LICENTIATE THESIS

Dependability and Maintenance Analysis of Railway Signalling Systems

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LULEÅ
UNIVERSITY
OF TECHNOLOGY

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PREFACE

The research presented in this thesis has been carried out at the Luleå Railway Research Centre (JVTC) at the Luleå University of Technology, and has been funded by the JVTC and the Swedish Transport Administration (Trafikverket). I would like to thank the JVTC and Trafikverket for providing the financial support to perform this research.

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I must thank Tåtte, family and friends for being there, even when “there” means thousands of kilometres of distance. I am here thanks to you.

Amparo Morant Estevan

January 2014.

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ABSTRACT

Railway signalling systems are composed of several different systems; each has its own purpose, but the main functionality of the overall system is determined by the interoperability between them. Railway signalling systems ensure the safe operation of the railway network, and their reliability and maintainability directly affect the capacity and availability of the railway network, in terms of both infrastructure and trains. The functionality of the signalling system is based on the principle of "fail safe"; this means that the railway section where a failure is located will be not fully operative until the failure is repaired (since safety cannot be ensured). Hence, the dependability of these systems directly affects the capacity of the network.

Signalling systems take up a large part of the railway's overall corrective maintenance. Railway managers need to have a holistic view of all systems to optimise maintenance. Signalling systems are especially important, given the need for interoperability. Given their complexity, knowledge must be correctly managed to ensure proper performance in all phases of the life cycle. Enhancing information logistics would lead to considerable improvements in this area.

This licentiate analyses the dependability and maintenance of railway signalling systems and proposes various approaches to improve maintenance performance. External factors affecting the reliability of signalling systems are identified, such as their location. The signalling system is treated as a system of systems because of its interoperability and because failures occurring on different systems can be associated with the same failure effect.

A data driven model for maintenance decision support is proposed, based on corrective maintenance work orders. The data driven model allows a holistic perspective of failure occurrence, as it integrates the information recorded in the many different parameters of the corrective maintenance work orders. With this model, existing maintenance policies could be reviewed and improved upon. This thesis proposes a model for configuration management, which simplifies the access and visibility of information. The model manages the change control process and ensures that configurations are updated in real-time. An enhancement of the configuration management has the potential to increase the efficacy of the maintenance actions in signalling systems by improving the accessibility of the information required to understand possible future failures. With increased accessible knowledge, the time needed to identify failures can be reduced, resulting in greater maintenance efficiency. It also establishes a framework for improving inter-organisational knowledge management between stakeholders, resulting in the creation of a holistic perspective of the maintenance and operation of the railway network, avoiding the loss of knowledge linked to outsourcing, and improving the effectiveness of the organisations involved.

Keywords: *railway, signalling systems, maintenance, dependability, RAMS, data driven, corrective maintenance, failure, configuration management, knowledge management*

LIST OF APPENDED PAPERS

Paper I Morant, A., Larsson-Kråik, P.-O. and Kumar, U., (2013), "Data driven model for maintenance decision support - A case study of railway signalling systems". Submitted for publication.

Paper II Morant, A., Karim, R. and Larsson-Kråik, P.-O., (2013), "Information logistics for maintenance of railway signalling systems: A case study". Accepted for publication in *International Journal of Railway Technology*.

Paper III Morant, A., Karim, R., Tretten, P. and Larsson-Kråik, P.-O. (2013), "Dependability improvement through configuration management – A study of railway signalling systems", International Journal of COMADEM, vol. 16, no. 4, pp. 31-40.

Paper VI Morant, A., Westerberg M and Larsson-Kråik P.-O., (2013), "Knowledge management in a railway network: The case of signalling systems", accepted for The Second International Conference on Railway Technology: Research, Development and Maintenance, France, 8-11 April 2014.

ACRONYMS AND SYMBOLS

A	Availability
A_o	Operational Availability
ATC	Automatic Train Control
CBM	Condition Based Maintenance
CM	Configuration Management
CMM	Capability Maturity Model
CMMI	Capability Maturity Model Integrated
COI	Continuously Operating Item
EB	Emergency Brake
ERTMS	European Railway Train Management System
F(t)	Failure probability
FAR	False Alarm Rate
FMECA	Failure Mode Effect and Criticality Analysis
FTA	Fault Tree Analysis
GSM-R	Global System for Mobile Communications – Railway; GSM-Railway
H(t)	Hazard Rate
IXL	Interlocking
LCC	Life Cycle Cost
LEU	Lineside Electronic Unit
LRU	Line Replaceable Unit
MTBF	Mean Operative Time Between Failures
MDT	Mean Down Time
MTBSF	Mean Time Between Safety System Failure
MTTM	Mean Time To Maintain
MTTR	Mean Time To Restore
MUT	Mean Up Time
NFF	No Fault Found
R(t)	Reliability (success probability)
RAMS	Reliability, Availability, Maintainability and Safety
RBC	Radio Block Centre
RBD	Reliability Block Diagram
RQ	Research Question
RRT	Relative Restoration Time
RT	Restoration time
SPICE	Software Process Improvement
THR	Tolerable Hazard Rate
TBF	Time between failures
TQM	Total Quality Management
TMS	Train Management System
TTM	Time To Maintain
TTR	Time To Restore
TTRS	Time To Return to Safety
UT	Up time

WO	Work Order
WT	Waiting time
λ	Failure rate
μ	Restoration Rate
μ_o	Operational restoration rate

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1. INTRODUCTION

The railway network is a complex and distributed system with several technologies working together to fulfil the demands on capacity, speed and mobility to transport goods and passengers. The railway system can be divided into different systems depending on functionality, such as the rolling stock, the track, the power supply, the signalling system, etc. (Pěnička, 2007). Railway infrastructure managers need maintenance analysis and planning tools that enable them to systematically analyse and optimise budget needs, minimise the total costs for the required reliability, availability, maintainability and safety (RAMS) level, and guarantee the quality of the railway assets in the long run (Zoeteman, 2001). Systematic maintenance management of the railway assets is required to deal with short-term costs and performance demands and to guarantee RAMS in the long term (Wilson, 1999).

The managers responsible for determining maintenance actions face an abundance of data and have a complicated task transforming these data into information that will support maintenance actions (Berggren, 2010). During the operation and maintenance of the railway infrastructure, lots of data are collected and managed. The purpose is to control and analyse the current state of the system. The data include the system architecture, maintenance reports, work orders performed, etc. If up-to-date documentation is lacking, maintainers have serious problems (De Souza et al., 2005). In addition, confusing data/remarks in the databases often lead to misinterpretations. Structured databases containing the complete information are required to identify where failures are located and the dominant factors causing them, (Kumar et al, 2008). Without properly functioning maintenance, the railway infrastructure would soon become efficient.

Signalling systems are complex combinations of software and hardware; they play an important role in the control, supervision and protection of rail traffic, and their availability affects the performance of the whole system. Further complicating the issue is the fact that signalling systems are composed of several different systems; each has its own purpose, but the main functionality of the overall system is determined by the interoperability between them.

Railway managers need to have a holistic view of the various railway systems (especially signalling systems which must be interoperable) to optimise maintenance. When performing the maintenance of a system which is a combination of software and hardware, as for example, a signalling system, the maintainer must understand how changes will affect the system, how the system is built, what role the different parts play and how they are interconnected.

The development of signalling is closely linked to the development of railways. It began as a manual system determining access to a line, but the growing demand for transportation and the increasing number of trains made this system inadequate. Advanced technologies were implemented to supervise and control railway lines. These were mainly analogue systems, based on relay technology (e.g. track circuit, axle counter, relay interlocking). Today these systems are being replaced by digital control systems based on electronics (e.g. balise, electronic interlockings, lineside electronic unit – LEU), but both systems coexist in most of the railway network. Over the years, many signalling and train control systems have evolved, creating a highly technical and complex industry. Every country has developed different solutions over the years. The operation of trains must not be country-dependent, however, and the creation of a unified signalling system would prevent the need to make changes between countries. In order to achieve interoperability between the control and supervision systems, several contributions via standardisation have been made (UNISIG SUBSET 026, 2011; EIRENE SRS, 2006). Standards have been developed for the RAMS of the different railway systems (EN 50126, 1999), with special focus on the systems for signalling, communications and processing systems on the railway (EN 50128, 2001; EN 50129, 2003). These standards aim to enable interoperability while ensuring safety.

There are a number of items within the larger category of signalling systems (Theeg and Vlasenko, 2009). For example, track circuits, axle counters and GPS-based systems can be used to locate a train. Track circuits and signals can help to control the traffic on the railway line to prevent collisions. Balises and radio based systems allow the train control centre to restrict the movement of trains, and advanced systems i.e. European Rail Traffic Management System (ERTMS) or Automatic train control system (ATC), supervise and control the railway network. They interpret the inputs from the other systems, creating restrictions on the train route to ensure safe operation. An example of the parts of a signalling system and their relationship is shown in Figure 1.

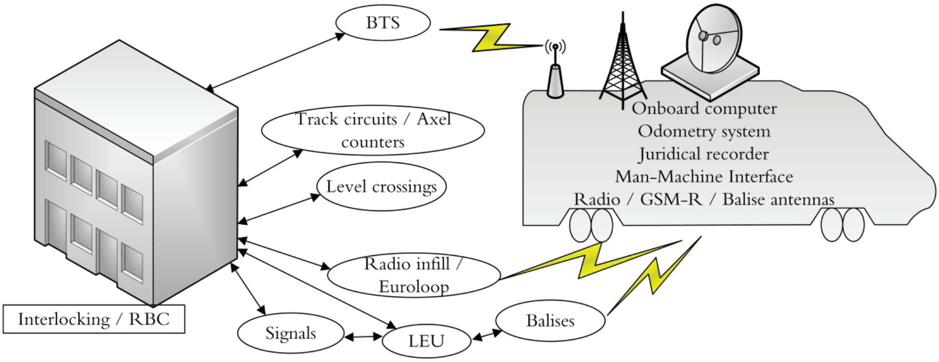

Figure 1: Different signalling systems and their interfaces.

The various systems, such as track circuits or level crossings, provide input to interlocking systems and radio block centre systems (RBC). Interlocking systems receive information, process it and make new restrictions on system components. For example, they can provide information to onboard signalling systems through the GSM-R system, by means of the base transceiver stations (BTS) located along the railway network. The onboard signalling system is composed of a centralised computer that processes the different inputs, giving supervision during the train's operation. An odometry system constantly measures the speed and acceleration of the train. The balise antenna reads the information from the balises placed on the track. The man-machine interface allows the driver to interact with the onboard computer. The juridical recorder records the information generated during the operation (e.g. driver operations, balises and odometry information, etc.). Other systems, such as the GSM-R or the radio infill, exchange information between the wayside signalling system and the onboard signalling system. Some auxiliary systems, such as the Lineside electronic unit (LEU) whose purpose is to exchange information between wayside systems, do not depend on the interlocking system to process information.

Railway signalling systems are composed of several different systems that have their own purpose but the main functionality is given by the interoperability between them: the supervision and protection of the railway network will not be possible if any of the items of the signalling system do not work properly or there is a lack of interoperability between them. Signalling systems are challenging to model, given the amount of information derived from both software and hardware in the various locations of the systems' many devices (Morant et al., 2012).

Previous studies have shown the importance of signalling systems on the dependability of the railway network (Patra, 2009; Granström, 2012; Stenström et al, 2013). Signalling systems supervise and control the railway operation with different technologies installed both in the infrastructure along the track and in the rolling stock. To operate on a specific railway corridor, the signalling systems of train and infrastructure must be interoperable. In Sweden, state companies such Transitio or Rikstrafiken (via ASJ) provide the operators with the necessary rolling stock to solve this problem (Alexandersson and Hultén, 2008). On the maintenance area, the train records can help to identify a failure since they contain the information received from the infrastructure.

Improvements in maintenance support performance can be achieved by considering the item structure and/or the organisation providing maintenance (IEC 60300, 2004). However, a complete information logistics system does not ensure that the required knowledge will be acquired by the proper personnel, or that the know-how will be stored and transferred.

Sweden's railway network is deregulated. The presence of many different stakeholders running maintenance and operation of the railway network needs a good knowledge transfer between them. Each stakeholder has different knowledge and needs, but they all work on the same railway system. When maintenance activities are outsourced, there is a risk of losing the knowledge required to perform these activities (Campbell, 1995, Espling, 2007). It can be difficult to find a company with the required knowledge, or to study the effects on maintenance of a change in the infrastructure design. The knowledge transfer of best practices between different stakeholders can provide benefits to all of them. Better efficiency of maintenance activities can be achieved by taking advantage of the available maintenance knowledge, thus contributing to time and costs savings (Mansor et al, 2012).

Various solutions have been proposed to improve the performance of a system by analysing maintenance data. To create a holistic picture of where failures are located and the dominant factors causing them, structured databases containing the complete information are required (Kumar et al, 2008). Failure analysis of a system will give information about how this system affects the operation and maintenance of the entire railway network and identify possible areas of improvement. Zhou et al. (2009) proposed a fault knowledge management method to improve maintenance support performance. Galar et al. (2012) proposed data fusion for maintenance decision through data integration. Pecht and Ramappan (1992) performed a failure analysis using failure records, stating that the primary objective of failure analysis is to provide feedback on the design to improve the performance of the component. Other methodologies (e.g. failure mode effect and criticality analysis (FMECA), fault tree analysis (FTA)) have been implemented to perform failure analysis on signalling systems (Vuille et al., 2004).

With the complexity of the railway signalling systems, there is a need to find ways to optimise their maintenance and operation while ensuring safety. Improving the dependability of railway signalling systems will have benefits for the whole railway. Some research has sought to improve maintenance of railway signalling systems: e.g. Availability analysis (Patra, 2009, Iwata, et al, 2009, Dersin et al, 2008); Reliability analysis (Flammini et al, 2006, Panja and Ray, 2007, MacChi et al, 2012); RAM performance (Vuille et al, 2004, Stamenkovic, 2009); Life cycle cost (Dersin et al, 2008, Beck et al, 2008); Risk evaluation (Iwata, et al, 2010); Electromagnitic compatibility (EMC) (Niska, 2008, Morant et al, 2012a); Dependability optimisation (Vernez and Vuille, 2009); Condition-based maintenance (Fararooy and Allan, 1995); etc.

With the complexity of the railway signalling systems, there is a need to find ways to optimize their maintenance and operation. To improve railway signalling systems dependability will have benefits for the whole railway.

1.1. Problem definition

Since signalling systems ensure the safe operation of the railway network, their reliability and maintainability directly affects the capacity and availability of the railway network, in terms of both infrastructure and trains. The functionality of the signalling system is based on the principle of “fail safe”; this implies that the railway section where a failure occurs will be not fully operative until the failure is repaired (since safety cannot be ensured). Ensuring the dependability of these systems during operation and maintenance will increase the efficiency of the railway operation.

Something that differentiates signalling systems from the other systems that compose the railway is their distributed location: part of the signalling system is located along the infrastructure and part on the rolling stock. All systems should be interoperable (different signalling systems are not compatible between them), and if one system is modified or updated, it will affect the rest.

Signalling systems are installed as a whole system. Therefore, their efficiency and costs should be studied together to determine performance and to suggest improvements and design updates. Maintaining them requires multidisciplinary skills, including mechanical, electrical, electronic and software skills. Hence, improved efficiency in maintenance can be achieved by taking a number of different perspectives.

Maintenance management of signalling systems is challenging, given the amount of information needed to perform good preventive and corrective maintenance. The lack of proper data can lead to incorrect failure identification, which, in turn, means more time spent on corrective maintenance and lower system availability.

Due to the deregulated environment of the Swedish railway system, it is necessary to study the knowledge management processes of the different stakeholders and to optimise performance and maximise benefits by sharing best practices. The information needs to be managed and adapted to suit various processes (e.g. design, manufacturing, operation, and maintenance processes). The complexity of the signalling systems makes the information and knowledge management a need in order to ensure a proper performance in all phases of the life cycle.

A great deal of work has been done on signalling systems, but there is still no holistic approach to improving the maintenance and operation of signalling systems by enhancing their dependability.

1.2. Purpose and objectives

The purpose of this research is to explore the areas that could improve the performance of railway signalling systems during the operation life cycle phase, by enhancing their dependability.

The main objective of this research is to study the dependability performance for signalling systems, which can be divided on the following sub-objectives:

- Identify the critical factors affecting the dependability of signalling systems.
- Identify possible improvements from the RAMS and processes points of view.
- Propose models to improve the dependability of railway signalling systems during maintenance.

1.3. Research questions

The following research questions (RQ) have been formulated:

RQ1. What are the issues and challenges of the existing railway signalling systems from a dependability and maintenance point of view?

RQ2. How can maintenance data and information help to improve the dependability of railway signalling systems?

RQ3. How can the management of information and knowledge of railway signalling systems be improved?

1.4. Scope and limitations

The scope of this research is to perform an exploratory analysis which will provide visibility to the best areas to consider to improve the dependability and maintenance of railway signalling systems. The case study of the Swedish railway signalling system is chosen as a good representation of the railway signalling systems. The proposed models are validated using sub-cases of a specific railway corridor during a determined period of time.

Some limitations related to the research must be acknowledged:

- The research focuses on the Swedish railway signalling systems specified in the architecture document of Trafikverket (2012a) and the data analysis is limited to a particular range of time on a specific railway corridor.
- The research focuses on studying the corrective maintenance performance, leaving preventive maintenance for further research.
- This research is based on the corrective maintenance recorded in the database; therefore, it does not take into account corrective maintenance that could be done and not recorded, e.g. during inspections.
- This research is based on maintenance data, documents, interviews and surveys. Since the maintenance work orders are manually recorded, human factors can affect the quality and reliability of the data.

Further work is oriented to minimise these limitations.

1.5. Structure of the thesis

The thesis consists of seven chapters and four appended papers:

Chapter 1, *Introduction*, introduces the area of research, the problem definition, the aim and goal of the thesis, the research questions, and the scope and limitations of the research.

Chapter 2, *Theoretical framework*, provides the framework used in the research.

Chapter 3, *Swedish railway system*, describes the Swedish railway system used as the basis for this research, particularly the signalling system.

Chapter 4, *Research methodology*, describes how the research was performed and gives the reasons.

Chapter 5, *Extended summary of appended papers*, summarises the appended papers.

Chapter 6, *Results and discussion,* summarises the results of the research as described in the appended papers.

Chapter 7, *Conclusions*, summarises the conclusions extracted from the results and links them to the defined RQs, synthesises the contribution of the thesis and suggests further work.

The four appended papers address the RQs (see Table 1). Table 1 shows the relationship between the research questions and the appended papers. RQ1 is answered in Papers I and II, RQ2 is discussed in Paper II, and RQ3 is addressed in Papers III and IV.

Table 1: Relationship between research questions and papers

	Paper I	Paper II	Paper III	Paper IV
RQ1	X	X		X
RQ2	X	X		
RQ3		X	X	X

Paper I describes the framework of signalling system and explores the challenges during the maintenance and operation. It proposes a data driven model for maintenance decision support based on the integration of the various parameters of the corrective maintenance actions. It validates the model using a case study, giving an overview of the failure phenomena.

Paper II explores the use of information logistics for railway signalling systems to improve the efficiency of their corrective maintenance. It discusses the information logistics used by the current Swedish infrastructure manager for railway signalling systems, identifies weaknesses and suggests improvements. It discusses the information logistics used by the current Swedish infrastructure manager for railway signalling systems, identifies weaknesses and suggests improvements.

Paper III proposes a model for CM, improving the efficiency of the information logistics by dealing with the areas of improvement found in Paper II.

Paper IV discusses the current situation of the knowledge management between the different stakeholders and suggests ways to improve the inter-organisational knowledge management and improve the knowledge transfer.

2. THEORETICAL FRAMEWORK

Standards have been developed for the RAMS of railway systems (EN 50126), with special focus on the signalling, communications and processing systems used by the railway (EN 50126, EN 50128, EN 50129). These standards aim to enable interoperability of the line without affecting the safety of the system. The railway standard CENELEC EN 50126 is the specification and demonstration of reliability, availability maintainability and safety in the railway applications. This standard defines RAMS in terms of reliability, availability, maintainability and safety; it stresses their interaction and defines a process, based on the system lifecycle and tasks within it, for managing RAMS.

