Data to Decision through Contextual Presentation of Railway Infrastructure Performance

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ABSTRACT

Asset performance measurement is an integral part of business process designed to support infrastructure managers in decision-making. Managing infrastructure performance throughout an asset's life cycle is a challenge; assessment is a complex issue involving various inputs and outputs, as well as conflicting requirements of different stakeholders. For railway infrastructure managers, the most critical issue is to reduce maintenance possession time, to minimise train delays and meet passengers' and societal needs. In this study, we collect and analyse work order and train delay data for one section of the iron ore railway line in Sweden. The aim is to present the overall performance of an asset for its end users, considering both the asset context and the user context, to ensure effective planning and decision-making. The case study results can also be used for internal and external benchmarking, and to identify performance problems of the infrastructure.

Keywords: Performance measurement, composite indicators, data quality, maintenance, eMaintenance, railway, train delay, failures, heavy haul, context

1. INTRODUCTION

Physical assets are a valuable part of the overall business process for which companies treats asset performance measurement and management an integral part of their strategic planning and policy making. In asset-intensive industries, the maintenance costs of assets constitute a significant amount of the total business cost. Non-availability and/or downtime of an asset will have an impact on the plant and asset capacity, product quality, and cost of production, as well as on health, safety and the environment. Asset performance measurement and management is a multi-disciplinary process; it provides critical support to heavy and capital-intensive industries by keeping assets, e.g. machinery and equipment, in a safe operating condition. It is generally accepted that asset performance management is key to the long-term profitability and sustainability of an organization.

Due to today's competitive global business environment, asset utilisation and performance optimisation throughout an asset's life cycle are important to asset owners and infrastructure managers (IMs). Physical assets represent the basic infrastructure of all businesses and their effective management is essential to meet business objectives and goals. Thus, it is necessary to plan, monitor and control assets' performance throughout their entire life cycle, from the development/procurement stage to their eventual disposal. Life cycle costing seeks to optimise value for asset owners and infrastructure managers; to this end, it considers all the cost factors of the asset during its entire operational life. Today, with available knowledge and technology, it is perceived that "asset performance measurement and management can be planned and controlled," thus, it is essential for management to understand and calculate an asset's availability and capacity utilisation to make effective repair and replacement decisions.

Health monitoring of the infrastructure or of any individual asset is a critical issue; management must provide right information on an asset's health status to achieve better performance and reliability, safely and with minimum costs. The advancement in information technology has had a significant impact on the asset management information system; we are now better able to determine an asset's health status, thereby supporting good decision-making. Technological advancements, including embedded and wireless sensors, automated controls and data analysis management, have led to new and innovative methods in asset health monitoring. Further, rapid growth in networking systems, especially through the internet, has overcome the barriers of distance, allowing real time data transfer to occur easily from different locations [27]. With the emergence of intelligent sensors to measure and monitor the health state of a plant and its machines and with the gradual implementation of information and communication technologies (ICT) in organizations, the conceptualization and implementation of eMaintenance is becoming a reality [21]. Improved connectivity, faster transfer of data and the ability to store and analyse large amounts of data are now required by maintenance managers. Current eMaintenance tools have already utilised existing web and computing network technology to form a maintenance infrastructure for integrating and synchronising various maintenance information, supporting and enhancing collaboration between different users [16].

Corporate strategy dictates how to achieve business objectives and create value for the stakeholders. However, without a comprehensive description of strategy, executives cannot easily communicate the strategy among themselves or to their employees [8]. The management of an organisation must

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convert the corporate strategy and objectives into specific objectives for each of the organisation's various hierarchical levels. An appropriate asset performance measurement system in an organisation has become a necessity, as without such assessment, it is not possible to attain the desired objectives.

A number of asset performance measurement frameworks have been developed applying the "Balanced Scorecard" [10] approach to ensure that all operational and maintenance activities of assets are aligned with an organisation's corporate strategies and objectives in a balanced manner. For details, see Parida and Chattopadhyay [20]. Parida and Chattopadhyay have developed a multi-criteria hierarchical maintenance performance measurement framework, which meets the organisational requirements of both external and internal stakeholders and identifies the various performance indicators (PIs) from a balanced and integrated view point. The framework has been tested in three Scandinavian industries with modifications to suit their individual organisational requirements.

