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Link and effect model for performance improvement of railway infrastructure

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

Abstract

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

1 Introduction

The level of railway traffic has increased over the last decade and is likely to further increase as more goods are transported via rail rather than road due to soaring energy costs, road congestion and the demand to reduce emissions (EC, 2011). The key goals set by the European Union (EU) include a 50 % shift of medium distance intercity passenger and freight journeys from road to rail and waterborne transport, and a 60 % cut in CO₂ emissions generated by transport systems. These goals need to be met by 2050 and thus there is considerable interest in methods to increase the capacity of existing railways and make them more environmentally friendly.

Efficient and effective maintenance is essential to ensure maximum dependability and capacity of the existing railway infrastructure. To manage maintenance successfully within stated objectives, the infrastructure performance needs to be measured and monitored. Performance indicators (PIs) for reliability, capacity, punctuality, etc. are extensively used by infrastructure managers (IMs) in making maintenance decisions. However, they are sometimes used in an ad hoc manner and not properly defined. A proactive management approach using performance measurements can lead to savings and improve profitability. However, as additional costs are associated with the measurement processes, it is important to thoroughly analyse what, where, when and how to measure (Parida

and Kumar, 2004). The efficiency and effectiveness of the railway infrastructure can be improved if an appropriate performance measurement (PM) system is selected. In traditional PM systems, PIs are given threshold values, indicating when an action needs to be taken, and since PIs commonly consist of aggregated data, e.g. total delay, PIs can appear to be abstract in nature. Therefore, aggregated PIs with thresholds can make the system reactive if not appropriately used. To meet these problems, in the proposed link and effect model, PIs are analysed for the underlying factors responsible for the performance, providing a starting point for improvements.

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

2 Performance improvement under a link and effect model

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

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

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

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

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

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

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

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

organisational changes can also affect the success of a PM system. Overall, PM systems need to be proactive and dynamic to handle changes such as:

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

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

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

3 The link and effect model

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

3.1 Step 1: Break down of objectives

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

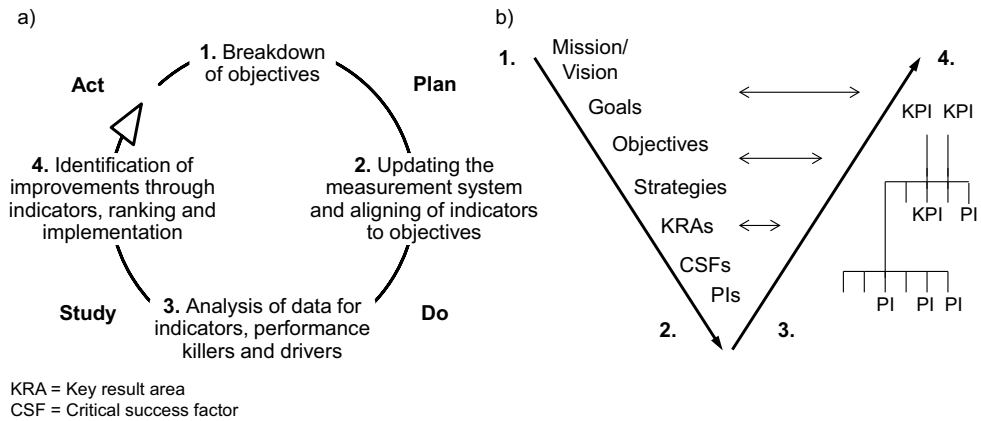


Figure 1: The link and effect model based on (a) a four-step continuous improvement process and (b) a top-down and bottom-up process. The numbers in (b) represents the steps in (a).

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

3.2 Step 2: Updating the measurement system and aligning of indicators

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

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

Table 1: Key elements of strategic planning.

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

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

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

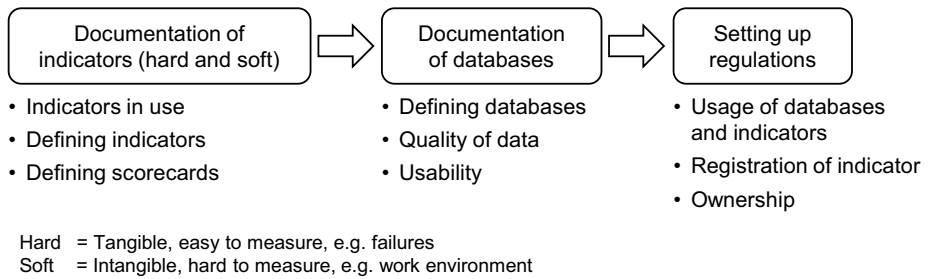


Figure 2: Key requirements for PM.