2.1. Maintenance and dependability

The system lifecycle is a sequence of phases, each containing tasks, covering the life of a system from initial concept through to decommissioning and disposal. It provides a structure for planning, managing, controlling and monitoring all aspects of a system, including RAMS, as the system progresses through the life phases, so that the right product is delivered at the right price within the agreed time frame (EN 50126, 1999). Figure 2 shows a “V” representation of the lifecycle: the top-down branch (left side) is generally called development and is a refining process ending with the manufacturing of system components; the bottom-up branch (right side) is related to the assembly, the installation, the receipt and then the operation of the whole system (EN 50126, 1999). The research of this thesis is based on the lifecycle phase of maintenance and operation.

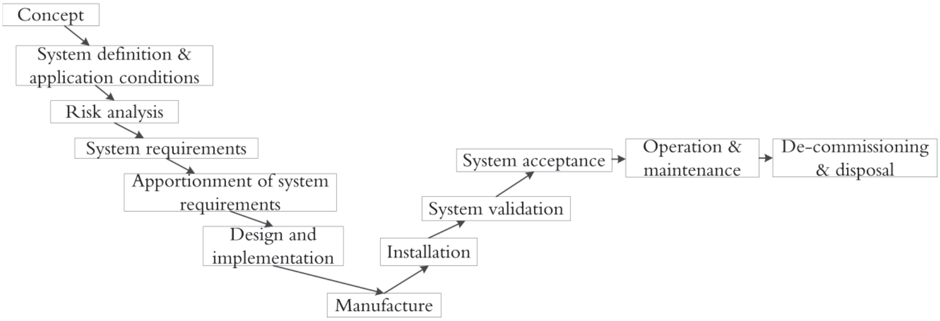

Figure 2: V-representation of the lifecycle (EN 50126).

Maintenance is defined as the combination of all technical and administrative actions, including supervision actions, intended to retain a product in, or restore it to, a state in which it can perform a required function. (IEC 60050). The purpose of the maintenance process is to sustain the capability of a system to provide a required service in order to achieve the customer satisfaction (ISO/IEC 15288, 2008; Liyanage and Kumar, 2003; Söderholm et al, 2007).

Maintenance can be corrective or preventive. In corrective maintenance, the maintenance is carried out after fault recognition and is intended to put a product into a state in which it can perform a required function. In preventive maintenance, the maintenance is done at pre-determined intervals or according to prescribed criteria and it is intended to reduce the probability of failure or the degradation of the functioning of an item (IEC 60050). Preventive maintenance can also be classified as condition based maintenance or predetermined maintenance; corrective maintenance can be deferred or immediate, depending when the action is taken. A schema of the different approaches of maintenance is shown in Figure 3.

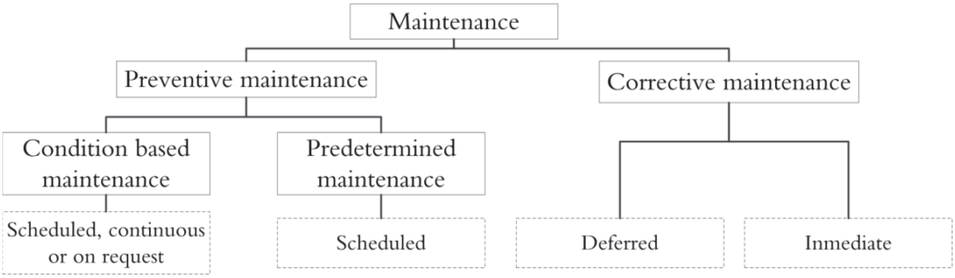

Figure 3: Maintenance approaches (EN 13306, 2010).

The dependability of a system refers to the availability performance of the system and the different factors that can influence on it, which are: reliability, maintainability and maintenance supportability (EN 13306, 2001), see Figure 4. Maintenance supportability (or maintenance support performance) is the ability of a maintenance organisation to have the right maintenance support at the necessary place to perform the required maintenance activity at a given instant of time or during a given interval (EN 13306, 2010).

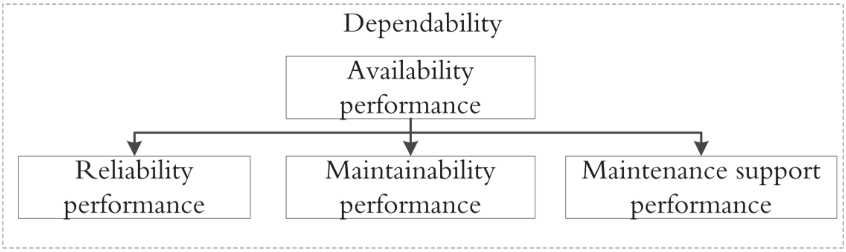

Figure 4: Elements of dependability (EN 13306, 2001).

To maintain dependable systems and optimise system performance, factors which could influence the RAMS of the system need to be identified, their effect assessed and the cause of these effects managed throughout the lifecycle of the system by the application of appropriate controls (EN 50126, 1999).

2.2. RAMS in Railway

The standard EN 50126 (1999) defines RAMS as:

- Reliability is the probability that an item can perform a required function under given conditions for a given time interval.
- Availability is the ability of a product to be in a state to perform a required function under given conditions at a given instant of time or over a given time interval assuming that the required external resources are provided.
- Maintainability is the probability that a given active maintenance action, for an item under given conditions of use, can be carried out within a stated time interval when the maintenance is performed under stated conditions and using stated procedures and resources.
- Safety is the freedom from an unacceptable risk of harm.

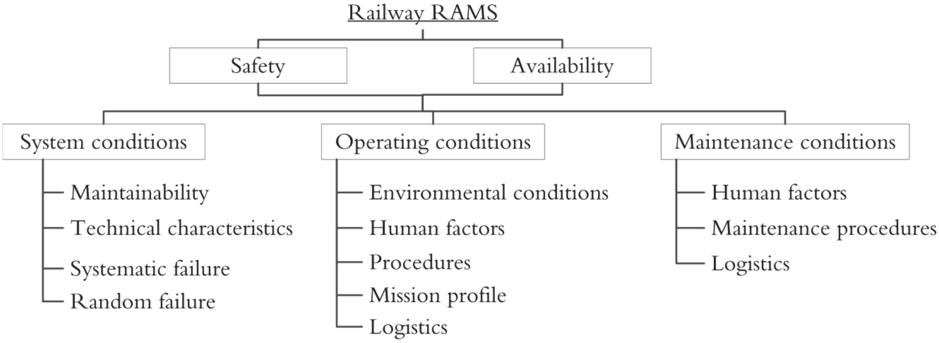

Figure 5: Factors influencing railway RAMS (adapted from EN 50129).

The RAMS of a railway system is influenced in three ways: by sources of failure introduced internally within the system at any phase of the system lifecycle (system conditions), by sources of failure imposed on the system during operation (operating conditions) and by sources of failure imposed on the system during maintenance activities (maintenance conditions) (EN 50126, 1999); see Figure 5. These sources of failure can interact. Improving the factors influencing the RAMS will improve the dependability.

RAMS during the operation and maintenance

Every phase of the lifecycle has a specific objective and input (usually the output of the previous phases). The standard EN 50126 (1999) defines the requirements to be accomplished in each phase, the deliverables to produce and the process verification. This section summarises the objectives and deliverables for the phases of operation and maintenance, performance and monitoring and modification and retrofit (the last two occur during the operation and maintenance phase of the lifecycle).

The objective of the phase of operation and maintenance is to operate (within specified limits), maintain and support the total combination of sub-systems, components and external risk reduction measures such that compliance with system RAMS requirements is maintained.

A record of all RAMS tasks undertaken within the phase should be maintained, along with any assumptions and justifications made during the phase. System documentation should be updated, as appropriate. The deliverables from this phase form a key input to subsequent lifecycle phases.

The objective of the performance monitoring phase is to maintain confidence in the RAMS performance of the system. A record of all performance monitoring tasks undertaken within the phase should be maintained, along with any assumptions and justifications made during the phase. System support documentation may be updated within this phase. The deliverables from this phase form a key input to subsequent lifecycle phases.

The objective of modification and retrofit phase is to control system modification and retrofit tasks to maintain system RAMS requirements. The key deliverable from this phase is a validated, modified system. The results of the phase should be documented, along with any assumptions and justifications made during the phase. The deliverables from this phase form a key input to subsequent lifecycle phases.

2.3. Models for maintenance optimization

Operational safety, maintenance cost effectiveness and asset availability have a direct impact on the competitiveness of organisations and nations. Today's complex and advanced machines demand highly sophisticated and costly maintenance strategies (Heng et al., 2009). Maintenance strategies have progressed from corrective maintenance after the breakdown of the asset to preventive maintenance, and to condition based maintenance (CBM). An extensive amount of research has been done towards maintenance optimization. The determination of optimal maintenance interval is critical for the preventive maintenance to work effectively (Heng et al., 2009). Several authors describe how to optimize the maintenance policies by RAMS methodologies (Blischke and Murthy, 2000, Sherwin and Bossche, 1993, Ebeling, 2010, Pecht, 2009).

Three key elements of effective CBM are data acquisition (i.e. the collection and storage of machine health information), data processing (i.e. the conditioning and feature extraction/selection of acquired data) and decision making (i.e. the recommendation of maintenance actions through diagnosis and/or prognosis) (Heng et al., 2009). Jardine et al. (2005) summarised and reviewed the recent research and developments in diagnostics and prognostics of mechanical systems implementing CBM with emphasis on models, algorithms and technologies for data processing and maintenance decision-making.

Table 2 summarizes the three main model categories used for maintenance optimization (adapted from Heng et al. (2009) and Bagul et al. (2008)). The models used on this thesis were chosen depending on the advantages and limitations of each type of model combined with the type of data gathered as input and the desirable output.

Table 2: Types of models used for maintenance optimization.

Theory based model	
	Statistical models Traditional approaches to reliability estimation are based on the distribution of event records of a population of identical units. These classical reliability approaches use historical time-to-failure data to estimate the population characteristics. Hence, they do not require condition monitoring. A limitation of these methods is that they only provide general overall estimates for the entire population of identical units and working on identical operational and environmental conditions.
	Physical models Most of the existing prognostics models can be divided into two main categories: physics-based models and data-based models. Physics-based models typically involve building technically comprehensive mathematical models to describe the physics of the system and failure modes. They also generally require less data than data-driven models. The limitations of these models are that the real-life physics is often too stochastic and complex to model, and they are specific to a single failure defect.
Data Driven model	
	Data-driven approaches attempt to derive models directly from routinely collected condition monitoring data instead of building models based on comprehensive system physics and human expertise. They are built based on historical records and produce prediction outputs directly in terms of condition monitoring data. The main advantages of these techniques are the simplicity of their calculations and that they do not require assumption or empirical estimation of physics parameters. However, they generally require a large amount of data to be accurate.

While theory based models can be implemented on collected data but also with stochastic simulated data, data driven models depend directly on collected data, hence the amount of data will influence directly on the validity of the results. However, a theory based model requires accepting several assumptions to be able to model the desired phenomena, which is challenging when dealing with empirical data. Hybrid models try to combine both theories based and data driven models to be able to take into account the physics of failure and the operational conditions.

2.4. Information logistics

In order to acquire accurate results of maintenance performance measurement, accurate information becomes an important factor, hence knowledge management is a must on maintenance (Mansor et al, 2012). Luxhøj et al. (1997) reviewed the relationship between maintenance improvement and organisational learning, stating that a company's knowledge base for maintenance is typically not well organised, structured, or current. Organisational learning can be defined as changes in organisational practices (including routines and procedures, structures, technologies, systems, and so on) that are mediated through individual learning or problem-solving processes (Ellström, 2001).

Conducting effective and efficient maintenance requires accurate information and appropriate knowledge provisioning. Insufficient or inadequate maintenance support information leads to the "No Fault Found" (NFF) phenomenon (Söderholm, 2007). Hockley and Phillips (2012) explained the relationship between NFF and lack of training, sharing information and communication as organisational causes of NFF.

Excessive data can cause problems in decision making if the right information cannot be extracted (Karim, 2008). In addition, information islands hamper the integration of the information related to a system (Parida et al., 2004). Thus, prevention of data overload and integration of the maintenance-related information from the various sources can avoid these problems (Candell and Söderholm, 2006).

Mansor et al. (2012) proposed a knowledge repository or warehouse for maintenance activities consisting of four elements: best practice, databases, discussion forums and assessment tools. Information logistics processes can approach the explicit knowledge management dissemination; however, these systems are not enough to cover all tacit knowledge transfer, which depends partly on the expertise of the personnel. Lee and Van den Steen (2010) proposed a model to explore the managerial decisions of a company seeking to maximise the knowledge-based performance of its employees, describing the factors used to determine which information is worth recording and managing and who should have access to that information.

Configuration management

The standard EN 50126 defines the process of CM as the discipline that by applying technical and administrative direction and surveillance, identifies and documents the functional and physical characteristics of a configuration item, as well as the control of and change to those characteristics, records and reports change, processing and implementation status, and verifies compliance with specified requirements (EN 50126, 1999).

For complex, safety-critical systems, achieving consistency has important social and monetary benefits. Therefore, being able to assess or make visible the configuration status of a product during a project is crucial (Burgess et al, 2003). CM has established niche positions on safety critical areas such as aerospace, defence and nuclear power (Fowler, 1993, Ali and Kidd, 2013, Burgess et al, 2003, Burgess et al, 2005), and for one particular product type, namely software, CM has become a key support in the life cycle (Burgess et al, 2005, Fowler, 1993).

CM is necessary on safety related complex systems. These principles can be applied to signalling systems, as they ensure the safety of the railway operation. The railway standard EN 50126 defines and establishes the relationship between RAMS and

CM. To establish and implement an adequate and effective CM process, addressing RAMS tasks within all lifecycle phases is a mandatory requirement (EN 50126, 1999).

Problems areas caused by poor CM include inefficient data storage and retrieval, inadequate revision control and incompatibility between design and production (Dhillon, 1987). Kidd (2001) states that the configuration should not only be related to the product life cycle but to the whole life cycle, from the first steps of the product concept generation to the retirement of the product or even longer if it can assist in future projects.

CM has four key elements (Kidd, 2001): identification, change management, status accounting and audit/reviews. The main benefit of CM is that assures information integrity (Kidd, 2001), but other benefits can result from CM:

- CM reduces product development time (Ali and Kidd, 2013, Burgess et al, 2003).
- It reduces change cycle time and cost (Kidd, 2001).
- It enhances overall product quality (Ali and Kidd, 2013).
- It forces analysis of problem causes, not just their effects (Fowler, 1993).

However, research has shown that despite the importance and benefits of CM, companies seem to regard CM as a compliance issue (Kidd, 2001, Burgess et al, 2005). CM meets with barriers in such diverse areas as management support, governance, training, principles and policies, planning, authority to implement, stakeholders support, communication, and resource requirements (Ali and Kidd, 2013).

Nevertheless, CM´s impact is expanding through the increasing awareness that business and society depends on complex man-made systems whose design and operation have to be managed in the face of demanding environmental change (Burgess et al, 2005).

The CM process can be set up or improved with various approaches such as Software Process Improvement (SPICE), Capability Maturity Model Integrated (CMMI), Six Sigma, Total Quality Management (TQM), etc. Some are general methods to improve processes (Six Sigma), others focus on software management (SPICE), and still others establish a model but not the specific process (CMMI). The appropriate tool for the model is determined by the infrastructure manager depending on his/her needs and priorities.

Knowledge management

Knowledge is personalised information related to facts, judgments, ideas, observations, etc. (Alavi and Leidner, 2001; Blumenberg et al., 2009). Knowledge can be classified depending on its capacity to be transmitted and articulated. Explicit or codified knowledge is transmittable in formal, systematic language, while tacit knowledge is linked to the individual and is very difficult to articulate (Nonaka, 1994; Blumenberg et al., 2009, Dyer and Nobeoka, 2000). Tacit and explicit knowledge have different methods of dissemination (Dyer and Nobeoka, 2000; Blumenberg et al., 2009), which have to be addressed by knowledge management theories.

Blumenberg et al. (2009) showed that combined knowledge-transfer processes for tacit and explicit knowledge are more effective than when the process is focused only on one kind of knowledge (tacit or explicit). Their results also indicated that high levels of shared knowledge positively influence outsourcing performance (Blumenberg et al., 2009).

Lane and Lubatkin (1998) determined that the ability of a company to learn from another company depends on the similarity of their knowledge bases, organisational structures, compensation policies, and dominant logics.

Tsai (2001) applied the concepts of network position and absorptive capacity to determine the effectiveness on inter-organisational learning and knowledge transfer. Organisational units can produce more innovations and enjoy better performance if they occupy a central position in the inter-organisational network, but the result will depend on the company´s absorptive capacity to successfully replicate new knowledge (Tsai, 2001).

Dyer and Nobeoka (2000) argued that if a network has a strong identity and coordinating rules, an organisation can create and recombine knowledge because of the diversity of knowledge that resides within a network. They described Toyota´s inter-organisational knowledge network and showed how Toyota has solved the three dilemmas of sharing knowledge: motivating members to participate and openly share valuable knowledge (while preventing undesirable spill over to competitors), preventing free riders and reducing the costs associated with finding and accessing different types of valuable knowledge. In the model used by Toyota, explicit knowledge is disseminated by the supplier association, while tacit knowledge is transferred by the consulting / problem solving division, the voluntary learning teams and the employee transfers (Dyer and Nobeoka, 2000).

3. RESEARCH METHODOLOGY

Many definitions can be found for research. Research can be defined as a systematic process by which we know more about something than we did before engaging in the process (Merriam, 2009). The goals of research can be classified in three categories, which are exploratory when exploring a new topic, explanatory when explaining the reasons to something occur anddescriptive when describing a phenomenon (Neuman, 2003). The differences between these categories are shown on Table 3.

Table 3: Goals of research (Neuman, 2003)

Exploratory	Descriptive	Explanatory
Become familiar with the basic facts, setting and concerns.	Provide a detailed, highly accurate picture.	Test a theory´s prediction or principles.
Create a general mental picture of conditions.	Locate new data that contradict past data.	Elaborate and enrich a theory´s explanation.
Formulate and focus questions for future research.	Create a set of categories or classify types.	Extend a theory to new issues or topics.
Generate new ideas, conjectures or hypotheses.	Clarify a sequence of steps or stages.	Support or refuse an explanation or prediction.
Determine the feasibility of conducting research.	Document a casual process or mechanism.	Link issues or topics with a general principle.
Develop techniques for measuring and locating future data.	Report on the background or context of a situation	Determine which of several explanations is best.

Two approaches can be used for research: quantitative and qualitative. Both have strengths and limitations (see Table 4). Both styles can be combined when researching (Neuman, 2003).

Table 4: Qualitative style versus quantitative style (Neuman, 2003)

Quantitative style	Qualitative style
Measure objective facts	Construct social reality cultural meaning
Focus on variables	Focus on interactive processes, events
Reliability is key	Authenticity is key
Value free	Values are present and explicit
Independent of context	Situationally constrained
Many cases, subjects	Few cases, subjects
Statistical analysis	Thematic analysis
Researcher is detached	Researcher is involved

3.1. Research strategy

The overall aim of this thesis “How railway signalling systems affect the operation and maintenance of the railway network?” is of an exploratory nature. An exploratory orientation gives fundamental knowledge and understanding of an area of interest and provides input which allows the narrowing down of future research (Yin, 2009). Accordingly, the results and conclusions of this licentiate thesis will be used as the basis for further research. A schema of the research methodology is shown in Figure 6.

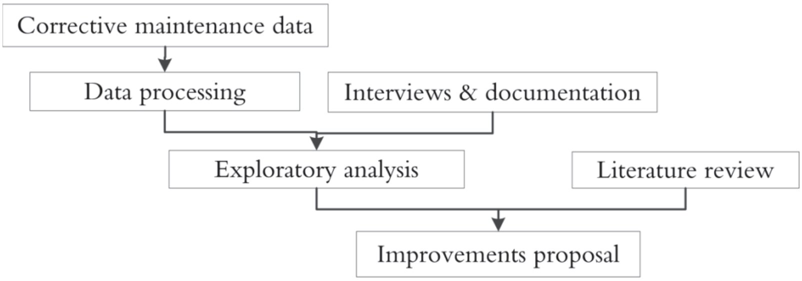

Figure 6: Research methodology

Depending on the purpose of the research, the research approach can be experimental, survey, archival analysis, historical or case study (Yin, 2009). A case study is an in-depth description and analysis of a bounded system (Merriam, 2009). Yin (2009) defines a case study as an empirical inquiry that investigates a contemporary phenomenon within its real-life context, especially when the boundaries between the phenomenon and the context are not clearly evident.

The case study of the Swedish railway signalling system is chosen as a good representation of the railway signalling systems. The proposed models are validated using sub-cases of a specific railway corridor during a determined period of time. The data for this research have been derived from the corrective maintenance WO database, documents and unstructured interviews.