In this study, after discussing the importance of performance measurement, work orders (WOs) and train delay data are collected and analysed for the iron ore railway line in Sweden. The aim is to present the overall performance of assets for the end users, considering both the asset context and the user context, to ensure effective planning and decision-making (Figure 1). The case study results can also be used for internal and external benchmarking, and to identify performance killers [25] of the infrastructure. Asset context and user context can be described as follows:

- The physical asset performance context: the asset's overall performance is determined using necessary performance indicators (PIs). In advanced setups, learning of PIs pattern for failure can be used in future prediction of similar events.
- The user context: asset performance with the right PIs, in the right format, is delivered to the right person, at the right time.

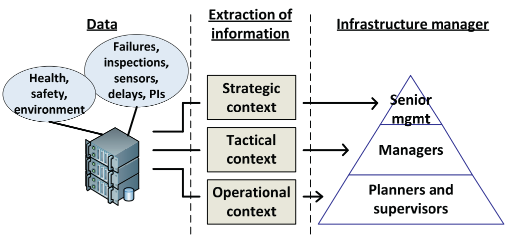

Figure 1. Visualisation of the need of a context based presentation of asset performance for business stakeholders

The structure of this paper is as follows. After introducing the topic in section 1, we discuss infrastructure performance measurement for decision-making in section 2. Section 3 deals with data quality issues in the decision process. The iron ore railway line case study and results are presented in section 4, followed by the discussion and conclusions.

2. INFRASTRUCTURE PERFORMANCE MEASUREMENT

- *What is infrastructure and why is PM required for infrastructure?*

Due to the increasing awareness that maintenance not only ensures safety and track performance, but creates additional value in the business process, Trafikverket (Swedish transport administration) is treating maintenance as an integral part of its business process, i.e. applying a holistic view to the infrastructure maintenance process to meet customer requirements [12]. Its infrastructure maintenance process visualises both front and back end processes in track maintenance [2]. One front end process is determining track maintenance demands, supported by measures such as track capacity and track quality [2].

From the infrastructure management perspective, achieving a punctual and cost-effective railroad transportation system requires ongoing development in maintenance engineering. Cost-effective maintenance processes help to achieve budget targets, while punctuality is required by stakeholders [1].

Companies are now using scorecards to manage their strategy over the long term in a number of critical processes [9] including the following:

1. Clarify and translate vision into objectives and strategy;
2. Communicate and link strategic objectives with the performance measures at different hierarchical levels;
3. Plan and set targets linked with KPIs/MPIs and aligned with strategic initiatives;
4. Enhance strategic and performance feedback and learning.

The KPIs translate aggregate measures from the shop floor to the strategic level. The real challenge lies in measuring all the KPIs; some are difficult to measure since they are intangible and qualitative in nature. Organizations need a framework to align their performance measurement system with the corporate strategic goals of a company by setting objectives and defining key performance at each level [14]. The performance measurement which forms part of the asset performance measurement system needs to be aligned with the organizational strategy [17]. The PIs must be considered from the perspective of the multi-hierarchical levels of the organization. As per [17], maintenance management must be carried out in both strategic and operational contexts and the organizational structure generally comprises three levels. Three hierarchical levels in most firms are the strategic or top management level, the tactical or middle management level, and the functional/operational level [20]. Two major strategic requirements of a successful corporate strategy relevant for the performance assessment are (Figure 2) the following:

1. Cascading the objectives down from the strategic level to the shop floor;
2. Aggregating performance measurements from the shop floor up to the strategic level.

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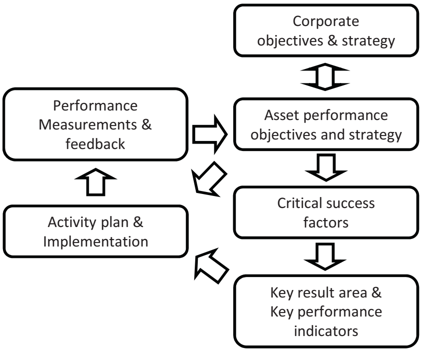

Figure 2. Strategic maintenance performance measurement process [19]

Results are visualised in key result areas (KRAs); critical success factors (CSFs) are those required to achieve the objectives of the KRAs.

2.1 Cascading down to the shop floor from the strategic level

The strategic objectives are formulated based on the requirements of the stakeholders, both internal and external. The plant capacity and resources are considered from a long-term point of view and are matched with each other. These strategic or corporate objectives cascade down the hierarchical level of the organization through the tactical level which considers the tactical issues, such as financial and non-financial aspects, both from the effectiveness and the efficiency point of view. The bottom level includes the shop floor engineers and operators.