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

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

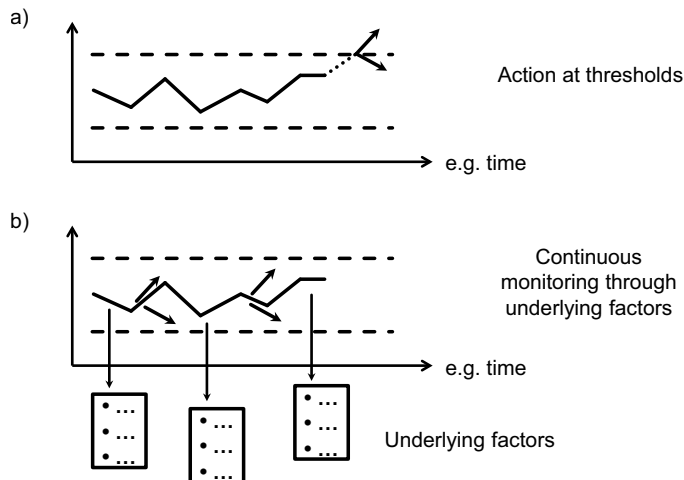


Figure 3: (a) Traditional PM system with thresholds and (b) link and effect model complemented with the underlying factors of the indicator.

3.4 Step 4: Identification of improvements, ranking and implementation

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

4 Case study

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

4.1 Step 1: Breaking down objectives

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

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

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

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

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

- overall goal: to ensure an economic, efficient and sustainable provision of transport services for people and businesses throughout the country (Näringsdepartementet, 2009);
- objectives: railway operation and maintenance related objectives can be found in Trafikverket's quality of service (QoS) scorecard (Söderholm and Norrbin, 2011).

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

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

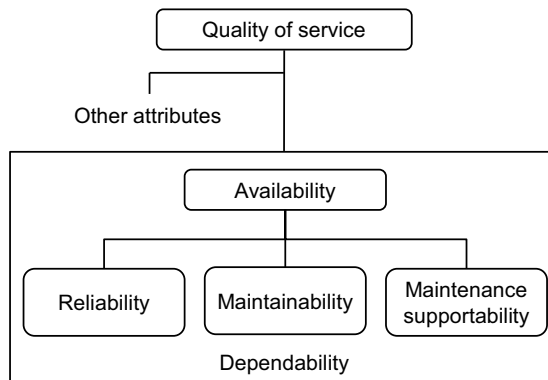


Figure 4: Quality of service.

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

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

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

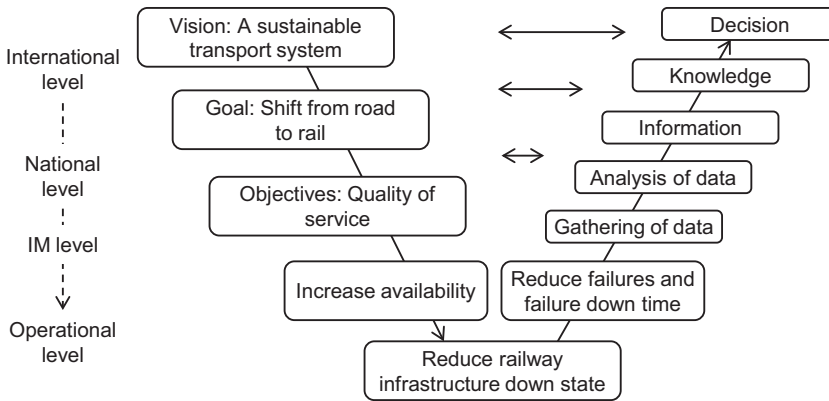


Figure 5: Breaking strategy into failure and down time components.

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

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

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

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

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

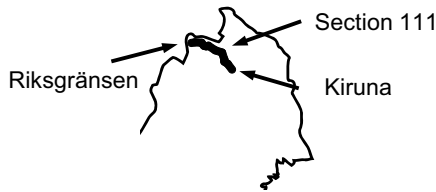


Figure 6: Section 111 between the border of Norway, Riksgränsen, and Kiruna city.