When studying maintenance records, it is necessary to establish boundaries on the research due to limitations of time. Hence, the corrective maintenance data used in this study is from a specific location during a limited amount of time. This research methodology is in line with the case study approach.

It may be difficult to generalise the results obtained from a case study, and this represents a limitation of this research approach (Yin, 2009, Eisenhart, 1989). The reliability and validity of the research entails the reproducibility of results obtained under identical or very similar conditions. In addition, an idea about reality should fit with actual reality (Neuman, 2003). The use of multiple sources of information such as data from different databases, unstructured interviews, documents and reports from the industry, research previously published and standards help to triangulate the evidences used on the research. The different input data together with the use of well-established analysis techniques contribute positively to the reliability of the research. The validation of the proposed models with different sub-case studies contributes to the validity of the models.

3.2. Data collection and analysis

The R software was used for the data processing and posterior analysis (Teetor, 2011), together with Excel and Minitab. We distinguished between work orders for signalling systems and other systems. We identified work orders (WOs) on the same system and location, as well as "no failure found" work orders.

Corrective maintenance WOs were gathered and processed from the corrective maintenance database 0felia from the Swedish infrastructure manager. The data comprise work orders from January 2003 until November 2012 for a railway corridor 203km long in the northern part of Sweden. This is a fully operative railway line; the signalling system ATC supervises and controls the network. The line has been operative with no major changes for many years; hence, we can assume that the work orders deal with maintenance and not design changes or failures. The data consist of 9030 WOs registered during that period, with 2455 of these associated to a signalling system.

From the information recorded in 0felia we consider the parameters that give more information about the failures. In order to identify them, an exploratory analysis was performed, looking at the quality of the data recorded for each parameter (amount of data and quality of information). This was necessary because not all the parameters are required to be filled in a WO in 0felia.

Some information can be extracted when studying the times spent on the different WOs. For example, from the database, the following times and dates for the corrective maintenance work orders: failure identification can be extracted: WO opened; start of the corrective action; end of the corrective action and closure of the WO.

We consider three possible states for the systems:

- Available state or Up time (UT): the system is fully operative.
- Not available – Waiting time (WT): the time between when a failure occurs until the corrective action is started. During the waiting time, the WO is opened, the failure is identified, the maintenance personnel is informed, the spare parts and tools needed are gathered and the personnel go where the failure is located.
- Not available – Restoration time (RT): corrective actions (repair or replacement) are performed and the WO is closed.

Signalling systems can be considered as repairable systems with non-zero time to restoration, and as continuously operating items (COI) (IEC 61703, 2001), since they supervise the railway at all times, not only when a train passes. Based on these assumptions, the following definitions appear in the standard EN60050 (1990):

- Time between failures (TBF): the time duration between two consecutive failures of a repaired item.
- Operating time between failures (equivalent to UT): total time duration of operating time between two consecutive restorations.

- Mean operating time between failures (MTBF): expectation of the operating time between failures.
- The Time To Maintain (TTM): the total downtime (DT) when the system is not available for operation.

It is important to mention the note related to the definitions of mean time between failures on the standard, where it states that the use of the abbreviation MTBF as the mean time between failures is now deprecated (EN60050, 1990). Figure 7 shows the correspondence between the different times. From this, the RAMS parameters can be estimated to study the dependability of the system; some of them are shown on Table 5. The RAMS of the signalling system will depend on the RAMS obtained for each system (e.g., interlockings, balises, track circuits, etc.), following the RBD configuration.

Table 5: RAMS parameters (adapted from EN 50126, 1999, IEC61703, 2001)

Reliability	
$\text{Mean Operative Time Between Failure (MTBF)} = \frac{\text{Total operative time}}{\text{Nr.of failures}}$	(1)
$\text{Failure rate } (\lambda) = \frac{1}{\text{MTBF}}$	(2)
Failure probability F(t)	
$\text{Reliability(success probability) } R(t) = \int_{t}^{\infty} f(s)ds$	
Availability (inherent, operational)	
Availability $(A) = \frac{\text{MUT}}{\text{MUT+MDT}}$	(3)
Mean Up Time (MUT), substitute as appropriate MTBF, MTBSF, etc.	
Mean Down Time (MDT), substitute as appropriate MTTM, MTTR, etc.	
Operational Availability $(A_o) = \frac{\text{MTBF}}{\text{MTBF+MTTR}}$	(4)
Maintainability	
Mean Time To Maintain (MTTM)	
Mean Time To Restore (MTTR)	
Restoration rate $(\mu) = \frac{1}{\text{MTTR}}$	(5)
Operational Restoration rate $(\mu_o) = \frac{1}{\text{MTTM}}$	(6)
$\text{MTTR} = \frac{\text{Total TTR}}{\text{Nr.of failures}}$	(7)
False Alarm rate (FAR)	
Safety	
Mean Time Between Safety System Failure (MTBSF)	
Hazard Rate H(t) and Tolerable Hazard Rate (THR)	
Time to Return to Safety (TTRS)	

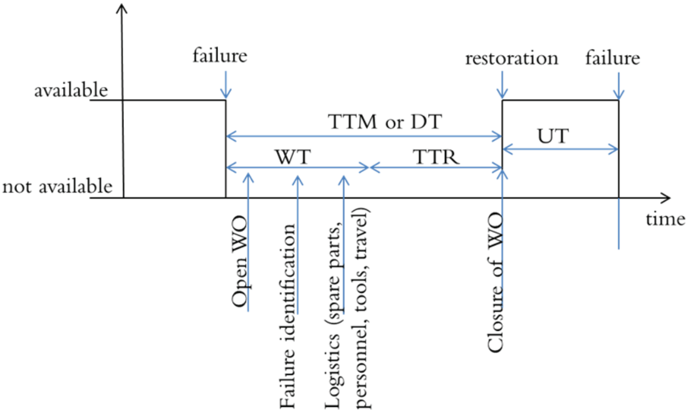

Figure 7: Correspondence between the different times.

To analyse the time data, we calculate the total time spent on the corrective action (TTM) given by Equation (10), the time to restore (TTR) given by Equation (11), and the relative restoration time (RRT) against the total time to maintain for each WO given by Equation (12), analysing the general characteristics of each and the relationship between them.

$$\mathrm{TTM} = \mathrm{t(finish\ of\ corrective\ action)} - \mathrm{t(failure\ identification)} \tag{10}$$

$$\mathrm{TTR} = \mathrm{t(finish\ of\ corrective\ action)} - \mathrm{t(start\ of\ corrective\ action)} \tag{11}$$

$$\mathrm{RRT}\,(\%) = \frac{\mathrm{TTR(sec)}}{\mathrm{TTM(sec)}} \tag{12}$$

Approximately 16% of the WOs have large times to restore and maintain (more than one day). This can be caused by a number of factors, e.g. the failure does not affect the normal operation of the railway network and can wait for other scheduled maintenance, the complexity of the restoration is high, it is difficult to identify the failure mode, etc. The procedures for corrective maintenance in Trafikverket say that a WO should be closed after 24 hours maximum (Trafikverket, 2011). Hence, the WOs which were open more than 24 hours were discarded when studying the RAMS, but not when looking on the total failures recorded and the relationships between the different information on the WOs.

3.3. Unstructured interviews

Interviewing is the best approach when we cannot observe behaviour, feelings or how people interpret the world around them (Merriam, 2009). The purpose for the interviews was to take into account the experience and opinions of the personnel involved in the maintenance of signalling systems when analysing the maintenance support performance for signalling systems, to complement of the data analysis and the literature review.

The interviews were exploratory and unstructured, which is useful when there is a need to find out the important topics to investigate, as well as what to exclude from the study (Merriam, 2009). The structure for interviews can vary from unstructured and informal to highly structured and standardised (Merriam, 2009). Highly structured interviews may not allow access to the participants´ perspectives and understanding (Merriam, 2009). Unstructured interviews are useful when little is known about the research topic and the researcher does not know enough to ask specific and relevant questions (Merriam, 2009). The personnel on these interviews were employees involved in some aspect of the maintenance and operation of railway signalling systems and with knowledge of the information logistics processes in Trafikverket. It was also possible to have short discussions with other stakeholders, such as a manufacturer and a consultancy. Other railway researchers were questioned about how to gather the information needed from Trafikverket.

Unstructured interviews have some limitations, such as the results are not measurable and are suitable only for exploratory purposes (Merriam, 2009). On the other hand, they help to identify the needs of improvement and can be the basis for a future survey to quantify the weight of each result.

3.4. Literature review

The literature review had two purposes. Trafikverket documentation and previous research related to the Swedish railway helped to visualize areas where an improvement could lead to better maintenance and operation of signalling systems. It was equally important to examine the current theories to find ways to improve the dependability of signalling systems. This included theories on failure analysis, information logistics, configuration management and knowledge management.

Sources for the document review were scientific publications databases, such as Scopus, Web of Science, Google Scholar, PRIMO and BVDOC. Various types of documents were reviewed, including conference and journal papers, books, PhD and Licentiate Theses, standards, technical specifications, manuals and technical reports. The subjects used for the searches included: railway signalling systems, maintenance signalling systems, configuration management, knowledge management, know-how, failure analysis, RAMS signalling systems. A summary of the results of these literature reviews appear in the "Theoretical framework" section, and applied in the "Results and discussion" section and in the "Further research" section. More information can be found in Paper 1 on failure analysis; Paper 2 on information logistics; Paper 3 on configuration management and Paper 4 on knowledge management.

Documents are a good source of data for numerous reasons, e.g. accessibility, and they contain information that would take a long time and effort to gather (Merriam, 2009). Data found in documents can be used in the same way as data from interviews or observations (Merriam, 2009). Another great advantage is that documentary data are "objective" sources of data compared to other forms, since the presence of the investigator does not alter what is being studied, unlike interviewing and observation (Merriam, 2009).

Some limitations, however, should be taken into account when using a literature review as a part of the research. Documents may be fragmentary, not fit the conceptual framework of the research, or their authenticity may be difficult to determine (Merriam, 2009). Hence, interviews and a literature review are used as a cross-check in this analysis of the signalling systems in the Swedish railway.

4. SWEDISH RAILWAY SYSTEM

The Swedish Transport Administration's total annual budget is SEK 51.9 billion, with its major investments primarily in the railway system (Trafikverket, 2012b). Traffic volume for passengers on the public railways amounted to 97 million train kilometres in 2012, while the traffic volume for railway goods transport on state-owned tracks totalled 42.9 million train kilometres, with rail transport volume reaching 21.0 billion tonne kilometres for 2012 (Trafikverket, 2012b).

The railway can be divided into different systems depending on functionality, such as the rolling stock, the track, the power supply, the signalling system, etc. (Pěnička, 2007). Signalling systems play an important role in the control, supervision and protection of rail traffic. This research focuses on how to improve the performance of railway signalling systems during the operation and maintenance phases of the life cycle.

4.1. Swedish railway signalling systems

The research is based on the architecture of the railway infrastructure implemented in Sweden (Trafikverket, 2012a). There are two main systems of control and supervision: ATC and ERTMS. The requirements and solutions will vary depending on which one is installed in a railway corridor. The signalling system is composed of the following systems:

- Traffic management system (TMS): creates an interface between the traffic operator and the railway network.
- Interlockings (IXL) / Radio Block Centre (RBC): receive the input from the different systems (e.g. track circuits, level crossings, signals, TMS), and calculate and return as an output the train operation restrictions to ensure safe traffic operation.
- Track circuits: are responsible for the train location.
- Balise group: give input from the track to the onboard signalling system (e.g. speed limits, driving mode, etc.).
- Level crossings: coordinate the road traffic crossing the railroad.
- Signals: give or restrict permission to the train on coming into a track section.
- Signalling boards: give the train fixed information (e.g. on tunnels, bridges, speed restriction areas, etc.).

The architecture of the whole railway infrastructure is managed by a software tool (BIS) which allows us to see which items compose a section of the railroad (signalling, power supply, track components, etc.) (Banverket, 2008). The specific location of each item is defined, together with its model and serial number.

Interoperability of railway signalling systems

The operation of a signalling system is based on the interoperability of its different systems. Controlling the railway requires combining the different systems´ roles, and these must be compatible. The need to assure the interoperability between the different parts to obtain the final result defines a system of systems (SoS) (Boardman and Sauser, 2006, Gorod et al, 2008). When managing SoS, it is not possible to consider the different parts independently; functionality depends on the relationship between them (Brownsword et al, 2006). Hence, this research focuses on the signalling system as a whole; since all of its systems depend on other systems to allow the operation on their specific track section. Figure 8 shows the Reliability Block Diagram for the minimum operative section from the point of view of signalling systems on the Swedish railway network.

Figure 8: RBD of a Swedish signalling system.

To ensure the safe operation, a track section is supervised by an interlockings located on the ends of that section, usually in a station. Signals are placed at the entrance of every section and sometimes in the middle to allow or restrict the passing of a train into that section. Signals restrict the passing of a train when a failure occurs on a track circuit or an interlocking, and warns it to circulate with caution when there is a failure in a level crossing. When a signal fails, the balise group associated with it will force the train to stop. If a balise does not work properly, it will produce an emergency brake (EB). If the TMS fails, the operation has an automatic mode that allows normal operation for a maximum of two hours. After that time, operation is not possible.

In case there is a stop caused by a failure on a track circuit, signal or a balise, the operation can be possible only if the dispatcher allows the driver to circulate with caution, with a maximum speed of 40 km/h to allow the driver ensure the safe circulation (e.g. there is no damage in the track, the switch is in the correct position, etc.). In other words, if they cannot perform the supervision and control, signalling systems can allow traffic operation by lowering the speed and depending on the driver’s visual supervision.

4.2. Railway stakeholders

Sweden’s railway network is a deregulated system. About 20 operators use the Swedish state’s rail infrastructure (Alexandersson and Hultén, 2008). The maintenance of the railway network (rolling stock and infrastructure) is managed by different companies. The Swedish transport administration (Trafkikverket) is responsible for investments in and maintenance of railway infrastructure; it also forms the long-term national transport policy (Alexandersson and Hultén, 2008).

A number of stakeholders can be present during the operation and maintenance of the railway infrastructure, depending on the policies of the country. Each stakeholder requires different information, depending on the work performed (e. g. operation management, corrective or preventive maintenance, RAMS studies, safety management, etc.). An example of these stakeholders is given in this section, based on the Swedish railway system:

- The infrastructure manager owns the public transport infrastructure and is responsible for its maintenance. It is also responsible for the transport planning infrastructure.
- Operators are responsible for train operation (passengers and freight).
- Maintenance companies are contracted to perform maintenance on the train or the infrastructure.
- Railway manufacturers design and produce the rolling stock, infrastructure, signalling systems, etc. depending on the requirements of the customer. They can be the Swedish infrastructure manager, operators, maintenance companies or other manufacturers.
- Consultancy companies give punctual support to the other stakeholders, e.g. performing punctual studies to suggest improvements in maintenance and operation performance.

Other stakeholders can be defined based on the work performed:

- Project manager is in charge of the development and implementation of a particular solution for the railway system.
- RAMS manager ensures the system fulfils the safety requirements to operate, analyses the RAMS parameters to measure the system performance and proposes improvements.
- Maintenance manager implements programs and procedures to ensure the optimal operation of the different railway systems.
- Maintenance personnel perform the corrective and preventive maintenance.
- Logistics manager organises the inventory and distribution of the railway assets.
- etc.

All these stakeholders play a part in the operation and maintenance performance of the railway signalling systems. Each one of them has different knowledge access and needs, but they all work on the railway systems.

4.3. Swedish railway databases

Trafikverket has a wide network of combined databases which gathers different information from the railway network, and to which the other stakeholders have access depending on their needs to perform the outsourced activity (e.g. maintenance, performance studies, design improvements, etc.). Table 6 lists the most important databases for signalling systems on the Swedish railway infrastructure. More information can be found in previous research (Patra, 2009; Holmgren, 2006).

Table 6: Trafikverket databases related to signalling systems

Database	Description
BIS	System architecture (Banverket, 2008; Trafikverket, 2012a)
BVDOC	Generic documentation
IDA	Project documentation (Banverket, 2004)
0felia	Corrective maintenance (Trafikverket, 2010, Trafikverket, 2011)
BESSY	Preventive maintenance inspections (Trafikverket, 2012c, Trafikverket, 2012d)
PATCY	ATC design performance
Duvan	Analysis of operation and maintenance performance

The architecture of the whole railway infrastructure is managed by a software tool (BIS) which allows us to see which items compose a section of the railroad (signalling, power supply, track components, etc.). The specific location of each item is defined, together with its model and serial number. The information in this database is the basis for a number of activities, such as infrastructure design, budgeting, operation and maintenance, traffic analysis and planning, reports, etc. The database allows to look for a specific item and to learn its historical data, or to look at a specific location and see what has been installed there and what inspections have been performed over time. A copy of the state of the architecture is saved periodically, and by comparing these, it is possible to trace changes through time. BIS exchanges information with several other railway databases; Figure 9 shows the relationships between them.

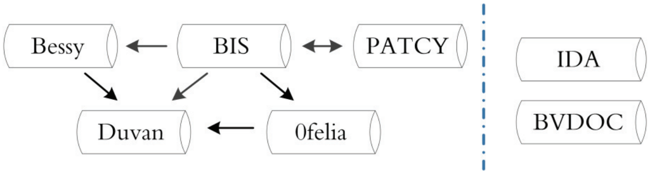

Figure 9: Data fusion architecture schema.

Corrective maintenance work orders related to the railway infrastructure in Sweden are managed in a software program called “0felia.” This software is based on the BMC Software Remedy User but adapted to the specific requirements of the management of the corrective maintenance for the railway infrastructure. 0felia has its own manual for data analysis (Trafikverket 2010). Each column of the records displays a different parameter giving information related to a failure and the corrective action performed (see Table 7).

The process of failure reporting is described in a document of the Swedish infrastructure manager (Trafikverket, 2011). The document lists the different steps and explains how to proceed from the time a failure is identified and reported until the corrective action is finished and the work order (WO) related to the failure is closed. Many partners are involved in the process, since the train operator can identify the failure, the railway infrastructure manager controls the activity performed on the railway network and a subcontracted company does the corrective maintenance. Since some parameters in 0felia are registered manually, processing the data is necessary to group information in an appropriate manner.

Table 7: 0felia corrective maintenance: parameter description

Report label	Label description
Failure report ID	Each WO record is assigned a code for identification.
Status	WO status associated to each report: open, in progress, closed.
Identification date	Date when the WO record was opened
Notification date	Date when personnel were notified of the WO
On the way dates	Date when personnel arrived at the failure location
Corrective action start date	Date when corrective action began
Found date	Date when the failure was identified
Corrective action end date	Date when the failure was corrected
Completed date	Date when the WO was closed
Response time	Response time between notification and start of corrective action
Corridor ID	Code of the railway corridor where the failure is located
Location from	Section of the track where the failure is located
Location until	
Symptom	Symptom that identifies a failure and opens the WO, usually observed by the driver. It is defined by the system asset that is affected.
Description	Description of the failure
Technology system failure	Technology related to the failure (power supply, signalling, track, etc.)
Field competence	Technology related to the WO (electrical, mechanical, telecommunications, etc.)
System Asset	System where corrective action is performed, following the architecture description of Trafikverket (Trafikverket, 2012a)
Location	Location where the corrective action is performed
Model type	Model identification of the asset (Part number)
Subsystem asset	Subsystem where corrective action is performed, following the architecture description of Trafikverket (Trafikverket, 2012a)
Component	Component where corrective action is performed
Device	Device where corrective action is performed
Failure mode (Real failure)	Real failure related to the corrective WO
Cause of failure	Reason for the failure
Action performed	Corrective action performed in order to close the WO.

The documentation is managed in two databases, depending on the type of the data. The documentation repository BVDOC stores and classifies generic regulations and manuals not assigned to any specific project. IDA is the name for the documentation and file database for the Swedish transport administration. It is an adaptation of ProjectWise from Bentley Systems. This tool gives support to the management while developing new projects and maintaining existing ones. It manages various types of information, from documentation to CAD files. Specific information from projects is stored on this database, such as the contracts, manuals, drawings, etc. The review and updating processes of information are described in the manuals for the software tool.

The maintenance and safety inspections in the infrastructure are registered in Bessy. The results and dates of these inspections are registered for each item inspected. Scheduled inspections are also indicated. The regulations governing the safety inspections required for each system and subsystem of the railway infrastructure are defined by the Swedish infrastructure manager; these can be found in the documentation database BVDOC.