2.2 Aggregating performance assessments from the shop floor up to the strategic level

The performance at the shop floor level is measured and aggregated to evaluate whether the corporate objectives have been achieved. Inspections, physical measurements or sensor/condition based measurements generate data which are analysed through programing or simulation, facilitating effective decision-making at the managerial/strategic level. The adoption of appropriate processes is vital to successfully align performance measurement to objectives. The energy and creativity of committed managers and employees needs to be harnessed to drive the desired organisational transformations [28]. This, in turn, leads to the empowerment of employees in the organization.

3. DATA QUALITY

For recording and conveying information about the maintenance management process, a maintenance documentation system is an essential operational requirement. Maintenance documentation can be described as any record, catalogue, manual, drawing or computer file containing information that might be required to facilitate maintenance work [13]. For maintenance, failure records are especially relevant; thus, failure data need to be recorded in a way that allows further computational analysis. A uniform definition of failure and a method of classifying failures are essential when data from different sources (plants and operators) are combined in a common maintenance database.

The process that begins by collecting the data and ends by presenting the information to the end user can be described as an interactive decision-making process. It can be divided into the following five steps: data collection, data transition, data fusion, data analysis and data presentation [29]. Each phase is important, as each affects the quality of the data.

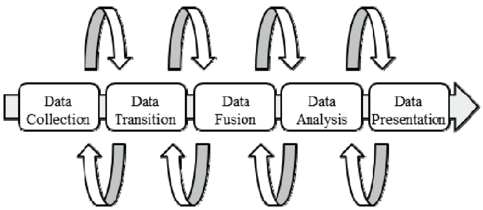

Figure 3. Generic decision making process, adapted from [29]

The lack of relevant data and information is one of the main problems for decision-making within the maintenance process [21]. The provision of the right information to the right user with the right quality and at the right time is essential [11, 21]. Data must be essential and relevant for its specific user; high-quality data are commonly defined as data that are appropriate for use by data consumers [26, 30]. Hence, to provide high quality data to the data consumer, one must understand what quality means to those who use the data [30].

Wang [30] presents a framework of data quality consisting of four categories: intrinsic, contextual, representational and accessibility. Each category relates to different data quality dimensions, as described in Table 1.

Table 1. Data quality aspects [30]

Category	Dimension
Intrinsic	Believability, Accuracy, Objectivity, Reputation
Contextual	Value-added, Relevancy, Timeliness, Completeness, Appropriate amount of data
Representational	Interpretability, Ease of understanding, Representational consistency, Concise representation
Accessibility	Accessibility, Access security

The context of the task for which the data will be used is essential to determine what data quality means in a particular instance. A study of data quality relating different contextual quality issues to the dimensions described in Table 1 has observed the following underlying causes for data not supporting the intended tasks: (i) missing or incomplete data;

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(ii) inaccurately defined or measured data; and (iii) data that could not be properly collected [26]. Figure 4 illustrates an example of how these contextual data quality issues can be linked to the different phases in the generic decision-making process, described above in Figure 3.

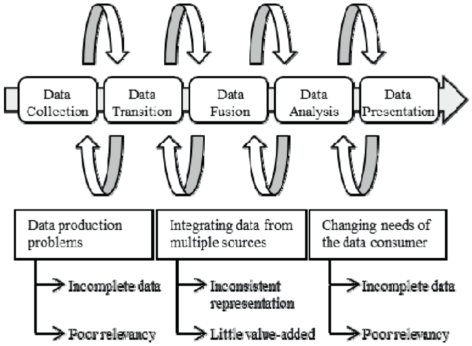

Figure 4. Data quality issues in a generic decision-making process, adapted from [26, 29]

4. CASE STUDY

The case study presents a railway asset's overall performance, considering the context of the asset and the context of the end user. Data have been collected and analysed for indicators considered important for the asset's performance. The results can facilitate efficient and effective decision-making for the operation and maintenance managers of the asset and can also be applied to the benchmarking of similar assets. The subject of the case study is a heavy haul railway line in Sweden.