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

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

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

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

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

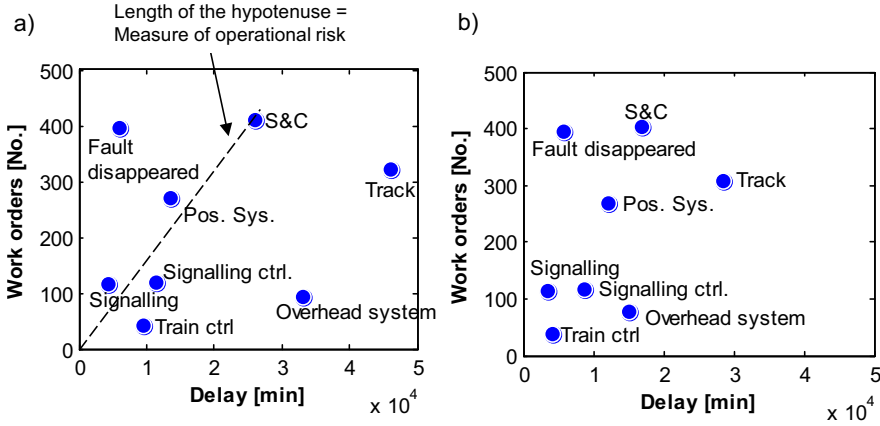


Figure 7: Risk matrix at the system level, displaying WOs and corresponding train delays (a) complete data set and (b) data up to the 98th percentile for delays.

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

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

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

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

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

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

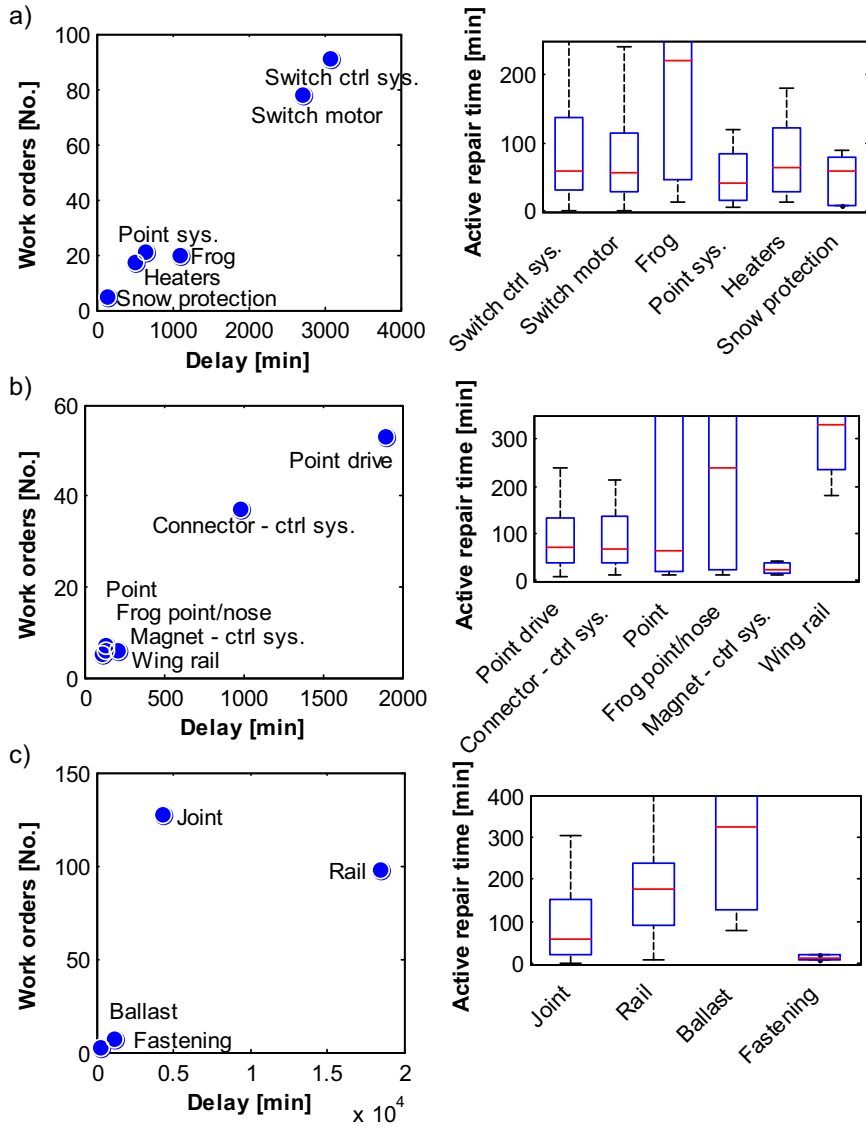


Figure 8: Analysis of (a) the subsystems of the S&C, (b) components of the S&C and (c) subsystems of the track. Delay data up to the 98th percentile are used.