Another database involved in the operation and maintenance of signalling systems is PATCY. The purpose of PATCY is to record and upload ATC projects to the architecture database BIS. Duvan is the platform for analysis of the operation and maintenance of the railway network based on the different information from the databases Bessy, 0felia and BIS. As the data are not updated immediately, there is a delay.

4.4. Inter-organisational knowledge management in the Swedish railway

Trafikverket uses performance-based contracts for the maintenance of the infrastructure. The condition of the track is assessed before a contract is set up, and changes on the condition of the assets are linked to bonuses and fees (Stenström, 2012, Espling 2007). All new contracts are performance-based with fixed payments for five years with an option of two more years (Stenström, 2012).

A bonus is used as an incentive and ensures gains for the contractor if he/she reaches the objectives or fulfils the demands, while penalties are incurred if the contractor does not reach them (Espling, 2007). The following conditions should be met:

- Failure reports should be reported back to the system.
- Inspection remarks should be reported back to the system.
- Contractor should be in time for repair, i.e. the time from when the contactor has been notified about a failure until he/she is in place to start the repair.
- Mean time to repair failures should not exceed prescribed time limits.
- Inspection remarks should follow prescribed time limits.
- Planned maintenance activities on the track should not be exceeded.
- Maintenance activities on the track should not cause train delays.

- All personnel working on the track should be informed about traffic and electrical safety demands.

Knowledge dissemination and distribution from Trafikverket to the other stakeholders is done by sharing access to the databases, but also other methods, such as emails, documentation, meetings and informal conversations. Knowledge is transferred from the stakeholders to Trafikverket by reports (i.e. delivering results) or person-to-person (email, phone, conversations, etc.). Knowledge is transferred between personnel working on the same project in different ways: emails, shared databases, documentation, meetings and informal conversation.

Two common thoughts were identified when interviewing experts from different stakeholders involved on the maintenance of railway signalling systems (maintenance contractors, Trafikverket and a consultancy). They all pointed out the risk of loss of knowledge and expertise due that more and more tasks are outsourced, and they all thought that Trafikverket should keep a deep knowledge of the system, to be able to manage the railway network in an efficient way.

Espling (2007) considered the maintenance strategy for a railway infrastructure in a regulated environment by implementing benchmarking techniques to compare different case studies from the Swedish railway network. Four risk areas were identified when outsourcing maintenance activities, which are the risk of losing control over maintenance costs, asset condition (asset measuring data to analyse the asset degradation), safety demands (concerning the contractor's employees' knowledge of track safety and asset knowledge) and core competence and asset knowledge (Espling, 2007). Maintenance costs and asset condition data are required to perform life cycle cost (LCC) analyses), hence it could be a lack of information when studying the effect of changes on the infrastructure during the maintenance phase of the life cycle.

Best practices in maintenance contracting include: goal-oriented maintenance contracts combined with incentives; scorecard perspectives, quality meetings and feedback to facilitate management by objectives; frequent meetings where top managers from the local areas participate; forms for cooperation and an open and clear dialogue; and the use of Root Cause analysis (Espling, 2007).

5. SUMMARY OF APPENDED PAPERS

PAPER I proposes a data driven decision support model which integrates the various parameters of corrective maintenance data and study maintenance performance by considering different RAMS parameters. This model is based on failure analysis of the historical events of the corrective maintenance actions. A case study was used to validate the model based on corrective maintenance data obtained for a specific railway line during a limited period of time. The model allows the creation of maintenance policies based on failure characteristics, as it integrates the information recorded in the various parameters of the corrective maintenance work orders. The model shows how the different failures affect the dependability of the system: critical failures indicate the reliability of the system, corrective maintenance actions give information about the maintainability of the components, and the relationship between corrective times measures the efficiency of corrective maintenance actions. All this information can be used to plan new strategies of preventive maintenance and failure diagnostics, reduce corrective maintenance, and improve maintenance performance.

PAPER II explores the use of information logistics for railway signalling systems to improve the efficiency of their corrective maintenance. It discusses the information logistics used by the current Swedish infrastructure manager for railway signalling systems, identifies weaknesses and suggests improvements. It finds that a great deal of information is gathered, but data suffer from a lack of visibility and the links between the different repositories are not well established. The lack of proper data can lead to incorrect failure identification, which, in turn, means more time spent on corrective maintenance and lower system availability. This leads to a dependency on the expertise of the personnel, an approach which is not beneficial in the long term. Two suggestions are offered to improve knowledge management and information logistics: the unification of databases with relevant information for signalling systems' stakeholders and, the implementation of a better CM process. Establishing an easier and simpler way to access the correct information in a timely fashion will result in improved knowledge management.

PAPER III investigates how the process of configuration management, can improve the dependability of the railway system. The lack of proper data can lead to an increase in failure identification time in corrective maintenance actions which, in turn, leads to lower availability of the system. Even when a failure is well identified, if its interoperability with the rest of the system is not assured during the restoration, the system will not be operable. Hence, a CM process is essential for the railway signalling system. The proposed CM model provides better control and visibility of information. Information and knowledge management can be improved by better accessibility to the information related to the system and any change performed on it. With better access to information, a faster and better diagnosis of failures can be performed, thus improving maintenance performance. This provides better availability of the system due to reduced downtime of the railway network. Hence, an improvement in maintainability is also achieved.

PAPER IV analyses the potential for improving inter-organisational knowledge management in the maintenance of railway signalling systems and make concrete suggestions for improvements. In this matter, this paper identifies areas of improvement on the railway signalling systems maintenance performance, and discusses how different theories of inter-organisational knowledge management can be applied to improve the maintenance and operation of the railway network, in particular signalling systems. The paper notes and discusses possible ways to improve the inter-organisational knowledge management. For example, frameworks such as that used by Toyota (Dyer and Nobeoka, 2000) or by Espling (2007) can be combined and improved. If stakeholders could share knowledge, they would have a holistic perspective of the maintenance and operation of the railway network and improve the effectiveness of their respective organisations.

6. RESULTS AND DISCUSSION

The analysis comprises the corrective maintenance data of the railway corridor Luleå – Gällivare during the last 10 years. In this chapter, the most relevant results obtained are summarised. The data analysis shows that 27% of the corrective maintenance records are related to signalling systems (see Figure 10 Left). Track maintenance actions, such as track breaks and track degradation, are costly, partly because corrective actions take more time; this makes their restoration a crucial aspect of maintenance infrastructure management. This results show that signalling systems play an important role in corrective maintenance, and improving their maintenance would bring about a general improvement in maintenance.

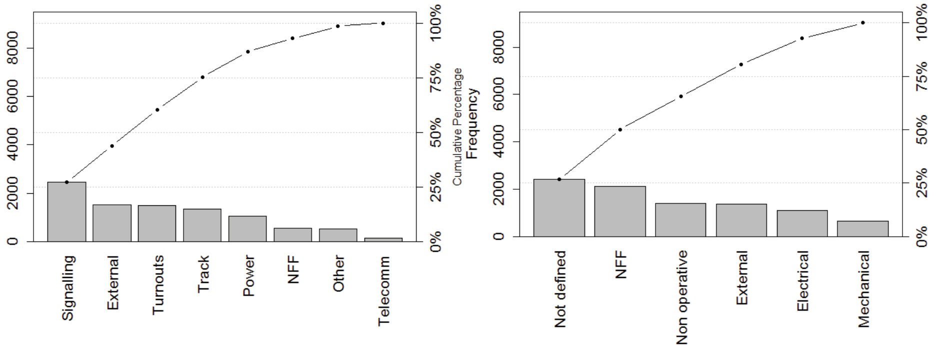

Figure 10: Left: Failure asset classification; Right: Failure mode associated to the WO.

Some conclusions can be drawn from the analysis of the failure identification (see Figure 10 Right); this analysis considers the number of work orders on the same railway line depending on the real failure recorded. The most outstanding result is that 23% of the work orders opened are NFF, and for another 27% it is not possible to define the failure.

When a WO is opened, it is identified by a symptom which indicates where the failure has occurred. Usually failures are identified by the train driver, but drivers cannot give an accurate estimation of the failure, since failures in different systems will have the same effect (e.g. a failure in the track circuit or a signal can be seen in the same way from the train perspective). Thus, the parameter Symptom is associated with many different systems and system failures. Figure 11 shows the relation between the parameter Symptom and the system group where it belongs, i.e., the system affected by the failure. As the figure shows, the parameter Symptom mostly identifies the system asset affected.

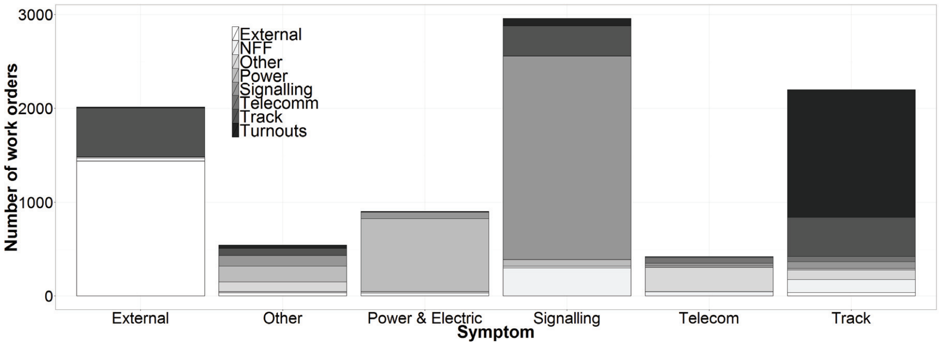

Figure 11: System where the failure occurs depending on Symptom

Grouping systems generically can maximise the usability of the parameter Symptom by giving information of the real failure, such as signalling systems (including track circuits, signals, interlockings, etc.), power and electrical (e.g. transformers, substations, etc.), telecommunications (e.g. radio, telephony, signal cable, etc.) and track (turnouts, rail, etc.). When the system is not defined, it is classified as "other", and when no fault is found, as "NFF".

6.1. Corrective maintenance data analysis of signalling systems

Paper I describes the results of the analysis of the corrective maintenance WOs, the most relevant results are summarised here. WOs were studied depending on the signalling system affected, the failure mode occurring, the cause to failure and the corrective action performed.

When looking at the failures on the different system assets, we found those most affected to be the interlockings, level crossings, track circuits and signals; these represent more than 80% of the failures (see Figure 12 Left).

Failure modes recorded are shown on Figure 12 Right. The most common modes are "not defined" (26%), "non operative" (24%) and NFF (21%). In the latter case, either there was no failure or a failure could not be identified (hence, the failure remains and it will fail again). Lacking the proper data can cause increased time for corrective maintenance actions, as incorrect failure identification decreases system availability.

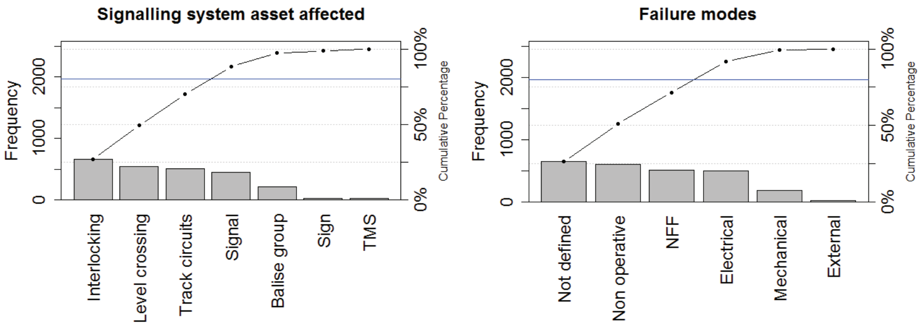

Figure 12: Left: signalling system asset affected; Right: failure modes;

The types of causes of failure related to signalling systems are shown on Figure 13 Left. The most recorded are "not defined" (29% of the WOs), mechanical causes (23%) and electrical causes (14%). Other causes of failure such as external causes, environmental causes and NFF are also relevant, as each represents 10% of the WOs recorded. Clearly, the causes of failure of the signalling systems are quite distributed, and the data should be studied in more depth to find possible trends.

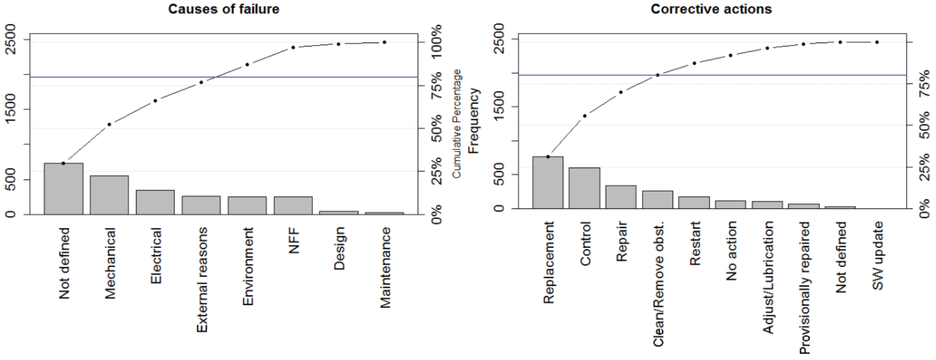

Figure 13: Left: failure causes; Right: corrective actions performed

The parameter of "corrective actions" shows which actions are performed to restart the failed system. The most common actions recorded for signalling systems (see Figure 13 Right) are "replacement" (31%), "control" (24%), "repair" (14%) and "clean or remove obstacles" (11%). Most of the architecture of signalling system is modular, allowing the replacement of the failed asset with a new one, reducing the time to restoration.

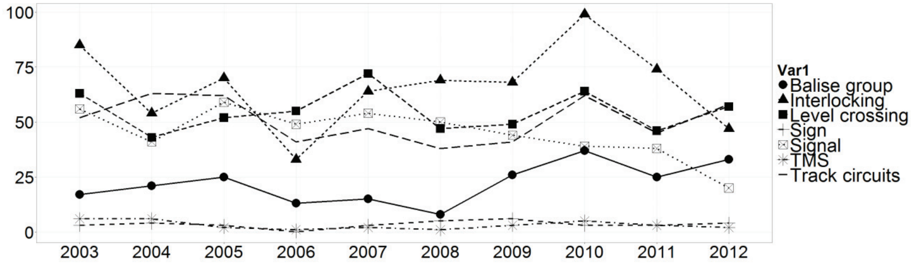

Figure 14: Failures of the signalling systems according to year and system asset

When looking at the failures by year, we see an improvement in 2007 when the related WOs for signals are reduced significantly (see Figure 14). At the same time, we observe an increase in the number of WOs for track circuits. These results lead us to focus our improvement measures on the dependability of the interlocking, level crossing and track circuit system assets, since they produce around 80% of the WOs related to corrective maintenance but also due to their criticality. This can be improved by enhancing the RAMS parameters: by increasing the reliability will be obtained a lower failure occurrence, a higher availability will reduce the downtime, to improve the maintainability will enhance the maintenance performance (e.g. reducing the human error), and ensuring the safety. An improvement in the performance of these systems will improve the performance of the signalling system and, hence, the overall performance of the railway network.

No fault found phenomena

When studying the real failure modes for the different WOs, it outstands the fact that an important part of the failure causes on record is “no failure found” or “could not identify the failure.” When the maintenance records are studied in more detail, it can be observed that approximately 24% of the WOs where no failure was found and 27% of the WOs where it was not possible to define if the failure were related to signalling systems. Figure 15 shows the relationship between symptoms and failure modes. Most of the WOs where no failure was found are related to WOs for a symptom found in the signalling system.

The number of WOs where the real failure is classified as “non operative” and “not defined” is also significant, possibly because signalling systems are composed of electronic items, and their failure can be random when the system nears the end of its life cycle. Other reasons should be taken into account as well, but from these data it can be deduced that better knowledge management of signalling systems would reduce the WOs and decrease the time spent on them to perform the corrective action.

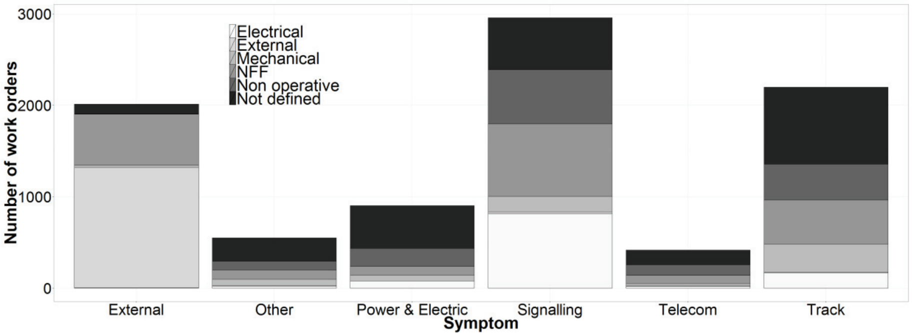

Figure 15: The system where the failure occurred related to the failure mode.

A practical example is given in Table 8. Four work orders are related to a failure reading an ATC code. The failed component was identified as the balise group. The first work order was open for four hours with two hours dedicated to corrective action. In this example, no corrective actions were performed since it was not possible to identify the failure. Looking at the data, we see that the failure appeared three more times during the following days. The third work order related to the same failure, and this time the failure was assigned to the component related to the ATC (part of the system of control and supervision on the interlocking system), but no failure was found. It was not until the fourth failure that corrective action was performed, and the component was replaced.

Table 8: Different work orders can be related to the same failure

WO parameters	**Example case**			
Failure report ID	FRXXX1	FRXXX2	FRXXX3	FRXXX4
Active restoration time	1 h. 50 min	15 min	1 h. 30 min	1 h.
Symptom	Failure code ATC	Failure code ATC	Failure code ATC	Failure code ATC
System	Balise group	Balise group	Interlocking / RBC	Interlocking / RBC
System asset	-	-	Control and supervision	Control and supervision
Component			ATC	ATC
Real failure	No failure	No failure	Not possible to define	Bad contact
Cause	No reason known	No reason known	No reason known	Material Fatigue / Aging
Action performed	Control	Control	Control	Unit replacement

NFFs require extra time in corrective maintenance because of the time taken to identify the failure, along with the repeated corrective actions to correct the same failure. To improve information logistics and knowledge management can help to reduce the identification time by an improved knowledge of the theory of failure on signalling systems, thus reducing the work orders and the time spent performing corrective actions related to them.

6.2. RAMS of signalling systems

The RAMS parameters can be defined in a variety of forms, depending on the focus of the research. One fundamental part of this Licentiate thesis is to define how to measure these parameters to establish the basis for further research. This research focuses on the view of signalling system as an SoS, as all systems depend on the others to allow the operation on the track section where they are located. Therefore, the following RAMS analysis will consider the various system assets (e.g. TMS, signals, interlockings, etc.) as systems on the SoS and their subsystems as the minimum level, since the corrective maintenance performed is the replacement or repair of these subsystems. Figure 16 shows a schema of the levels of the SoS.

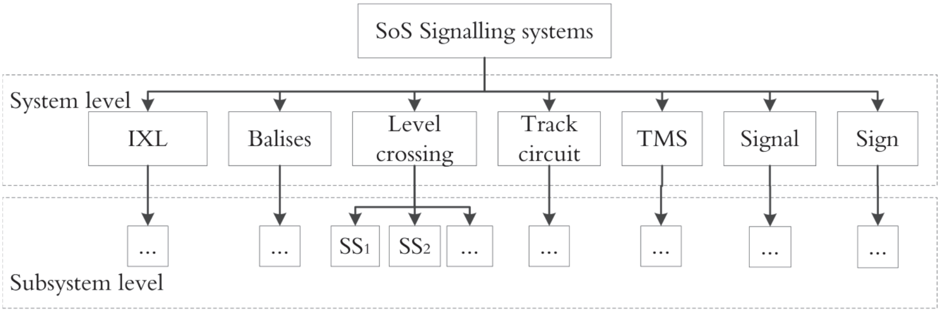

Figure 16: System levels of the SoS of a signalling system.

Considering a signalling system as a SoS allows us to compare the performance between different signalling systems (such as ERTMS and ATC). Hence, the RAMS of the system will be given by the ability to perform the main functionality of the whole signalling system (i.e., to protect and supervise the railway operation in a limited area). If one of the systems is not operative, this will not be possible; even if the operation is possible (the driver is, in that case, responsible for the supervision).

To perform these RAMS analyses, the unit of analysis must be defined. In order to include all the elements of the signalling system and based on the information in the corrective maintenance database, the minimum units for analysis are the track sections which divide up a railway corridor. A section includes one interlocking, a group of track circuits, signals and balises; it can also include one or various level crossings. A RAMS comparison of track sections from different railway corridors can help to identify the external factors and determine the performance of different signalling systems.