The infrastructure and the IM are divided into three levels: strategic, tactical and operational, i.e. senior managers, middle managers and supervisors, respectively. Each level monitors the asset to meet its own needs (Figure 5). However, given the vast amount of data at the strategic level, the case study focuses on the tactical and operational levels. The asset morphology follows:

Corridor or network → Lines or routes → Sections → Zones → Systems, e.g. signalling system

The iron ore line is one line out of 84 lines in the Swedish network. Section 111 is one section out of 6 within the iron ore line, and there are 16 zones within that section. The management hierarchy of the asset takes the following form:

Senior managers: Lines
Middle managers: Sections
Operational managers or supervisors: Zones and systems

Given three scorecards, strategic, tactical and operational, the case study focuses largely on the operational scorecard, paying some attention to the tactical scorecard.

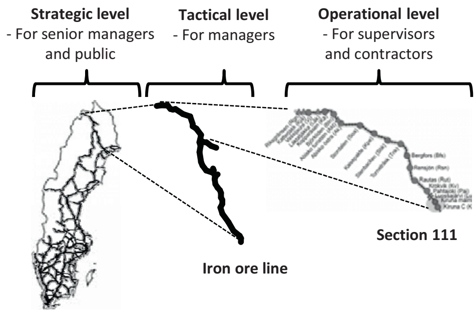

Figure 5. Railway network of Sweden, showing the subsystems and their stakeholders, each with specific needs for monitoring performance

4.1 Data collection and analysis

Railway section 111 of the iron ore line is a 128 km 30 tonne axle load mixed traffic heavy haul line stretching from Kiruna to Riksgränsen, on the Norwegian boarder (Figure 6). The data presented in Table 2 are considered important for a context focused presentation of railway infrastructure performance.

Table 2. Data for analysis

Data	Background
Overview of the asset	Important to know the operational environment and how it affects maintenance planning etc.
Sections and zones of the line	The sections of the line can have different subsystems, e.g. number of switches and crossings, and therefore the performance can vary
Length of each section/zone, and number of switches and crossings (S&C)	Number of failures in a section or zone can depend on the length of the section/zone or on the number of switches and crossings
Corrective maintenance work orders (WOs), i.e. failures	Failure frequencies of systems, etc.
Train delay (due to WOs)	Severity
Maintenance time	Important for administrative, logistic and repair time analysis and planning

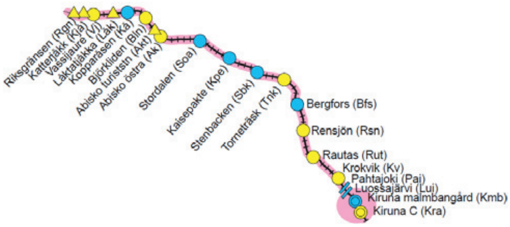

Figure 6. Zones of section 111, stretching from Kiruna city to Riksgränsen, the boarder of Norway

Corrective maintenance WOs were collected for 2001.01.01 - 2009.12.01, i.e. 8 years and 11 months. Out of 7 476 WOs in total, 1 966 mention train delays, i.e. 26 %. However, the train delay data have a skewed distribution with some long delays resulting in a long tail. The two percent with the longest delays are therefore considered as outlier cases. Outliers are preferably analysed before decision-making, but this is beyond the scope of this research. In fact, some railway infrastructure assets tend to give very long delays when it fails, e.g. the overhead contact system due to tear down of the contact wire by locomotive pantographs; alternatively the outliers could have been discounted per asset type. However, the analysis is based on WOs with delays up to the 98th percentile. In terms of WOs, 1 926 out of 1 966 WOs are considered; in terms of delay, this represents 112 616 minutes out of 166 693 minutes.

The corrective maintenance work order data consist of urgent inspection remarks reported by the maintenance contractor, as well as failure events and failure symptoms identified outside the inspections, commonly reported by the train driver, but occasionally reported by the public. The work order failure reports include the three categories of RAM (reliability, availability and maintainability) failure as identified by the European Standards EN 50126 [4], see Figure 7. Immediate action is required, if the fault negatively influences safety, causes train delay, or affects a third party or the environment.

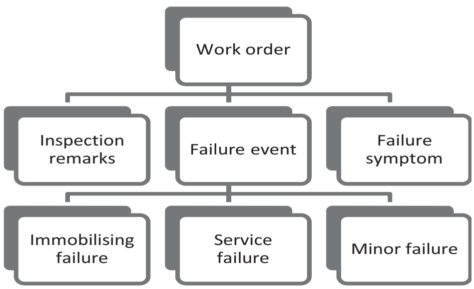

Figure 7. Work order description. The three RAM (reliability, availability, maintainability) categories are: immobilising failure, service failure and minor failure [4]

Indicators extracted from the data are presented in Table 3 below.