Table 2 gives an indication of potential savings in WOs and train delays; however, aggregating data over 9 years does not necessarily give accurate information on the present state. Another goal of the link and effect model is to present PIs with the underlying

factors, thus providing direction for improvements, rather than merely presenting an aggregated measure. The data of railway section 111 (up to the 98th percentile) were used to calculate a yearly risk ranking and the results are plotted in Figure 9. As in the risk matrices, the risk is given by the hypotenuse. The top three systems appear for each year. It can be seen that the track (letter B) disappears after 2006, coinciding with a major rail replacement (Figure 10).

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

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

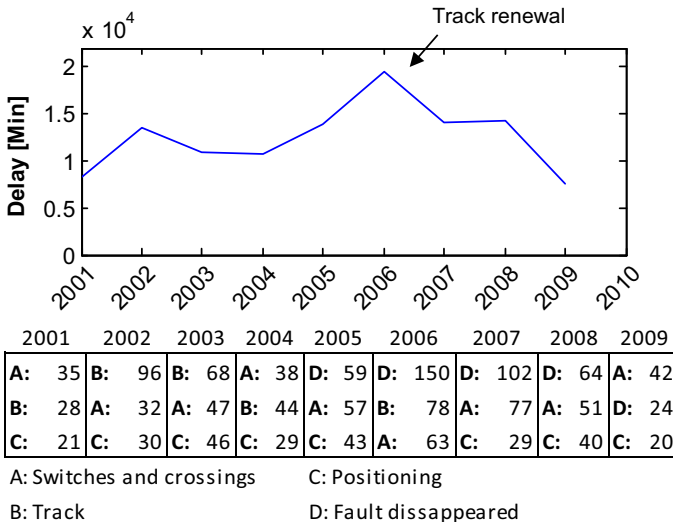


Figure 9: Train delay with the three underlying systems of highest operational risk, note that the track (letter B) disappears after 2006 from the top three; see Figure 10.

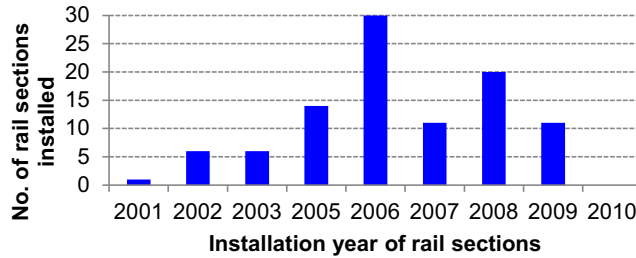


Figure 10: Renewal of rail sections. The large number of renewals in 2006 coincides with the disappearance of the track in the top three poor performing systems in 2006; see Figure 9. A total of 99 out of 188 rail sections were replaced between 2001 and 2010.

4.4 Step 4: Identification of improvements, ranking and implementation

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

5 Discussion and conclusions

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

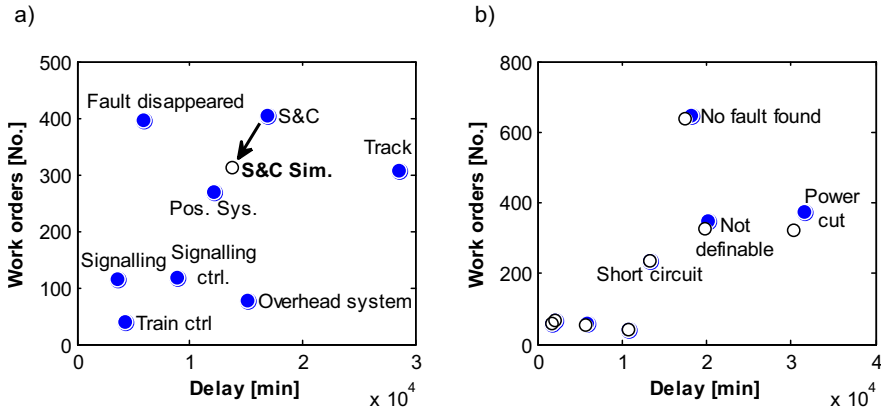


Figure 11: Simulation at system level (a) impact on the S&C system when all the WOs of the switch controller subsystem are removed from the data set and (b) all WOs sorted on the registered actual fault. The open circles show the result when all the WOs of the switch controller subsystem are removed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