Figure 17 shows the RBD for the case study. The railway corridor consists of 50 track sections, composed of different systems; the railway corridor depends on a single TMS which controls the railway traffic of various corridors simultaneously.

The configuration used is given by the average of the number of systems for each track section.

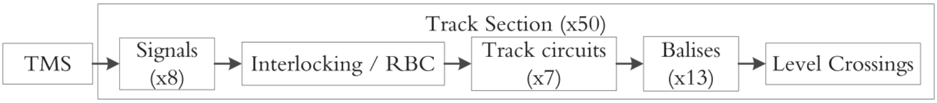

Figure 17: RBD for the case study of a signalling system.

Two approaches can be considered when studying the performance of a system. While the intrinsic RAMS only depends on the design of the asset and the time required to perform a corrective action with no external factors involved, the operational RAMS takes into account the maintenance performance and the external factors particular to the location (the environment, human factors, random failures, logistics, etc.). While for the intrinsic approach a model could be based on the theory of failure, by studying the different components and the theory of failure for each of them, for the operational approach a data-driven model would be a better choice, since the corrective maintenance records reflect the performance of the system with all the external factors involved in the operation and maintenance. Moreover, since signalling systems are a combination of mechanical, electronic and electrical components, the theory of failure becomes very complex to model. A data-driven model can reflect the failure phenomena with greater accuracy than models based on the theory of failure.

Some parameters have been calculated for the corridor Luleå-Gällivare considering the corrective maintenance data for the last 10 years (see Table 9). To model the performance of the different systems of a track section, we considered a standard track section from our case study with the configuration shown in Figure 17. We consider the failure occurrence as the average of the failure occurrences in the sections of the case study. The results show that interlockings and level crossings are the systems that most affect the availability of the track section with a MTBF of a less than a year and a high value of MTTM (more than five hours). Discussions with experts indicate that some of the WOs related to failures in the interlockings, track circuits and balise groups can be misidentified, since they all can have similar symptoms.

Table 9: MTBF, MTTR, MTTM and FAR for the case study.

	MTBF (years)	**MTTR (h)**	**MTTM (h)**	**FAR (%)**
Track circuit	7,00	1,66	3,17	40
Interlocking	0,88	2,07	5,54	18
Balise group	37,47	2,34	9,06	48
Level crossing	0,91	1,43	3,07	21
Signal	9,84	1,18	5,08	19
TMS	0,39	3,63	4,60	16

The values of FAR were obtained from the WOs where the failure mode is classified as NFF or "not defined" and the corrective action performed is recorded as “control” or “no action”. The FAR values can measure how the NFF phenomena affect the dependability of the system. Of the WOs recorded on an average track section, 16% are a false alarm, mostly related to NFF on balise groups (48%) and track circuits (40%).

The results indicate a high variance between different track sections of the same railway corridor, even if they have the same configuration design. Figure 18 shows the occurrences of failure for the different track sections; some have more than 100 and others have less than 10 during the 10 years of the data analysis. In particular, there is one track section with 257 failures.

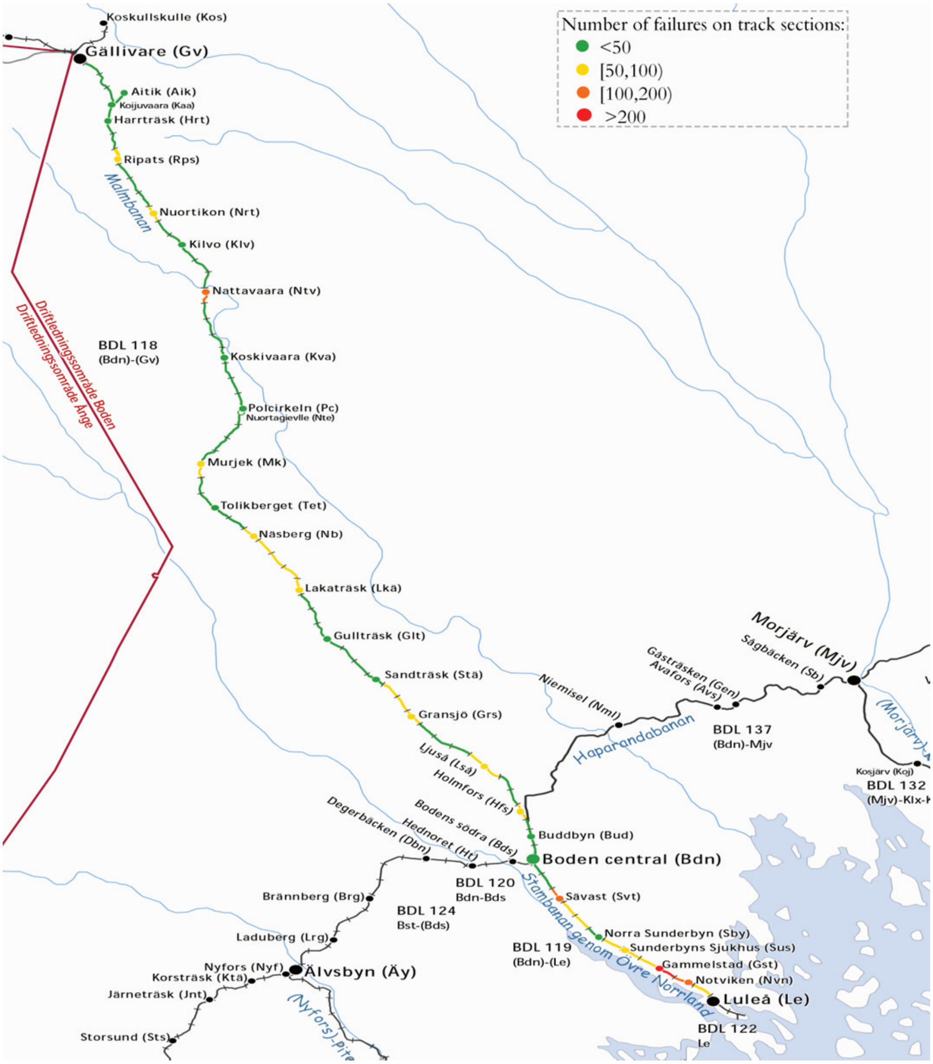

Figure 18: Failure frequency depending on track section

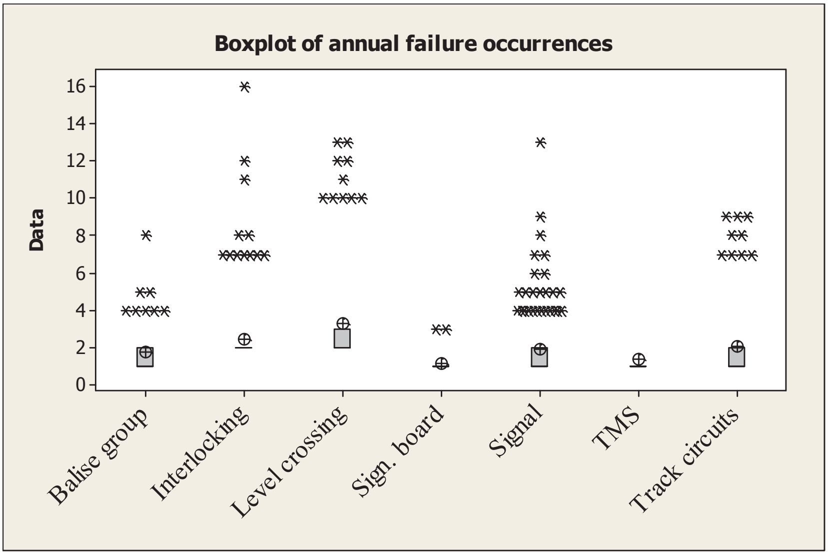

Figure 19: Boxplot of annual failure occurrences depending on the system affected

Figure 19 shows the annual failure occurrences for each track section of the Luleå – Gällivare corridor for each system, during the last 10 years, with a 95% of confidence interval. The graphic shows the boxplot for each system, showing also the outliers. It can be observed that while the mean values of annual failure occurrence vary between 1 and 4, there are years when some locations had more than 10 failures related to a system. The high number of outliers corroborates the results that indicate the importance of external factors on the reliability of the signalling system. Further work can be oriented to measure the effects of the external factors on the dependability of signalling systems, and propose measures to minimise the effect on efficiency.

6.3. Data driven model for maintenance decision support

Since this model is based on the corrective maintenance records, it will consider all the factors when a system is in operation (e.g. environment, human error, etc.) that are quantitatively related to the probability of occurrence. The study can be automatically performed on a software-based platform using the WOs already recorded as input. But basing a study on empirical data implies that if a failure mode does not affect the system, it will not be taken into account.

From the results of the exploratory analysis of the corrective maintenance records, we include the following parameters in our model:

- Symptom: Symptom that identifies a failure and opens the WO, usually observed by the driver and defined by the system asset affected.
- System asset/subsystem asset: Asset where corrective action is performed

- Failure mode: Real failure related to the WO.
- Cause of failure: Reason for the failure.
- Corrective action: Action performed to close the WO.
- Failure date: Date when WO is generated.

Analysing the relationship between these parameters allows to study the RAMS of the system and to evaluate the maintenance performance and the differences between the assets. Figure 20 shows the proposed decision support model based on the maintenance records.

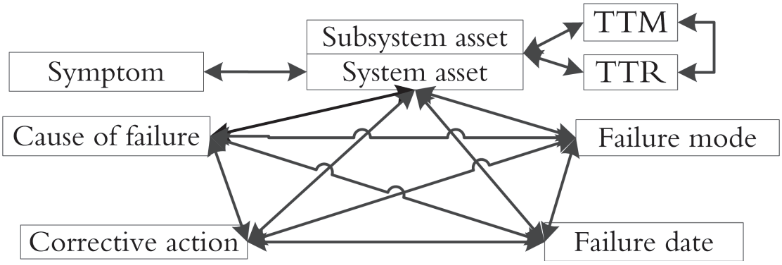

Figure 20: Failure analysis model: Parameter integration

From this analysis, the weakest points in the different system assets can be identified, such as low reliability of components, problems of information accessibility, high frequency of failures, long times to restore or/and maintain, problems of identification of failures, etc. From the result of the analysis, different points of view were taken in order to identify where the general maintenance performance can be improved. The number of failures in a determined interval will give a measure of the reliability of the system, while TTR and TTM will indicate the maintenance support performance, and the uptime and downtime will show maintainability (61703, 2001). The cause of failure and the failure mode permit us to analyse the common cause failures, and with the failure data, we can analyse the historical events.

The analysis of the relationship between the various parameters on the corrective maintenance WOs provide insight into the RAMS parameters of the system and allow us to evaluate the maintenance performance of each asset. In the next section, some of the results obtained from the application of the model are summarised, with more information can be found in Paper I.

Parameter integration

In what follows, we describe how a case study was used to validate the model, using corrective maintenance data from a specific railway line during a limited period of time. With these data, it was possible to identify the most frequent values for each parameter depending on the system or system where the failure was occurring. Failure modes, causes of failures and corrective actions were related to identify possible improvements, such as establishing an action procedure list for corrective maintenance performance. Finally, the times to restore were analysed to find patterns and to compare the total time to maintain with the time to restore.

Table 10 shows the relationship between the parameters of the system asset affected and the failure mode. From these data, we can identify how the different system assets fail. For example, interlockings have "non operative" as the most common failure mode. We can assume that one of the reasons for this finding is the complexity of the system where the failure occurs, especially in the case of the signal and the level crossings. Balise groups and track circuits have "NFF" as the most recorded failure mode, possibly because a failure on a balise can have the same effect as a failure on the connection of the signalling systems or the interlockings.

Table 10: Failure modes depending on system asset affected.

	System affected						
Failure mode	Balise group	IXL	Level crossing	Sign	Signal	TMS	Track circuits
Electrical	15	71	54	0	207	5	140
External	1	4	9	1	4	0	1
Mechanical	16	31	92	10	26	0	10
NFF	80	86	107	2	66	6	162
Non operative	55	290	84	2	51	4	118
Not defined	53	181	202	19	96	16	78

The comparison of the number of WOs for each system and the real failure recorded suggests that the more complex the system, the more often no clear failure mode is identified. Identifying failures on electronic based systems presents some difficulties since aging is not directly visible (unlike mechanical fatigue). This can be seen in the high number of WOs with failure modes recorded as NFF, "not defined" or "not operative"; these signify failures where the failure mode is not identified, and either no action is taken or the component is replaced. These WOs require extra time for corrective maintenance because of the time spent trying to identify a failure (sometimes unsuccessfully).

Table 11: Cause of failure depending on system asset affected.

	System affected						
Cause of failure	Balise group	IXL	Level crossing	Sign	Signal	TMS	Track circuits
Design	8	16	7	0	6	4	5
Electrical	14	166	43	14	53	6	47
Environment	5	82	129	2	10	1	24
External reasons	16	22	99	0	17	0	105
Maintenance	1	6	11	1	4	0	0
Mechanical	29	143	96	7	210	6	59
NFF	40	35	47	0	37	3	87
Not defined	107	193	116	10	113	11	182

Different system assets have different failure causes, since their architecture differs, as well as their operating conditions. When we study the failure causes recorded based on the system asset where the failure occurred, some trends emerge. The causes of failure recorded depending on the system assets are shown in Table 11. The most common cause of failure for four of the seven systems is "not defined". If more is known about the causes of failure, preventive measures to reduce the occurrence of these causes or minimise their effects on the systems could be formulated.

Table 12 shows the relationship between system assets and corrective actions. While for track circuits and balise groups the most common action is control (45% and 31% respectively), for other systems such as interlocking assets and signals, the replacement of the failed component is more important (40% and 50% respectively). For the TMS, the most common corrective actions are replacement and restart, both at 29% of the WOs. Balise groups and track circuits are easily affected by environmental or external factors (they are located along the track), and the failure may not be permanent. Interlockings are designed based on LRU (lineside replacement unit) to optimise maintenance while promoting replacement over repair on site to minimise the downtime of the system.

Table 12: Corrective action depending on system asset affected

	System affected						
Corrective action	Balise group	IXL	Level crossing	Sign	Signal	TMS	Track circuits
Adjust/Lubrication	10	23	32	6	27	1	5
Clean/Remove obst.	5	20	139	1	19	0	76
Control	99	119	128	2	90	6	158
No action	7	15	5	0	17	0	71
Not defined	2	8	5	1	7	0	5
Prov. repaired	0	26	9	2	3	4	19
Repair	23	82	71	15	49	2	101
Replacement	65	268	131	3	227	9	64
Restart	9	101	28	4	11	9	10
SW update	0	1	0	0	0	0	0

For the interlockings, 15% of the failures are restored with the restart of the system. Scheduled restarts could reduce the appearance of failures related to this corrective action during the normal operation of the railway.

Balise groups have "replacement" as the second most common corrective action. Since a failure on a balise can affect the operation of the track section where it is located, it is more effective to replace the balise with a new one and bring the failed one to the workshop to study the failure, thus minimising the downtime.

Examining the relationship between the corrective actions and the systems affected allows to study the maintainability of the systems, and to propose improvements to reduce the time and increase the efficiency and efficacy of the performance of the corrective maintenance actions. A review of the corrective maintenance procedures can help to achieve this goal.

Table 13 shows the relationship between the parameters of cause of failure and corrective actions. The number of NFFs linked to "control" is one of the most commonly recorded corrective actions for signalling systems. In fact, the most common corrective actions are "control" and "replacement" of the asset; "control" is related to “external”, NFF and “not defined” causes of failure, while “replacement” is associated with “electrical”, “mechanical” and “non operative” causes of failure. This can be explained by the modular architecture of signalling systems and the high number of NFFs and “not defined” failure modes.

Table 13: Corrective action depending on failure mode

	Failure mode					
Corrective action	Electr.	External	Mech.	NFF	Non operative	Not defined
Adjust/Lubrication	21	0	11	2	12	58
Clean/Remove obst.	90	1	6	16	20	127
Control	16	7	1	402	7	169
No action	7	0	0	80	1	27
Not defined	5	1	3	5	2	12
Prov. repaired	13	0	9	0	27	14
Repair	54	4	48	1	171	65
Replacement	267	2	91	1	325	81
Restart	19	5	16	2	39	91
SW update	0	0	0	0	0	1

For failure modes classified as “mechanical”, the most common corrective actions are the replacement or repair of the component. The number of mechanical failures could be reduced by visual inspections and studies of the remaining useful life of these components.

Restoration and maintenance time

Figure 21 shows how the times to restore are distributed, depending on the system asset and the sample size. This figure shows the boxplots for every system asset, indicating the log of repair time and the quartiles for each. Depending on the number of WOs, the boxplot will have different widths. The symmetric curve along each boxplot is the density for each restoration time. This type of figure allows us to visualise and compare the characteristics of the restoration time.

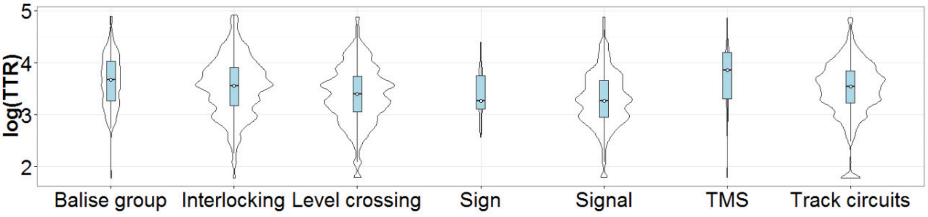

Figure 21: Restoration time depending on system asset

It can be observed that the median values for the level crossing, signal and sign are quite similar and slightly lower than for the other systems. Possibly failures on these systems are easier to identify since their architecture is simpler than that of other systems such interlockings or TMS. In more mature designs (the design has not been modified to a great extent) the system is better known; hence, the knowledge of the failure modes and their corrective actions is higher. For other systems, such as the TMS, the time to restoration is higher, mainly due to the complexity of the architecture, which hinders failure identification and restoration. Some systems show an increased number of WOs with low restoration times (e.g. the level crossing, signal and track circuits). Possible causes are the easy identification of the failure and quick restore (e.g. replacing the lamp of the signal), and the impossibility of finding the failure (NFF).

Table 14 shows the main parameters for TTM, TTR and RRT for the whole signalling system; note that approximately half of the total time is restoration time (46%). A number of factors can influence these values, including failure mode identification and specification of the needs required for restoration, distance to the failure location, human and /or material resources, etc. We can compare the maintainability of system assets by comparing the respective values of the Mean Time To Restoration (MTTR), Mean Time To Maintain (MTTM), Mean Waiting Time (MWT) and Mean Relative Time To Restore (MRTTR) obtained from the empirical data.

Table 14. TTM, TTR and RRT

	Min	**1st Qu.**	**Median**	**Mean**	**3rd Qu**	**Max.**
TTM (sec)	180	4560	8700	16580	17400	86340
TTR (sec)	60	1260	3060	6094	6960	83880
RRT (%)	0	19	43	45	70	100

Figure 22 shows the relationship between the time variables (MTTM, MTTR and MWT) for the system assets. As can be observed, the values for MTTM and MWT have the same relationship in all systems with the exception of TMS, where the MTTR is proportionally much higher. The other outstanding result is the lower value of MWT for level crossings and TMS. This is due to their criticality and the easy access to their location.

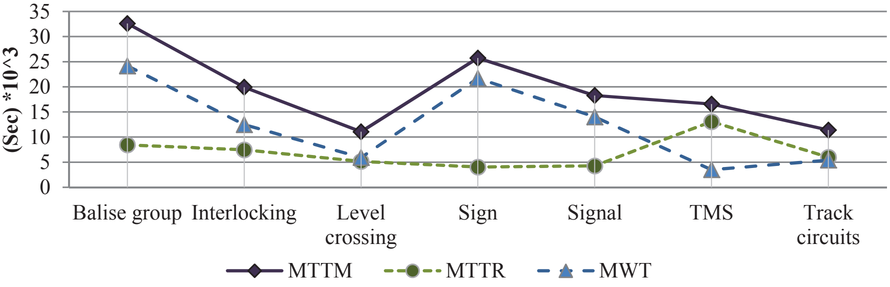

Figure 22: MTTM, MTTR and MRTTR depending on system asset

Figure 23 visually summarises the relative restoration time depending on the system asset affected by the failure. This figure shows the maximum and minimum times spent, along with the median and first and third quartiles. The density distribution is shown by the perimeter of the boxplots, and the thickness is given by the number of WOs associated with a failure of the system asset. It can be observed that the relationships between TTR and TTM depend on the asset affected.