Table 3. Indicators calculated

Indictor	Comment
Number of WOs [No.]	Corrective maintenance work orders, i.e. functional failures
Train delay [min]	Delay caused by the WOs
Maintenance time	Consists of administrative time, logistic time and active repair time. For details, see [3, 6]
Risk [a.u.]	Risk is a composite indicator [18, 22] of WOs and train delay, defined as: $\text{Risk} = (a\alpha^2 + b\beta^2 + c\gamma^2)^{1/2}, \quad a,b,c \in \mathbb{R}$ where α = WOs, β = train delay, γ = maintenance time. The indicator can be seen as a measure of business risk. For further background, see probability-consequence diagram [7] or failure mode effect analysis.

4.2 Results

From the collected and analysed data, we find performance results for the operational and tactical levels. Table 4 and Figure 8 give the performance for the various zones of the railway section (Figure 6). The zones in the table correspond to the points in Figure 6, including the track metres to the next zone, e.g. zone Kv = Point Kv + track to Rut. Table 5 gives the top three systems with the highest risks, i.e. the performance killers. Table 6 shows the tactical level of section 111. However, the iron ore line consists of six sections; one is considered.

A similar study of the iron ore line carried out by [5] is useful for comparative purposes.

Table 4. Railway zones performance for the operational level. Some noteworthy values are marked in grey and bold

Zone	Length [m]	S&C [No.]	WOs /length [No./km]	Delay /length [min/km]	Maint. time (median) [Min]
Kmb (Pea)	4394	1	20	1396	157
Kv	9039	7	28	1646	135
Rut	8869	3	12	680	160
Rsn	7778	3	12	583	144
Bfs	8907	3	21	1147	151
Tnk	8477	4	23	777	129
Sbk	7929	6	15	700	**198**
Kpe	10612	3	16	716	148
Soa	8974	3	11	436	108
Ak	912	12	**122**	**3063**	112
Akt	6562	0	5	260	151
Bln	7164	3	25	1584	136
Kå	6742	4	13	1361	182
Låk	1130	0	19	1617	**202**
Vj	4088	4	**36**	**2662**	**227**
Kjå-Rgn	1767	0	8	1285	**195**
Whole sec.	103344	56	18	1020	153

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Table 5. Railway zone systems performance for the operational level. Some noteworthy values are marked in grey and bold. Risk = $(\alpha^2 + (100^{-1}\beta)^2 + \gamma^2)^{1/2}$

Zone	Top three systems in terms of risk (no.)	WOs [No.]	Delay [min]	Risk rank [a.u.]	Risk rank /length [a.u./km]
Kmb (Pea)	Track	58	4731	**75**	**17**
	Pos. Sys.	11	175	11	2,5
	Fault disappeared	10	150	10	2,3
Kv	S&C (7)	74	4443	**86**	-
	Fault disappeared	64	1072	**65**	7,2
	Track	32	3435	47	5,2
Rut	Fault disappeared	19	231	19	2,2
	Track	14	1170	18	2,1
	Pos. Sys.	15	421	16	1,8
Rsn	Fault disappeared	18	236	18	2,3
	Track	17	588	18	2,3
	Pos. Sys.	16	564	17	2,2
Bfs	Fault disappeared	58	781	**59**	6,6
	Track	42	3439	54	6,1
	Pos. Sys.	31	1353	34	3,8
Tnk	S&C (4)	**55**	**1648**	**57**	-
	Fault disappeared	47	560	47	5,6
	Pos. Sys.	32	862	33	3,9
Sbk	Fault disappeared	21	191	21	2,7
	Signalling	20	481	21	2,6
	S&C (6)	20	348	20	-
Kpe	S&C (3)	46	1743	49	-
	Signalling	35	820	36	3,4
	Track	23	1257	26	2,5
Soa	Fault disappeared	30	408	30	3,4
	S&C (3)	20	734	21	-
	Pos. Sys.	12	459	13	1,4
Ak	S&C **(12)**	**37**	**833**	**38**	-
	Fault disappeared	26	363	26	**29**
	Track	13	255	13	**15**
Akt	Pos. Sys.	7	160	7	1,1
	Track	4	194	4	0,7
	Fault disappeared	4	110	4	0,6
Bln	S&C (3)	40	1013	41	-
	Fault disappeared	40	821	41	5,7
	Signalling	13	2876	32	4,4
Kå	Pos. Sys.	15	1546	22	3,2
	Track	11	1558	19	2,8
	S&C (4)	16	368	16	-
Låk	OCS	5	734	9	7,9
	Pos. Sys.	5	479	7	6,1
	Track	3	401	5	4,4
Vj	S&C (4)	**55**	**2966**	**62**	-
	Signalling ctrl	16	1207	20	4,9
	Pos. Sys.	17	720	18	4,5
Kjå-Rgn	Signalling ctrl	4	834	9	5,2
	Sectioning station	1	513	5	3,0
	Track	2	442	5	2,7