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

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

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

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

The algorithms developed in the case study take spreadsheets of raw data as inputs, which most computer software can generate. Thus, automatic analysis for specific needs can be carried out in-house, without large investment, to complement commercial CMMSs. The method is highly efficient, as the data cleaning process is simple. Therefore, detailed analysis needs to be carried out before taking specific actions. Additionally, simulations can be performed by modifying the input spreadsheets. Tests showed that

modification of the data at the component level of the S&C appears on the indicators at the system level in terms of risk, failures, delays and maintenance times. In other words, it is possible to simulate the effect at the system level before carrying out improvements at the component level.

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

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References

- Åhrén, T. and Kumar, U. (2004). Use of maintenance performance indicators: A case study at Banverket. In Nezamirad, K., Higgins, P. G., and Dunstall, S., editors, *Conference proceedings of the 5th Asia-Pacific Industrial Engineering and Management Systems Conference (APIEMS2004)*, pages 30.8.1–30.8.9.
- Åhrén, T. (2008). *Maintenance Performance Indicators (MPIs) for Railway Infrastructure: Identification and Analysis for Improvement*. PhD thesis, Luleå University of Technology.
- Andersson, M. (2002). Strategic planning of track maintenance: State of the art. Technical report, Royal Institute of Technology.
- Armstrong, J. S. (1982). The value of formal planning for strategic decisions: Review of empirical research. *Strategic Management Journal*, 3(3):197–211.
- Berggren, E. G. (2010). Efficient track maintenance: Methodology for combined analysis of condition data. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 224(5):353–360.

- Boston, J. and Pallot, J. (1997). Linking strategy and performance: Developments in the New Zealand public sector. *Journal of Policy Analysis and Management*, 16(3):382–404.
- Bourne, M., Neely, A., Platts, K., and Mills, J. (2002). The success and failure of performance measurement initiatives: Perceptions of participating managers. *International Journal of Operations & Production Management*, 22(11):1288–1310.
- CEN (1999). EN 50126: Railway specifications - The specification and demonstration of reliability, availability, maintainability and safety (RAMS). Technical report, European Committee for Standardization (CEN).
- CEN (2010). EN 13306: Maintenance terminology. Technical report, European Committee for Standardization (CEN).
- Davenport, T. H., Harris, J. G., Long, D. W. D., and Jacobson, A. L. (2001). Data to knowledge to results: Building an analytic capability. *California Management Review*, 43(2):117–138.
- Davis, C. E. and Davis, E. B. (2010). *Managerial accounting*. John Wiley & Sons.
- EC (1996). Council directive 96/48/EC of 23 July 1996 on the interoperability of the trans-European high-speed rail system. *Official Journal of the European Communities*, (L235):6–24.
- EC (2011). *White paper: Roadmap to a single European transport area: Towards a competitive and resource efficient transport system*. European Commission (EC).
- Fitzgerald, L., Johnston, R., Brignall, S., Silvestro, R., and Voss, C. (1991). *Performance measurement in the service business*. Performance measurement in the service business (CIMA), London.
- Gates, L. P. (2010). Strategic planning with critical success factors and future scenarios: An integrated strategic planning framework. Technical report, Carnegie Mellon University.
- IEC (1990). IEC 60050-191: International electrotechnical vocabulary: Chapter 191: Dependability and quality of service. Technical report, International Electrotechnical Commission (IEC).
- Imai, M. (1986). *Kaizen: The key to Japan's competitive success*. McGraw-Hill, New York, 1st edition.
- ISO/IEC (2009). ISO/IEC 31010: Risk management: Risk assessment techniques. Technical report, International Organization for Standardisation (ISO).