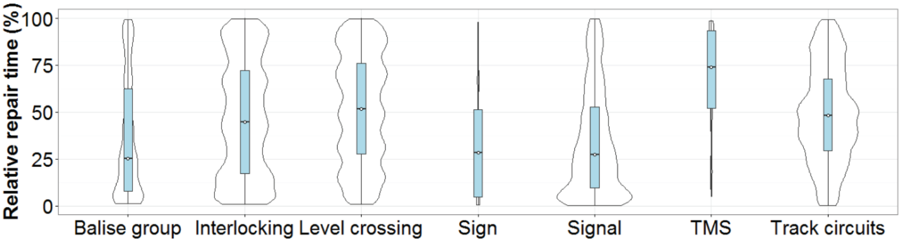

Figure 23: Relative restoration time depending on system asset

For example, the mean values for the level crossing, signal and sign are quite similar and slightly lower than for the other assets. Possibly failures on these systems are easier to identify since their architecture is simpler than for systems such as interlockings or TMS. Having more mature designs (the design has not been modified to a great extent) means the system is better known than other systems; hence, the knowledge of the failure modes and their corresponding corrective actions is greater. For other systems, such as TMS, the time to restoration is higher, mainly due to the complexity of the architecture, which hinders failure identification and restoration. Some systems show an increase in the number of WOs for low restoration times (e.g. the level crossing, signal and track circuits). One possible cause is an easy identification of the failure and quick restoration (e.g. to replace the lamp of the signal); another is the impossibility of finding the failure (NFF).

For system assets mostly affected by mechanical failures (e.g. signal, signal boards), the relative restoration time is proportionally less and the distribution of the relative restoration time decreases when the values of TTR and TTM are more similar. Mechanical failures may be easier to identify; these assets also have a simpler architecture which facilitates repair or replacement, thus reducing TTR. The balise groups also have a smaller relative restoration time, even though most of the failures are electronically based due to the simplicity of their architecture.

For electronically based system assets with more complex architecture (e.g. interlockings, traffic management system), the relative restoration time is proportionally higher than for the mechanically based assets, and the distribution of the relative restoration time does not show a trend. Arguably, more time is spent on identifying the occurred failure and finding the proper corrective action.

NFFs are more common in electronically based systems whose architecture is more complex. Having better knowledge of the systems to maintain can reduce the time needed to identify the required corrective maintenance action in these cases.

Depending on the system asset, a number of different factors can influence the times to maintain and to restoration. These include failure mode identification and specification of the needs required for restoring, distance to the failure location, human and /or material resources, etc. Analysing the factors that affect the maintenance performance in each system can help to decrease the time required for corrective maintenance and to improve the dependability of the system.

6.4. Information logistics and knowledge management

As a result of our analysis of the databases containing information on the Swedish infrastructure maintenance, it can be concluded that the Swedish infrastructure manager could improve some areas of its information logistics management. A great deal of information is gathered, but data suffer from a lack of visibility and the links between the repositories are not well established. This leads to a dependency on the expertise of the personnel, an approach which is not beneficial in the long term. Suggestions for improvement include the following:

- Modify control management so that the changes in a specific component or on a railway corridor can be analysed chronologically, along with the reasons for those changes.
- Make information related to different systems / subsystems / items more visible to improve failure identification (thus improving the overall maintenance).
- Facilitate access to maintenance and diagnostics tools (e.g. hardware and software tools, manuals, procedures) to reduce downtime.
- Reduce the dependency on the expertise of personnel
- Improve inter-organisational knowledge transfer between stakeholders.

Solutions include the use of a common database, improving CM by changing control management processes, and establishing frameworks to improve the knowledge transfer between stakeholders. The following subsections summarise models for improving CM and facilitating inter-organisational knowledge management (more information can be found in Papers II, III and IV).

Configuration management

In this section, we propose a model for CM to improve the supportability of signalling systems by enhancing information logistics. This model is based on the CMMI model (more information about the CMMI model and reasons for choosing it are in Paper III) and establishes three key points:

- Defines the required baselines and the items which compose them.
- Tracks and distributes the changes and modifications of both configurations and processes.
- Ensures the integrity of the configuration baselines.

Baselines describe the status of a determined system at a fixed point in time; they serve as a reference for tracking changes (such replacement of items due to failure) on that system. They can also be determined for a particular item and show the changes performed on it during a specific time.

Table 15 shows the system design baseline. Every design solution can be described as part of a different system (e.g. different design baselines depending on whether the control system is ATC, ERTMS, or SW). The table identifies the systems and their components. The SW for the systems and the tools for testing and uploading SW are included in the baseline since they are linked to the system. This integrates all the information of a specific design, thus facilitating change control management.

Signalling systems are based on modularity and line-replaceable units (LRU) to make maintenance operations easier and increase availability. The modules can be replaced quickly in case of failure to restore the system to service while the failed module is brought to the maintenance facility to be restored. This procedure increases availability by reducing downtime. The model proposed takes the LRUs as the minimum level to control in the configuration baselines.

The installation baseline describes how the design baseline is implemented in the different corridors, e.g. the number of systems and subsystems and where they are located, the specific SW to answer the requirements that depend on external parameters (e.g. speed limitations and balise groups), and finally the status of the components associated with a particular system (if the component is in operation, being restored or in stock) (see Table 16). This information will be needed to manage the components affecting interoperability. Note that it is not necessary to control the components of the systems which are replaceable and standardised (e.g. fasteners, connectors, cables, etc.).

The documentation baseline gathers all the information that corresponds to the different systems, subsystems and components (see Table 17). Standards and specifications indicate what must be accomplished and the proper procedures; drawings give information on installation and maintenance; reports supply the historical data of every component and help in the analysis of possible improvements. Including certificates in the baseline simplifies the number of databases to maintain, since these represent information related to the system that some stakeholders may need (e.g. quality, RAMS, etc.).

Table 14. System design baseline

Design Baseline	
IXL / RBC	Control & supervision
	Power supply
	Transmission
	Manoeuvre equipment
	IXL / RBC SW
	SW update tool for IXL / RBC
	Testing tool for IXL / RBC
Track circuit	Resistance
	Choke coil
	Joint isolations
	Cable
	Battery
	Safety relay
	Cable connectors
	Rail
Balise group	Balise
	Cable
	Connectors
	Fasteners
	Generic SW for balise
	SW update tool for balise
	Testing tool for balise
Level crossing	Manoeuvre equipment
	Control and supervision
	Transmission
	Power supply
	Understructure
	Overstructure
	Gateway
	Bean
	Signal & Sign
	Level crossing SW
	SW update tool for level crossing
	Testing tool for level crossing
TMS	Central system
	Power supply
	Transmission
	Understation
	Working station
	TMS SW
	SW update tool for TMS
	Testing tool for TMS
Signal	Lamp
	Cable
	Connectors
	Pole
	Base
Sign	Sign
	Pole
	Base
	Fasteners
	Grounding

Table 15. Installation baseline

Installation Baseline (for every system / component)	
Location	(Corridor, section, etc.)
Serial Number	(Part number of the SW and HW)
SW files	Generic files
	Specific files
Operative status	Working
	On restoration
	In stock

Table 16. Documentation baseline

Document Baseline (system / component)
Installation procedure
Corrective maintenance procedures
Inspection procedure
SW update manual
Testing manual
Mechanical drawings
Electrical schemas
Quality
ISA (independent safety assurance)
EMC (electromagnetic compatibility)
RAMS (CENELEC 50126, 50128, 50129)
ERTMS specification (UNISIG)
GSM-R specification (EIRENE / MORANE)
Functional Interface Specification (FIS)
Form Fit and Functional Interface Specification (FFFIS)
Operational requirements (Trafikverket)
Change report
Inspection report
Corrective maintenance work orders

Each configuration item has related information in the different baselines. The procedure makes visible all the information related to the item (e.g. location, software and hardware, documentation, maintenance performed, etc.). The proposed baselines and their relationship are shown in Figure 23.

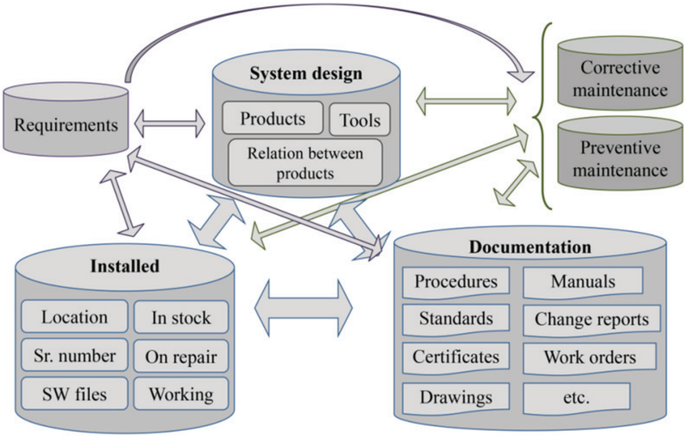

Figure 23: System configuration baselines.

The change control management process includes the steps from the identification of the reason for the work order to the closure of the request. The procedure defined here allows us to consider both restoration and design modification, since the consequence of both is a change in the system. Figure 24 shows a diagram of the process. Any failure identification should generate a change request. When a failure is identified by any person involved in the operation or maintenance of the railway line where the signalling system is located, the maintenance manager is notified of the failure. Any change in the system should be reflected in the configuration database and linked to the change request, work orders, and evidence of the change performed.

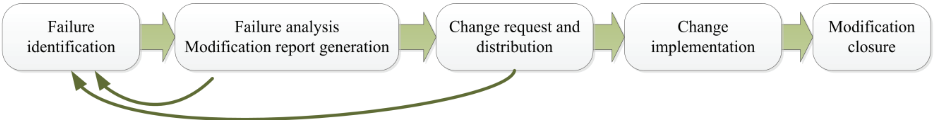

Figure 24: Change control management process.

A review of the configuration has the goal of verifying that an element or group of elements in a configuration which constitutes a baseline fulfils the system requirements and is consistent with the real configuration of the signalling system installed in the railway network. An overview of the review process is given in Figure 25. A change report identifies the need for a modification of the active baseline. The baseline is then modified to implement the change, creating a draft. This draft is reviewed by the personnel affected by the change to assure the update of the baseline is consistent with the real modification. If a gap is identified, a new draft version will be generated and sent to review, until the baseline reflects the real state of the railway network. Once the integrity of the baseline is assured, the definitive version of the baseline will be released and distributed.

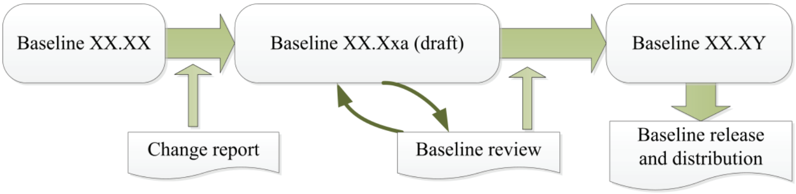

Figure 25: Integrity process assurance.

These reviews concern all personnel affected by the change requests affecting the baseline, as well the maintenance, configuration, quality and safety managers. After each review, the configuration manager publishes a report on the state of the configuration database and the changes performed. This is important as it renders visible the real status of the system and any changes that have been made.

The proposed CM simplifies the number of databases to manage. It integrates the different types of information for each system / subsystem / component; hence, it simplifies the access to the correct information and improves the change control management process.

Inter-organisational knowledge management

Paper 4 deals with the proposal of improving the maintenance performance by enhancing the knowledge transfer between the stakeholders involved in the maintenance and operation of signalling systems. A brief summary of the improvement proposals discussed in Paper 4 appears below:

- Create an association between the different stakeholders to facilitate the creation of opportunities to share knowledge. It would give a sense of belonging to a community, and facilitate the belief that all members pursue the same objectives (optimise performance with minimum cost).
- Set up a consulting division inside Trafikverket to support the stakeholders; this would incur an extra cost for Trafikverket, but it would help to keep knowledge inside Trafikverket and facilitate benchmarking best practices.
- Inaugurate intra- and inter-organisational periodical meetings to improve tacit and explicit knowledge management. These meetings can provide a framework to exchange procedures and best practices, and over time, become an inter-organisational structure for problem solving and best practices identification.
- Follow other knowledge management strategies such as formal training in short courses, workshops or seminars for all stakeholders to generate networking opportunities and knowledge transfer between stakeholders.

- Stakeholders can report their maintenance performance; this can be analysed by the Swedish infrastructure manager to find the best practices.
- Redistribute best practices to all stakeholders, with a common repository to keep the knowledge and facilitate knowledge transfer between projects, stakeholders and/or locations.
- Finally, consider expanding the knowledge network, not only to the maintenance companies but also to other stakeholders involved in signalling systems, such as manufacturers and rolling stock owners.

7. CONCLUSIONS AND FURTHER RESEARCH

The following conclusions derive from the results of this thesis, answering the RQs given in Chapter 1.

RQ1: *What are the issues and challenges of the existing railway signalling systems from a dependability and maintenance point of view?*

- By analysing the work orders related to corrective maintenance actions, it is possible to identify the weak points of the system and determine how to improve them.
- External factors affect the dependability of signalling systems, reducing their reliability, such as the location where they are installed. Measuring how much these factors affect signalling systems would allow better estimations of RAMS during operation.
- The complexity of the system and the maturity of the design architecture play an important role in identifying a failure and performing corrective maintenance actions (e.g. in better known systems, it is easier to identify a failure). Improving the maintenance supportability of the systems can reduce the time needed to identify the required corrective maintenance action.
- The need to improve failure identification and reduce the WOs with "not defined", "non operative" and "NFF" is indicated by the number of WOs with these characteristics. Improving knowledge transfer and information logistics could make a difference.
- The lack of proper data can lead to incorrect failure identification, which, in turn, means more time spent on corrective maintenance and lower system availability. This leads to a dependency on the expertise of the personnel, an approach that is not beneficial in the long term.

RQ2: *How can maintenance data and information help to improve the dependability of railway signalling systems?*

- The data driven model creates a holistic perspective of failure occurrences, since it integrates the information recorded in the different parameters of corrective maintenance work orders. It allows a review of the actual maintenance policies and permits continuous improvements based on the actual performance.
- New policies can be generated from the results of this model focusing on different areas of maintenance, including: reducing the most common causes of failure, optimising the most frequent corrective actions, reducing the time between failure and corrective action, establishing more effective failure identification, reducing certain corrective actions by implementing new preventive maintenance, etc.
- Maintenance policies can be oriented to reducing the corrective maintenance WOs related to those failure causes (i.e., mechanical failures) that can be reduced or avoided through preventive maintenance.

RQ3: *How can the management of information and knowledge of railway signalling systems be improved?*

- An enhancement of the CM would increase the efficacy of the maintenance actions. Improving the accessibility of the necessary information would increase the understanding of further possible failures, thereby reducing the time needed to identify failures and resulting in greater efficiency in the maintenance action.
- Inter-organisational knowledge management between stakeholders would allow a holistic perspective of the maintenance and operation of the railway network, avoiding the loss of knowledge inherent to outsourcing and improving the effectiveness of the various stakeholder organisations.

7.1. Contribution

The contributions of this thesis can be summarised as:

- Evaluation of the dependability of the railway signalling systems.
- Development of a data driven model for maintenance decision support based on the corrective maintenance WOs.
- Development of a model for the CM process which simplifies the access to and visibility of the information and establishes how to manage the change control process and to ensure that the configuration is updated in real-time.
- Development of a framework for improving inter-organisational knowledge management.

7.2. Further research

Based on the results of this thesis, further research can consider the following areas:

- Develop models for dependability improvement based on RAMS analysis.
- Develop a Life Cycle Cost model for cost effective maintenance policies.
- Evaluate RAMS between the signalling systems ERTMS and ATC during the operation and maintenance.

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Paper I

Data driven model for maintenance decision support - A case study of railway signalling systems

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Data-driven model for maintenance decision support - a case study of railway signalling systems

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ABSTRACT

Signalling systems ensure the safe operation of the railway network. Their reliability and maintainability directly affect the capacity and availability of the railway network, in terms of both infrastructure and trains, as a line cannot be fully operative until a failure has been repaired. The purpose of this paper is to propose a data-driven decision support model which integrates the various parameters of corrective maintenance data and to study maintenance performance by considering different RAMS parameters. This model is based on failure analysis of historical events in the form of corrective maintenance actions. It has been validated in a case study of railway signalling systems and the results are summarised. The model allows the creation of maintenance policies based on failure characteristics, as it integrates the information recorded in the various parameters of the corrective maintenance work orders. The model shows how the different failures affect the dependability of the system: the critical failures indicate the reliability of the system, the corrective actions give information about the maintainability of the components, and the relationship between the corrective maintenance times measures the efficiency of the corrective maintenance actions. All this information can be used to plan new strategies of preventive maintenance and failure diagnostics, reduce the corrective maintenance, and improve the maintenance performance.

Keywords

Railway, signalling systems, decision support model, data-driven model, failure analysis, maintenance, corrective maintenance, dependability, case study, RAMS, data integration

1. INTRODUCTION

The railway network is a complex system with several technologies working together to handle the increasing demands on capacity, speed and mobility for the transportation of goods and passengers. Railway infrastructure managers need planning tools that will enable them systematically to analyse and optimise budget needs, minimise the total costs while achieving the required levels of reliability, availability, maintainability and safety (RAMS), and guarantee the quality of the railway assets in the long run [1]. In order to deal with the short-term cost and performance demands and to guarantee RAMS over time, systematic maintenance management of the railway assets is needed [2]. The EN 50126 standard [3] establishes the processes for the specification and demonstration of RAMS requirements in the railway network.

Railway signalling systems are composed of several different sub-systems, each with its own purpose; however, their interoperability is crucial to the signalling system as a whole. Previous studies have shown the importance of signalling systems for the dependability of the railway network [4,5]. Since signalling systems ensure the safe operation of the railway network, their reliability and maintainability directly affect the capacity and availability of the railway network, in terms of both infrastructure and trains. The functionality of the signalling system is based on the principle of “fail safe” operation, meaning that the railway section where a failure is located will not be fully operative until the failure has been repaired (since safety cannot otherwise be ensured); hence, the dependability of the signalling system directly affects the capacity of the network.

Rail industry records show that for common railway signalling assets, the occurrence of no-fault-found (NFF) events can be as high as 50% [5]. The high amount of NFF events can be attributed to a limited understanding of the root causes and characteristics of failures on complex systems, inappropriate means of diagnosing the condition of the systems, and the inability to duplicate the field conditions [6]. Some research shows the importance of NFF events, not just technically, but also organisationally and behaviourally, and proposes addressing this issue as an integrated problem [5,7,8,9]. Granström [10] describes how the number of NFF events of the railway signalling systems can be reduced by updating the maintenance requirements for these systems. Another important cause of failure is human error when performing corrective maintenance [11,12]. Other external factors such as environmental conditions can affect the number of corrective maintenance actions [13,14]. For a holistic picture of where failures are located and the dominant factors causing them, structured databases containing the complete information are required [15]. A failure analysis based on the empirical data recorded on the corrective maintenance work orders (WOs) would take the external factors into account and be able to measure their relative importance for the dependability of the system.

Maintenance managers responsible for deciding maintenance actions face an abundance of data and have a complicated task transforming these data into information that supports maintenance actions [16]. Failure analysis of a signalling system will give information about how this system is affecting the dependability of the operation and maintenance of the railway network, and identify possible areas of improvement. Pecht and Ramappan [17] find that the primary objective of failure analysis is to provide design feedback to improve the performance of the component. A number of proposals have been made to improve maintenance support performance by analysing maintenance data [18,19].

Two approaches can be considered when studying the performance of a system. While the intrinsic RAMS only depends on the design of the asset and the time required to perform a corrective action with no external factors involved, the operational RAMS takes into account the maintenance performance and the external factors particular to the location (the environment, human factors, random failures, logistics, etc.). While for the intrinsic approach a model could be based on the theory of failure, by studying the different components and the theory of failure for each of them, for the operational approach a data-driven model would be a better choice, since the corrective maintenance records reflect the performance of the system with all the external factors involved in the operation and maintenance. Moreover, since signalling systems are a combination of mechanical, electronic and electrical components, the theory of failure becomes very complex to model. A data-driven model can reflect the failure phenomena with greater accuracy than models based on the theory of failure.