a.u. = arbitrary unit

Table 6. Railway section performance for the tactical level. Risk = $(\alpha^2 + (100^{-1}\beta)^2 + \gamma^2)^{1/2}$. One section out of six is presented.

	Length [m]	S&C [No.]	WOs /length [No./km]	Delay /length [min/km]	Risk rank /length [a.u./km]	Maint. time (median) [Min]
Section 111	103344	56	18	1020	21	153

Top three systems in terms of risk	WOs [No.]	Delay [min]	Risk rank [a.u.]	Risk rank /length [a.u./km]
S&C	404	16880	438	-
Track	308	28590	420	3,28
Fault disappeared	396	5876	400	3,13

a.u. = arbitrary unit

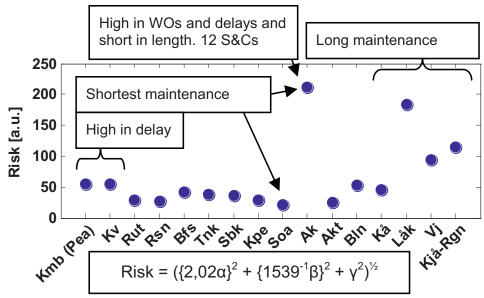

Figure 8. Risk ranks of the zones, taking into account WOs (α), train delay (β) and maintenance time (γ). Constants chosen to normalise parameters to give the same weight on the risk, i.e. equal weighting. Risks are divided by the length of the zones.

5. DISCUSSION

Various data and indicators are identified as important for presenting railway infrastructure performance in its context. However, railway infrastructure has a wider context than the one presented in this study, e.g. preventive maintenance and cold climate effects [24]. Moreover, the analysis comes from data over a nine year period, but aggregating data over nine years does not necessarily provide accurate information of the present state. Thus, analysis of shorter timespans is also important and needs to be considered [23].

Risk ranks are calculated in different ways for the section, zones and systems (Tables 5 and 6, Figure 8), by use of different weights and considering two or three parameters. It shows its variability but also constrains of the various levels, e.g. track system failures (WOs) may fit to be divided by zone length, while S&C does not. Moreover, the weights in Figure 8 were calculated from the 16 zones, such calculation was not possible in Table 6 since only one section was considered. It should also be noticed that failures, train delay and maintenance time are functions of each other to some extent.

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The case study shows how a physical asset's performance can be presented in its unique working context. However, even if descriptive statistics give valuable information for decision-making, it is lagging indicators. Simple and multiple linear regressions have been carried out to predict the train delays and number of work orders, but it provided weak results, requiring further work in this area.

The quality of the data has not been the main focus in the presented case study. However, in order to gain high quality data, one must understand what quality means to those who use the data [30]. The context of the task, i.e. where the data are used, is essential to determine data quality and this case study can be used as a starting point for further research in data quality issues related to contexts.

Contextual data quality emphasizes that the data must be relevant, timely, complete, and appropriate in terms of amount in order to add value. However, achieving contextual data quality is a subject for future research, since contexts and tasks vary over time and between data consumers [15]. Letting the data consumer parameterize the contextual dimensions (presented in Table 1) for each task is a possible approach [30].

6. CONCLUSIONS

This study takes some initial steps in presenting railway infrastructure performance while considering both the asset context and the user context, to facilitate efficient and effective decision-making. A composite indicator has been constructed to summarise the overall performance of a complex asset into a single number, easier to interpret by decision-makers then presenting multiple indicators and plots (Figure 8). However, parameter correlation, expert opinion weighting and sensitivity analysis are future work to consider. Moreover, further work is also needed for prediction and for taking into account more indicators to create a broader context.

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