- Johnson, H. T. (1983). The search for gain in markets and firms: A review of the historical emergence of management accounting systems. *Accounting, Organizations and Society*, 8(2-3):139–146.
- Kaplan, R. S. (1984). The evolution of management accounting. *The Accounting Review*, 59(3):pp. 390–418.
- Kaplan, R. S. and Norton, D. P. (1992). The balanced scorecard: Measures that drive performance. *Harvard Business Review*, 70(1):71–79.
- Kaplan, R. S. and Norton, D. P. (1993). Putting the balanced scorecard to work. *Harvard Business Review*, Sep./Oct.:134–147.
- Kaplan, R. S. and Norton, D. P. (2000). *The strategy-focused organization: How balanced scorecard companies thrive in the new business environment*. Harvard Business Press Books, Boston, 1st edition.
- Karim, R., Candell, O., and Söderholm, P. (2009). E-maintenance and information logistics: Aspects of content format. *Journal of Quality in Maintenance Engineering*, 15(3):308–324.
- Kaydos, W. (1991). *Measuring, managing and maximizing performance*. Productivity Press, Portland, 1st edition.
- Keegan, D. P., Eiler, R. G., and Jones, C. R. (1989). Are your performance measures obsolete? *Management Accounting*, 70(12):45–55.
- Kumar, S., Espling, U., and Kumar, U. (2008). Holistic procedure for rail maintenance in sweden. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 222(4):331–344.
- Leidecker, J. K. and Bruno, A. V. (1984). Identifying and using critical success factors. *Long range planning*, 17(1):23–32.
- Liyanaage, J. P. and Kumar, U. (2003). Towards a value-based view on operations and maintenance performance management. *Journal of Quality in Maintenance Engineering*, 9(4):333–350.
- Locke, E. A., Shaw, K. N., Saari, L. M., and Latham, G. P. (1981). Goal setting and task performance: 1969-1980. *Psychological bulletin*, 90(1):125–152.
- Näringsdepartementet (2009). Overall objective of the Swedish transport policy, N9012.
- OECD & JRC - EC (2008). *Handbook on constructing composite indicators: Methodology and user guide*. Organisation for Economic Co-operation and Development (OECD), Paris, France, 1st edition.

- Parida, A. and Kumar, U. (2004). Managing information is the key to maintenance effectiveness. In *Proceedings of the IMS 2004 International Conference on Intelligent Maintenance Systems*.
- Parida, A. and Kumar, U. (2006). Maintenance performance measurement (MPM): Issues and challenges. *Journal of Quality in Maintenance Engineering*, 3(12):239–251.
- Pritchard, R. D., Roth, P. L., Jones, S. D., and Roth, P. G. (1990). Implementing feedback systems to enhance productivity: A practical guide. *National Productivity Review*, 10(1):57–67.
- Santos-Reyes, J., Beard, A. N., and Smith, R. A. (2005). A systemic analysis of railway accidents. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*, 219(2):47–65.
- Sinclair, D. and Zairi, M. (1995). Effective process management through performance measurement: Part III - An integrated model of total quality-based performance measurement. *Business Process Re-engineering & Management Journal*, 1(3):50–65.
- Söderholm, P. and Norrbin, P. (2011). A risk-based dependability approach to link maintenance performance measurement and management to overall objectives: A case study within the Swedish railway. In Galar, D., Parida, A., Schunnesson, H., and Kumar, U., editors, *1st International Conference on Maintenance Performance Measurement and Management (MPMM)*, pages 241–247. Luleå University of Technology.
- Stenström, C. (2012). Maintenance performance measurement of railway infrastructure with focus on the Swedish network. Technical report, Luleå University of Technology.
- Stenström, C., Parida, A., and Galar, D. (2012). Maintenance performance indicators for railway infrastructure management. In Pombo, J., editor, *Proceedings of the First International Conference on Railway Technology: Research, Development and Maintenance*. Civil-Comp Press, Stirlingshire, UK.
- Swanson, L. (2001). Linking maintenance strategies to performance. *Int. J. Production Economics*, 70:237–244.
- Tsang, A. H. C. (2002). Strategic dimensions of maintenance management. *Journal of Quality in Maintenance Engineering*, 8(1):7–39.
- U.S. Dept of Defense (1949). Mil-p-1629 - procedures for performing a failure mode effect and critical analysis. Technical report.
- U.S. Dept of Energy (1993). Total quality management implementation guidelines. Technical report.