The EN 50129 standard [20] lists methods to identify and evaluate the effects of faults on railway signalling systems, including failure mode, effects and criticality analysis (FMECA), fault tree analysis (FTA), and other methods based on historical data, i.e. common cause failure analysis and historical event analysis. We propose a decision support model for maintenance policies based on data-driven failure analysis of the corrective maintenance. A data-driven model will consider all the factors when a system is in operation (e.g. the environment, human error, etc.), making it possible to quantify the probability that failure will occur. It can be performed on a software-based platform using the WOs already recorded as input.

The purpose of this paper is to propose a data-driven decision support model which integrates the various parameters of corrective maintenance data and to study the maintenance performance by considering different RAMS parameters. This model is based on failure analysis of historical events in the form of corrective maintenance actions. It has been validated in a case study of railway signalling systems and the results are presented. The model allows the creation of maintenance policies based on failure characteristics, as it integrates all the information recorded in the various parameters of the corrective maintenance WOs. All this information can be used to plan new strategies of preventive maintenance, reduce the corrective maintenance, and improve the maintenance and operating performance.

2. RESEARCH METODOLOGY

Corrective maintenance records formed the basis of the analysis. A schematic diagram of the research methodology is shown in Figure 1. Internal documentation, a literature review and interviews with experts were key to interpreting the data and discussing the results of the model. The research is based on data obtained from Trafikverket (the Swedish infrastructure manager). Corrective maintenance WOs related to the railway infrastructure in Sweden are managed in Trafikverket's failure reporting system, called "0felia". This system is based on the BMC Software Remedy, which was adapted to the specific requirements of the management of corrective maintenance for railway infrastructure. 0felia has its own manual for data analysis [21].

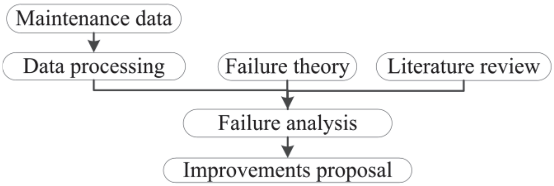

Figure 1: Research methodology process

The process of failure reporting is described in a document published by Trafikverket [22] and specifying the proper procedure from the point in time when a failure is identified and reported to the point in time when the corrective action is finished and the WO related to the failure is closed. A number of partners are involved in the process: the failure can be identified by the train operator, the railway infrastructure manager controls the activity in the railway network, and a subcontracted company performs the corrective maintenance. Since some parameters in 0felia are registered manually and the data can be in several formats, processing the data is necessary to group the information into the correct parameters.

The IEC 61703 standard [23] relates the performance aspects of maintenance to the maintenance variables to measure the dependability of a system. In our case, based on the information recorded in 0felia, we consider the parameters that give more information about failures. In order to identify these parameters, we performed an exploratory analysis looking at the quality of the data recorded for each parameter (the amount of data recorded for each parameter and the quality of the information). This was needed because not all the parameters are indicated in a WO in 0felia.

Manuals, standards and interviews with experts helped define the parameters for our model [21,22,24]. Parameters with a low data quality (information not recorded or incomplete information) were discarded. The chosen parameters were analysed and the information was integrated to obtain the maximum possible information on corrective maintenance. We studied the values of the parameters themselves, their interrelations with other parameters, and the variations over time.

Corrective maintenance WOs were gathered from Trafikverket's corrective maintenance database and then processed. The R software was used for the data processing and posterior analysis [25]. The failure modes, causes of failures and corrective actions were related to identify possible improvements, such as establishing an action procedure list for corrective maintenance performance. The times to restore were analysed to find patterns and to compare the total time to maintain (TTM) with the time to restore (TTR).

A case study was used to validate the model; some of the results are summarised in this paper. Based on the analysis, we could identify the weakest points, such as a low reliability of components, problems with information accessibility, a high failure frequency, high times to restore or/and maintain, problems identifying failures, etc. The analysis allowed us to see where the general maintenance performance could be improved.

It is assumed that all the failures were recorded in the corrective maintenance database. One limitation of this research is that the failure data are related to a specific railway corridor, with specific environmental and operational characteristics. Since this research is based on empirical data, the results are limited to the information that could be obtained from the recorded data. Finally, the results showed here are limited to the system asset level for simplification.

3. MODEL DESCRIPTION

To develop our model, we considered the different parameters recorded on the corrective maintenance WOs as the inputs for our model. The output of the model is the relations between the different parameters, and a presentation of the relations which occur more frequently. Figure 2 shows the proposed decision support model based on the maintenance records. Based on the results of the exploratory analysis of the corrective maintenance records, we included the following parameters in our model:

- Symptom: a symptom that identifies a failure and triggers the opening of a WO, usually observed by the train driver and defined by reference to the system asset affected.
- System asset/subsystem asset: the asset where corrective action is performed.
- Failure mode: the real failure which is related to the corrective action.
- Cause of failure: the reason for the failure.
- Corrective action: the action performed in order to close the WO.
- Failure date: the date when the WO was generated.

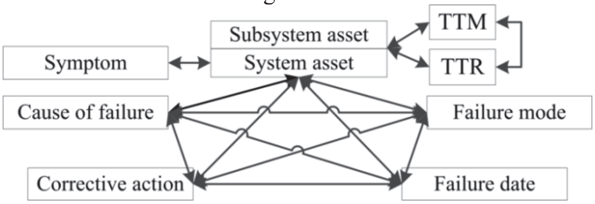

Figure 2: Decision support model based on failure analysis

Some conclusions can be made based on the times spent on the different WOs. From the database, we can extract the following times and dates for the corrective maintenance WOs: the times and dates for the failure identification, the opening of the WO, the start of the corrective action, the completion of the corrective action, and the closure of the WO. Our objective is not only to study the mean values for each parameter, but also to determine how the values are distributed. This will allow us to analyse how the maintenance performance is affected by external factors. We define three possible states for the assets during operation:

- The available state, corresponding to the up-time (UT): the system is fully operative.
- The unavailable state corresponding to the waiting time (WT): the time between the failure occurrence and the start of the corrective action. During the waiting time, the WO is opened, the failure is identified, the maintenance personnel are informed, the spare parts and tools are gathered, and the personnel go to the location of the failure.
- The unavailable state corresponding to the restoration time (RT): corrective actions are performed and the WO is closed.

Based on these three states, we define the following parameters: the time to maintain (TTM), which is the total downtime (DT) when the system is not available for operation; the time to failure (TTF), which is the time when the system is available for operation without a failure; and the relative restoration time, which is the ratio between the restoration time and the total downtime (see Equations 1, 2 and 3). Figure 3 shows the correspondence between these parameters.

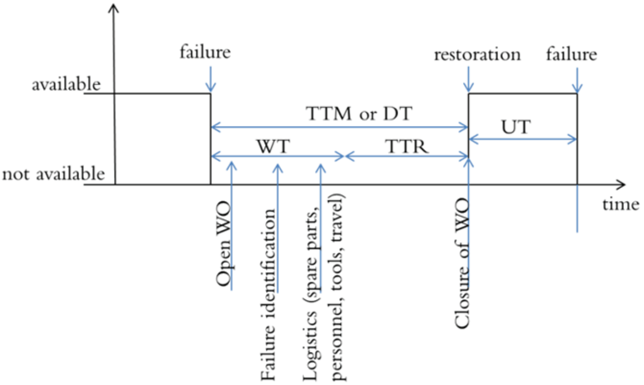

Figure 3: Correspondence between times

$$\text{TTM} = \text{t(finish of corrective action)} - \text{t(failure identification)} \quad (1)$$

$$\text{TTR} = \text{t(finish of corrective action)} - \text{t(start of corrective action)} \quad (2)$$

$$\text{RRT}\ (\%) = \frac{\text{TTR(sec)}}{\text{TTM(sec)}} \quad (3)$$

The number of failures in a determined interval will give a measure of the reliability of the system, while the TTR and TTM will indicate the maintenance support performance and the up-time and downtime will show the maintainability [23]. The cause of failure and the failure mode permit us to analyse the common cause failures, and with the failure data we can analyse the historical events. An analysis of the relationship between the various parameters on the corrective maintenance WOs yields insight into the RAMS parameters of the system and allows us to evaluate the maintenance performance of each asset.

4. CASE STUDY

The analysis is based on a fully operative railway line where the ATC (automatic train control) signalling system supervises and controls the network. The line has been operative with no major changes for many years; hence, we can assume that the WOs represent maintenance and not design changes or failures. The data cover the WOs from January 2003 until November 2012 on a 203 km long line in the northern part of Sweden.

More specifically, 9,030 WOs were registered during that period, of which 2,455 were associated with signalling systems. Due to the number of WOs directly related to signalling systems (27%) and in consideration of the criticality of the good performance of the signalling systems, we focused our research on these systems, even though the methodology can be extrapolated to the whole railway network.

The signalling system in the corridor investigated in this case study is composed of the following systems [24]:

- Track circuits, which are responsible for the train location.
- Balise groups, which give input from the track to the on-board signalling system (e.g. speed limits, driving mode, etc.).
- Level crossings, which coordinate the road traffic crossing the railroad.
- Signals, which give permission to or place restrictions on the trains coming into a track section.
- Signalling boards, which give fixed information to trains (e.g. tunnels, bridges, speed restriction areas, etc.).
- Traffic management system (TMS), which is the interface between the traffic operator and the railway network.
- Interlockings (IXLs) and radio block centre (RBC), which receive the input from the different systems (e.g. track circuits, level crossings, signals and the TMS), perform calculations and return as an output the train operation restrictions to ensure safe operation.

Every WO has associated values for the analysed parameters. The values found for each parameter include values for failure modes, causes of failure and corrective actions. More values can be considered, but since this research is based on empirical data, it focuses on the causes of failure for the signalling systems recorded in the corrective maintenance data.

The values found for the parameter of failure mode are as follows: “not defined” (the failure mode is not specified in the WO), “non-operative” (the asset is not working properly), “NFF” (no failure was found), “electrical”, “mechanical” and “external”.

The causes of failure for the signalling systems recorded in the corrective maintenance data include the following:

- Design (e.g. improper design/installation/mounting, etc.);
- Electrical causes, such as electrical overstress, improper isolation, abnormal feeding, power failure, etc.;
- Environmental causes, such as strong winds, extreme temperatures, thunderstorms, snow, ice, etc.;
- External reasons (e.g. railway vehicles, obstacles, third party work, etc.);
- Lack of maintenance or incorrect operation;
- Mechanical reasons, such as fatigue, wear, mechanical overstress, etc.;
- NFF - no failure found (it was impossible to find any failure);
- Not defined (unknown reason), which is recorded when the failure cannot be defined or is not described on the WO.

When the failure of a signalling system asset occurs, the different possible corrective actions performed to return it to the optimal state are classified into the following groups:

- Repair or replacement (restoration) of the failed component;
- Restart/software (SW) update when the failure is attributed to SW causes;
- Provisional repair, but further corrective actions should be scheduled;
- Adjustment/lubrication between modules/connections;
- Cleaning or removal of obstacles (due to an external factor or dust accumulation);

- Control of the system (it is not considered to need repair or replacement, or the failure could not be found, but certain symptoms indicate possible future failure);
- Not defined (the action performed is not specified in the WO);
- No action performed (it is considered that the system does not need the repair or replacement of a component, or the failure could not be found).

When studying the time to restore in the WOs, we found that, of the 2,456 WOs related to failures of signalling systems, 103 WOs had a restoration time of 0 seconds. Only 19 of these had a corrective action which could be used to calculate the restoration time, such as “repair” (1 WO), “replacement” (10 WOs), “restart” (3 WOs), and “removal of obstacles” (3 WOs). We decided not to consider these data, as their omission would not greatly affect the results of the analysis. The other abnormal result was that one WO had a negative time, probably due to an error when writing the “correction action start date”.

Approximately 16% of the WOs have large times to restoration and maintain (more than one day). This can be due to different factors; e.g. the failure may not have affected the normal operation of the railway network and could wait for other scheduled maintenance; the complexity of the restoration may have been high; or it may have been difficult to identify where the failure was, etc. The procedures for corrective maintenance at Trafikverket state that a WO should be closed within a maximum of 24 hours [22]. Hence, we discarded the WOs which were open for longer than 24 hours.

A preliminary analysis could be made by determining the values for each of the parameters that were more important (considering the WOs that comprised 80% of the total). However, to state the maintenance characteristics and needs for each asset, we not only had to examine the total number of failures during the time frame of our sample, but also had to consider the yearly occurrences. This helped to show if the failures had occurred in one particular year (caused by specific environmental factors, for example), or if the results could be generalised. To study how the different parameters were related for the different assets in the railway signalling systems, we needed to find trends and differences in behaviour related to where the failure had occurred. The results of our analysis varied and are summarised in the next sections, together with a discussion of how to improve the dependability of the system based on our analysis.

5. RESULTS

Figure 4 shows the Pareto diagrams for the chosen parameters (system asset, failure mode, cause of failure and corrective action); these parameters and the relationship between them will be summarised in this section.

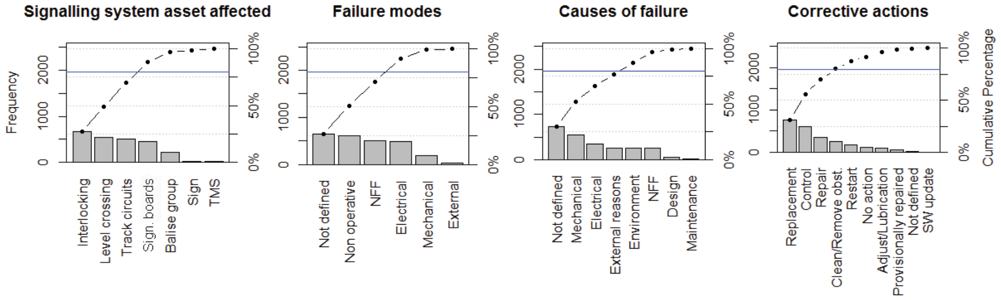

Figure 4: Pareto graphs showing the values for the different parameters: (a) signalling system asset affected; (b) failure modes; (c) failure causes (d) corrective actions performed

5.1. The parameter of system asset affected

When examining the different system assets that comprise signalling systems, we found that the interlockings, the level crossings, the track circuits and the signals account for more than 80% of the failures overall (see Figure 4a).

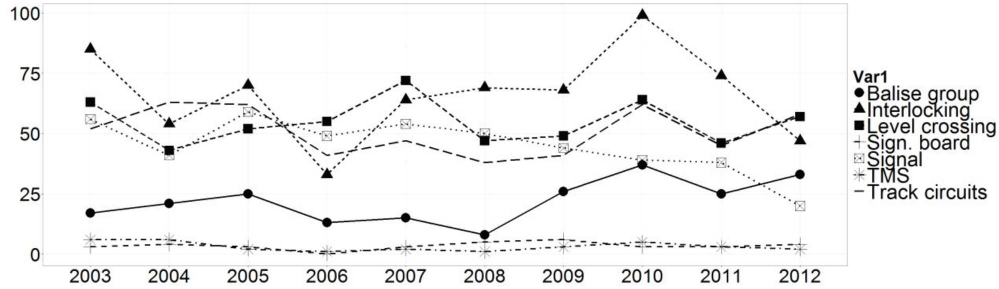

Figure 5: Failures of the signalling systems according to the year and system asset

When studying the failures by the year, we detected maximum value of WOs related to signalling systems during 2010, followed by an improvement. The number of WOs for interlockings were reduced significantly (see Figure 5). At the same time, we observed an increase in the number of WOs for the track circuits, level crossings and balise groups during the last years. The results shown in Figure 4a and 5 led us to focus our improvement measures on the RAMS of the following system assets: interlockings, level crossings and track circuits; this is because they produce around 80% of the WOs related to corrective maintenance. An improvement in the performance of these systems will improve the performance of the entire signalling system and, hence, the overall performance of the railway network.

5.2. The parameter of failure mode

The failure modes recorded are shown in Figure 4b. The most common values recorded for this parameter are "not defined" (26%), "non-operative" (24%) and "NFF" (21%). In other words, either there was no failure or it was not possible to identify a failure (hence, if there actually was a failure, it would remain unremedied and the asset in question would fail again). Lacking the proper data can cause an increased amount of time to be devoted to corrective maintenance actions, as incorrect failure identification decreases the system availability.

Table 1. Failure modes according to the system asset affected

	System asset affected						
Failure mode	Balise groups	IXLs	Level crossings	Sign. boards	Signals	TMS	Track circuits
Electrical	15	71	54	0	207	5	140
External	1	4	9	1	4	0	1
Mechanical	16	31	92	10	26	0	10
NFF	80	86	107	2	66	6	162
Non-operative	55	290	84	2	51	4	118
Not defined	53	181	202	19	96	16	78

Table 1 shows the relations between the system asset parameters that are affected and the failure modes. Based on these data, we can identify how the system assets fail. The most common value recorded for the failure mode of the interlockings is "non-operative". We can assume that one of the reasons for these results is the complexity of the system where the failure occurs in the case of the signals and the level crossings. For the balise groups and track circuits, "NFF" is the most recorded value for the failure mode.

5.3. The parameter of cause of failure

The types of failure causes related to the signalling systems are shown in Figure 4c. The most recorded values for this parameter are "not defined" (29% of the WOs), "mechanical" (23%) and "electrical" (14%). Other values recorded for the cause of failure, such as "external", "environment" and "NFF", are also relevant, as each represents 10% of the WOs recorded. Clearly, the causes of failure of the signalling systems are quite widely distributed, and the data should be studied in more depth to find possible trends.

Different assets have different failure causes, since their architecture and operating conditions differ. Studying the causes according to the asset where the failure occurred, we can identify some trends. The different causes of failure recorded for the various system assets are shown in Table 2.

The most commonly recorded value for the cause of failure for four of the seven systems is "not defined". Signalling boards have an "electrical" cause and signals have a "mechanical" cause as the most common failure cause. Electrical causes derive from thunderstorms affecting the cable that connects the signalling board to the ground. For the signals, the mechanical causes of failure are higher because failures in assets such as the signal lamp or bulb are recorded as mechanical.

Table 2. Cause of failure according to the system asset affected

	System asset affected						
Cause of failure	Balise groups	IXLs	Level crossings	Sign. boards	Signals	TMS	Track circuits
Design	8	16	7	0	6	4	5
Electrical	14	166	43	14	53	6	47
Environment	5	82	129	2	10	1	24
External	16	22	99	0	17	0	105
Maintenance	1	6	11	1	4	0	0
Mechanical	29	143	96	7	210	6	59
NFF	40	35	47	0	37	3	87
Not defined	107	193	116	10	113	11	182

5.4. The parameter of corrective action

The parameter of corrective action shows which actions were performed to restart the system when it failed. The most common actions recorded for the signalling systems (see Figure 4d) are "replacement" (31%), "control" (24%), "repair" (14%) and "cleaning or removal of obstacles" (11%). The architecture of most signalling systems is modular, allowing the replacement of an asset that fails with a new one, reducing the time to restoration.

Table 3 shows the relationship between the system assets and the corrective actions. While for the track circuits and balise groups the most common action is a control (45% and 31%, respectively), for the interlockings and signals, for example, replacement of the failed component is more important (40% and 50%, respectively). For the TMS, the most common corrective actions are replacement and restart, both corresponding to 29% of the WOs. Balise groups and track circuits are easily affected by environmental or external factors (they are located along the track), and their failure may not be permanent. Interlockings are designed as LRUs (lineside replacement units) to optimise maintenance while promoting replacement over repair on site to minimise the downtime of the system. Balise groups have replacement as the second most common corrective action. Since the failure of a balise can affect the operation of the track section where it is located, it is more effective to replace the balise with a new one, taking the failed one to the workshop to study the failure, thus minimising the downtime.

Table 3. Corrective action according to the system asset affected

	System asset affected						
Corrective action	Balise groups	IXLs	Level crossings	Sign. boards	Signals	TMS	Track circuits
Adjustment/lubrication	10	23	32	6	27	1	5
Cleaning /removal of obstacles	5	20	139	1	19	0	76
Control	99	119	128	2	90	6	158
No action	7	15	5	0	17	0	71
Not defined	2	8	5	1	7	0	5
Provisional repair	0	26	9	2	3	4	19
Repair	23	82	71	15	49	2	101
Replacement	65	268	131	3	227	9	64
Restart	9	101	28	4	11	9	10
SW update	0	1	0	0	0	0	0

5.5. Relationship between the parameters “corrective action” and “failure mode”

Table 4 shows the relationship between the parameters “corrective action” and “failure mode”. The number of “NFFs” linked to the corrective action “control” contributes to making this measure one of the most commonly recorded corrective actions for the signalling systems. The most common corrective actions are a “control” and” replacement” of the asset. For example, “control” is related to the following values for “failure mode”: “external”, “NFF” and “not defined”; while “replacement” is associated with the following values for “failure mode”: “electrical”, “mechanical” and “non-operative”. This is due to the modular architecture of signalling systems and the high incidence of “NFFs” and “not defined” failure modes.

