevance Lost: The Rise and Fall of Management (Book review). *Contemporary Accounting Research.* Canadian Academic Accounting Association.

SIS (2001) Maintenance Terminology - SS-EN 13306. Swedish Standard Institute, Stockholm, Sweden.

Smith, R. (2003) Key performance Indicators - Leading or Lagging and when to use them. www.reliabilityweb.com.

Stricoff, R. (2000) Safety Performance Measurement; Identifying Prospective Indicators with High Validity. *Professional Safety,* 45**,** 36-39.

Swanson, L. (2001) Linking maintenance strategies to performance. *International Journal of Production Economics,* 70**,** 237-244.

The Local Government Management Board (1995) Sustainable Indicators Research Project: Consultants' Report of the Pilot Phase. London.

Toellner, J. (2001) Improving safety & health performance: Identifying & measuring leading indicators. 46**,** 42-47.

White, E. N. (1973) *Maintenance planning, control and documentation,* Epping, Essex, Gower.

Wiklund, R. (2005) *En banbrytande innovation: elektrifieringen av Riksgränsbanan,* Luleå, Luleå tekniska universitet.

Wireman, T. (1998) *Developing performance indicators in maintenance,* New York, Industrial Press.

Wireman, T. (2004) *Benchmarking Best Practice in Maintenance Management,* New York, Industrial Press Inc.

Woodhouse, J. (1997) What is Asset Management. *Maintenance & Asset Management,* 12**,** 26-28.

Yin, R. K. (1994) *Case study research: design and methods,* Thousand Oaks, CA, Sage.

Åhrén, T. (2004) Indikatorer: en översikt inom Banverket. Luleå, Luleå tekniska universitet (In Swedish).

Åhrén, T. & Kumar, U. (2004) Use of maintenance performance indicators: a case study at Banverket. *Conference proceeding of the 5th. Asia-Pacific Industrial Engineering and Management Systems Conference (APIEMS2004).* Gold Coast, Australia.