Table 4. Corrective action according to the failure mode

	Failure mode					
Corrective action	Electr.	External	Mech.	NFF	Non-operative	Not defined
Adjustment/lubrication	21	0	11	2	12	58
Cleaning /removal of obstacles	90	1	6	16	20	127
Control	16	7	1	402	7	169
No action	7	0	0	80	1	27
Not defined	5	1	3	5	2	12
Provisional repair	13	0	9	0	27	14
Repair	54	4	48	1	171	65
Replacement	267	2	91	1	325	81
Restart	19	5	16	2	39	91
SW update	0	0	0	0	0	1

5.6. Relationship between the parameters “failure mode” and “cause of failure”

When analysing the failure data, it is important to remember that different values can refer to the same kind of failure, since there is not any exact way to evaluate them. This can be seen when comparing the parameters “failure mode” and “cause of failure” (Table 5). For example, 37% of the WOs where the cause of failure was recorded as “not defined” have “NFF” as the failure mode. With regard to the WOs where the failure mode was recorded as “non-operative”, 32% of the failures were mechanical failures, 29% electrical failures and 16% were not defined.

Table 5. Failure mode according to the cause of failure

	Failure mode					
Cause of failure	Electrical	External	Mechanical	NFF	Non-operative	Not defined
Design	5	2	3	2	11	23
Electrical	62	1	15	3	172	90
Environment	32	0	7	15	65	134
External	73	5	66	7	62	46
Maintenance	2	9	1	3	0	8
Mechanical	234	0	67	0	193	56
NFF	5	0	0	211	1	32
Not defined	79	3	26	268	100	256

5.7. Relationship between the parameters of system asset affected, restoration time and maintenance time

Table 6 shows the main parameters for the TTM, TTR and RRT for the whole signalling system; note that approximately half of the total time is due to the restoration time (46%). A number of factors can influence these values, including failure mode identification and specification of the repair requirements, the distance to the failure location, human and/or material resources, etc. We can compare the maintainability between the different system assets by comparing the respective values of the mean time to restoration (MTTR), mean time to maintain (MTTM), mean waiting time (MWT) and mean relative time to restore (MRTTR) obtained from the empirical data.

Table 6. TTM, TTR and RRT

	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
Maintenance time (TTM, sec)	180	4560	8700	16580	17400	86340
Restoration time (TTR, sec)	60	1260	3060	6094	6960	83880
Relative restoration time (RRT, %)	0	19	43	45	70	100

Figure 6 shows the relationship between the time variables (MTTM, MTTR and MWT) for the different system assets. As can be observed, the values for the MTTM and MWT have the same relationship in all the systems with the exception of the TMS, where the MTTR is proportionally much higher. The other outstanding result is the lower value of the MWT for the level crossings and the TMS. This is due to the criticality of these assets, as well as the ease of access of the asset locations.

Figure 7 visually summarises the RRT according to the system asset affected by a failure. This figure shows the maximum and minimum times spent on restore, along with the median and first and third quartiles. The density distribution is shown by the perimeter of the boxplots, and the thickness depends on the number of WOs associated with a failure of the system asset. It can be observed that the different relationships between the TTR and TTM depend on the asset affected.

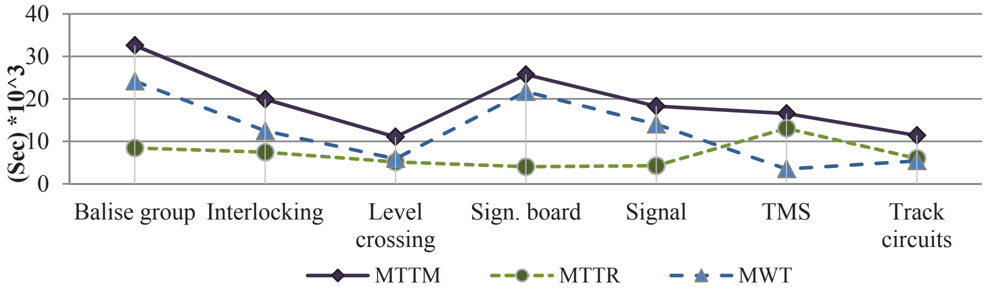

Figure 6: MTTM, MTTR and MRTTR according to the system asset

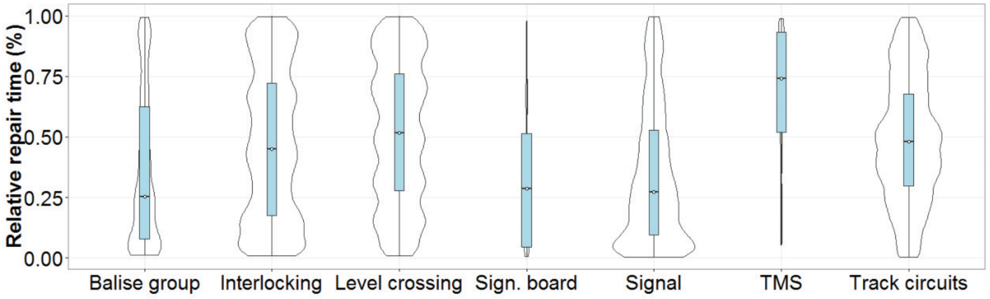

Figure 7: Relative restoration time according to the system asset

For example, the mean values for the level crossings, signals and signalling boards are quite similar and slightly lower than those for the other assets. It is possible that failures of these systems are easier to identify, since their architecture is simpler than that of systems such as interlockings or the TMS. Systems with a more mature design (i.e. a design which has not been modified to a great extent) are more familiar to the maintenance personnel than other systems; hence, the personnel's knowledge of the failure modes and their corresponding corrective actions is greater. For other systems, such as the TMS, the time to restore is higher, mainly due to the complexity of the architecture, which hinders failure identification and restoration. Some systems show an increase in the number of WOs for low restore times (e.g. the level crossings, signals and track circuits). One possible cause is the ease of identification of failures and the quickness of restorations of these systems (e.g. replacing the lamp of a signal); another possible cause is the impossibility of finding failures (NFF) on occasions.

For the system assets mostly affected by mechanical failures (e.g. signals and signalling boards), the relative restoration time is proportionally smaller and the distribution of the relative restoration time decreases when the values of TTR and TTM are more similar. Mechanical failures may be easier to identify; assets prone to mechanical failure also have a simpler architecture which facilitates repair or replacement, reducing the TTR. The balise groups also have a smaller relative restoration time, even though most of the failures are electronically based, due to the simplicity of their architecture.

For the electronically based system assets with a more complex architecture (e.g. interlockings and the traffic management system), the relative restoration time is proportionally higher than that for the mechanically based assets, and the distribution of the relative restoration time does not show a trend.

Arguably, more time is spent on identifying the failure that has occurred and finding the proper corrective action.

“NFFs” are more common for electronically based systems and the architecture of these systems is more complex. Better knowledge of the systems to be maintained can reduce the time needed to identify the required corrective maintenance action in these cases.

5.8. Relationship between the parameters of symptom and system asset affected

We studied the relationship between the parameters “symptom” and “system asset affected” to determine how much information could be extracted from the former. When a WO is opened, there is a symptom indicating where the failure has occurred. Failures are usually identified by the train driver, and it is not always possible for them to make an accurate identification of the failure, since failures of different systems may have the same failure effect (e.g. it can be difficult for a train driver to differentiate between a failure in the track circuit and a signal failure). The values of the “symptom” parameter are associated with the different systems; therefore, they may differ from what was reported when the WO was opened and from the system where the failure actually occurred.

To maximise the usability of the symptom parameter for giving information on the real failure, we grouped the systems into more generic groups, such as signalling systems (including track circuits, signals, interlockings, etc.), power and electric systems (e.g. transformers, substations, etc.), telecommunication systems (e.g. radio, telephony, signal cable, etc.) and track systems (turnouts, rail, etc.). When the system was not defined, it was classified as “other systems” and, when no fault was found, it was classified as a system with “NFF”. Figure 8 shows the relationship between the symptoms and the system groups affected; the identification given by the symptom mostly relates to the system asset affected.

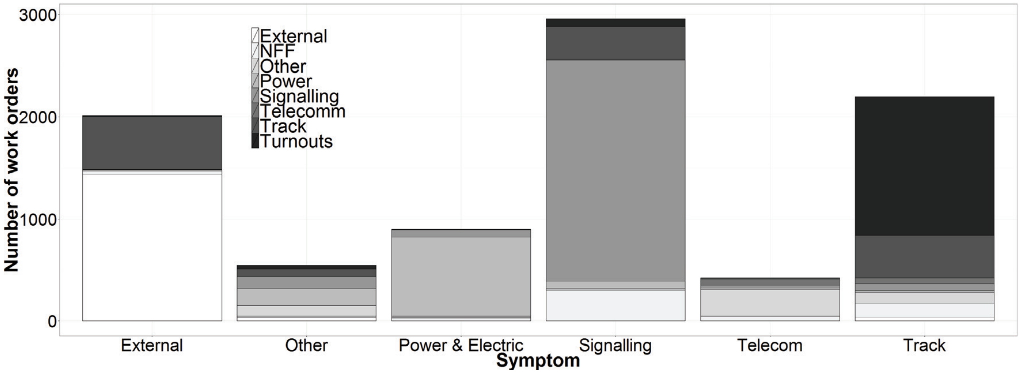

Figure 8: The system where the failure actually occurred related to the symptom

Having a more general classification of the symptoms may result in better accuracy; in addition, data classified in this manner can be used by the maintenance personnel. Therefore, using broader groups for the symptom classification can give the maintenance personnel a better initial idea of which technology has failed.

6. DISCUSSION

Based on the number of WOs related to failures, we conclude that signalling systems play an important role in the dependability of the railway system. Interlockings, level crossings and track circuits are the systems most affected by failures and cause most of the WO actions. Improving the performance of these systems will improve the overall performance of the railway network.

“Non operative”, “not defined” and “NFF” are the most common values recorded for the failure mode for signalling systems. There are two possible reasons for this: either there was no failure or it was not possible to identify a failure (hence, if there actually was a failure, it would remain unremedied and the asset in question would fail again). The most common value recorded for the cause of failure is “not defined”. The comparison of the number of WOs for each system and the real failure recorded shows that the more complex the system is, the more often a clear failure mode is not identified. Identifying failures in electronically based systems presents some difficulty, since aging in such systems is not directly visible (unlike mechanical fatigue). This can be seen in the high number of WOs with the following values recorded for the failure mode: “NFF”, “not defined” or “non-operative”; these WOs concern failures for which the failure mode was not identified, and either no action was taken or the component was replaced. These WOs require extra time for corrective maintenance due to the time spent trying to identify a failure (sometimes unsuccessfully).

The complexity of the system and the maturity of the design architecture (e.g. it is easier to identify failures in a well-known system) play an important role when identifying failure and performing corrective maintenance actions. Better knowledge of the systems to be maintained can reduce the time needed to identify the required corrective maintenance action.

Factors such as environmental conditions or electromagnetic compatibility (EMC) can affect the normal operation of the assets, producing random failures, for which it is difficult to identify the failure cause and mode. Better failure identification would lead to better preventive measures, reducing the occurrence of failures or minimising their effects.

Studying the relationship between the corrective actions and the systems affected allows us to examine the maintainability of the various systems, and to propose improvements to reduce the time for corrective maintenance actions and increase the efficiency and efficacy of such actions. A review of the corrective maintenance procedures can help to achieve this goal. From our observations of the time to maintain, the time to restoration and the relative restoration time, we conclude that, depending on the system asset, a number of different factors can influence the times required to maintain and to restore. Analysing the values for the factors affecting maintenance performance for each system can help reduce the times spent on corrective maintenance, thus improving the dependability of the system. Proposals for improvement depend on the focus; e.g. one can reduce the waiting time by improving the maintenance support, and one can decrease the restoration time by striving for a more efficient corrective maintenance performance, etc.

Depending on the system asset, different factors can influence the time to maintain and to restore for different reasons; examples of such factors are failure mode identification, specification of the repair requirements, the distance to the failure location, human and/or material resources, etc. Analysing the values of the factors that affect the maintenance performance for each system can help to reduce the time spent on corrective maintenance and improve the dependability of the system.

7. CONCLUSIONS

The purpose of this paper was to propose a data-driven decision support model which would integrate the various parameters of corrective maintenance data and study maintenance performance by considering different RAMS parameters. To develop our model we considered the different parameters recorded on the corrective maintenance WOs as the inputs for our model. The output of the model is the relations between the different parameters and a presentation of the relations which occur more frequently. This makes it possible to review the current maintenance policies and propose continuous improvements depending on the current performance. A limitation of the model is its dependence on the quality of the data recorded on the WOs. Depending on the quality of the input data, the reliability of the output for the decision support process can vary.

The proposed model is based on failure analysis of historical events in the form of corrective maintenance actions. It has been validated with corrective maintenance data from a specific case study. We have focused on signalling systems for two reasons. Firstly, the failure of a signalling asset may mean that the railway section where it is located will be not fully operative until the failure has been repaired (since safety cannot otherwise be ensured); hence, the availability of the whole railway section will be affected. Secondly, signalling systems receive a great deal of corrective maintenance WOs (27% in our case study).

Implementation of the proposed decision support model has shown that it can be successfully applied, with the following results:

- The model treats the failure occurrence from a holistic perspective; it integrates the information recorded in the different parameters of the corrective maintenance WOs.
- The model is based on empirical data and can therefore be used to validate results from other methodologies.
- The model allows a chronological review of actual maintenance policies, such as scheduled maintenance and inspection procedures, and their effect on corrective maintenance.
- New policies can be oriented to a reduction of the most common causes of failure and to an optimisation of the most frequent corrective actions to reduce the time spent on maintenance.
- The need to improve failure identification and reduce the number of WOs with “not defined”, “non-operative” and “NFF” recorded for the failure mode is indicated by the number of WOs with these values recorded. Improvements in knowledge transfer and information logistics could reduce them.
- The model links failure modes and causes of failure, establishing the basis for possible future improvements, such as the implementation of condition-based maintenance (e.g. condition-based maintenance of track circuits depending on the rainfall).
- The model identifies the assets that affect railway availability most; improving their reliability will maximise the global benefits.

Signalling systems are designed based on the “fail safe” mode; a failure can mean that the railway section where they are located will be not fully operative until the failure has been repaired. Hence, the failure of a single component can affect the availability of the whole railway network. The model identifies which systems are more likely to fail, the causes of failure and the most common corrective actions. Maintenance policies can be proposed to improve the reliability and availability of these systems.

From the results of the case study, we conclude that signalling systems play an important role in the dependability of the railway system, and this is particularly true of such assets as interlockings, track circuits and level crossings. We also find that “non-operative”, “not defined” and “NFF” are the most common values recorded for the failure mode. Further research on the NFF phenomena can help to optimise maintenance performance and reduce the corrective maintenance WOs.

For the analysis performed in the research study presented herein, we assumed that all the failures were recorded in the corrective maintenance database. Since this research is based on empirical data, the results are limited to the information that could be obtained from the recorded data. Further research can reduce these limitations and examine the results more closely.

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Paper II

Information logistics for maintenance of railway signalling systems: A case study

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Information logistics for maintenance of railway signalling systems: A case study

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Abstract

The purpose of this paper is to explore the use of information logistics for railway signalling systems to improve the efficiency of their corrective maintenance. The signalling system is used to control, supervise and protect railway traffic; therefore, its reliability, maintainability and related maintenance support affect the availability of the railway network. The paper reviews the current status of the maintenance of railway signalling systems, looking at company surveys and company data for a specific case study and consulting relevant literature. It describes how and where data are processed and analyses corrective maintenance work orders to determine how much time is spent on corrective action and knowledge management Areas of improvement are identified and possible improvements are proposed. The efficiency of information logistics has a clear effect on the dependability of the railway signalling system. Signalling systems' performance can be improved by having better control of and accessibility to the information required for each maintenance action.

Keywords: railway, signalling systems, information logistics, knowledge management, dependability, maintenance.

1 Introduction

During the operation and maintenance of the railway infrastructure, lots of data are collected and managed to control and analyse the current state of the system. These data include the system architecture, maintenance reports, work orders (WO) performed, etc. The managers responsible for determining maintenance actions face an over-abundance of data and have a complicated task transforming these data into information that will support maintenance actions [1]. In addition, confusing data/remarks in the databases often lead to misinterpretations. For a holistic picture of the location of failures and the dominant factors causing them, structured databases containing the complete information are required [2].

The railway network can be divided into different systems depending on functionality, such as the rolling stock, the track, the power supply, the signalling system, etc. [3]. The signalling system plays an important role in the control, supervision and protection of rail traffic, and its availability affects the performance of the whole system. There are a number of items within the larger category of signalling systems [4]. For example, track circuits, axle counters and GPS-based systems can be used to locate a train. Track circuits and signals help control the traffic on the railway line to prevent collisions. Balises and radio based systems allow the train control centre to restrict the movement of trains, and advanced systems i.e. European Rail Traffic Management System (ERTMS) or Automatic train control system (ATC) supervise and control the railway network. They interpret the input from other systems, creating restrictions on the train route to ensure safe operation. An example of the parts of a signalling system and their relationship are shown in Figure 1.

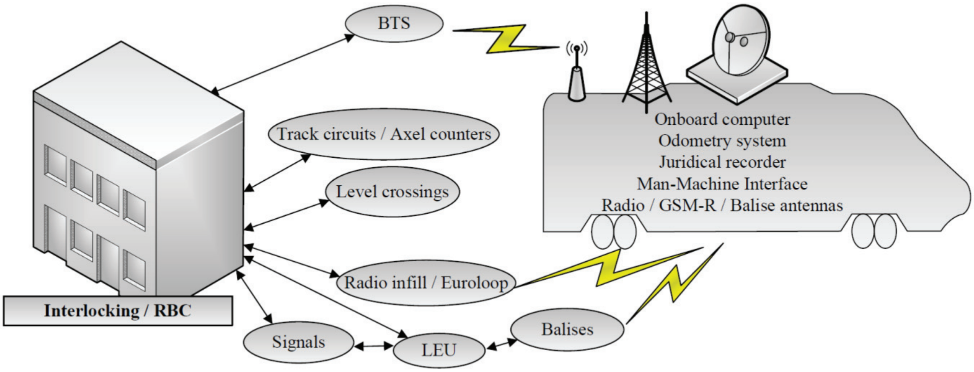

Figure 1: Signalling systems and their interfaces.

Many signalling systems are currently on the market, each with different specifications and based on different technologies (e.g. ERTMS, ATC, etc.) [4,5,6]. The various systems, such as track circuits or level crossings, provide input for interlocking systems and the radio block centre systems (RBC). Interlocking systems receive information, process it and make new restrictions on system components. For example, they can provide information to onboard signalling systems through the GSM-R system, by means of the base transceiver stations (BTS) located along the railway network. The onboard signalling system is composed of a centralized computer that processes the different inputs, giving supervision during the train's operation. An odometry system constantly measures the speed and acceleration of the train. The balise antenna reads the information from the balises placed on the track. The man-machine interface provides the interaction between the driver and the onboard computer. The juridical recorder records the information generated during the operation (e.g. driver operations, balises and odometry information, etc.). Other systems such as the GSM-R or the radio infill exchange information between the wayside signalling system and the onboard signalling system. Some auxiliary systems, such as the Lineside electronic unit (LEU) whose purpose is to exchange information between wayside systems, do not depend on the interlocking system to process information.

The main characteristic of a signalling system is that every system within it has a particular function, but the overall function is fulfilled by the sum of the functions of the different parts: the supervision and protection of the railway network will not be possible if any of the items of the signalling system do not work properly or there is a lack of interoperability between them. These characteristics define a system of systems (SoS) [7,8]. When managing SoS, it is not possible to consider the different parts independently; functionality depends on the relationship between them [9].

A signalling system is a complex combination of software and hardware; the maintenance manager must understand how changes will affect the system, how the system is built, what role the different parts play and how they are interconnected. If up-to-date documentation is lacking, maintainers have serious problems [10]. The complexity of signalling systems makes information management a necessity to ensure proper performance in all phases of the life cycle.

Performing effective and efficient maintenance requires the appropriate dissemination of accurate information. Two potential problems in doing so are data overload and information islands. Excessive amounts of data can cause problems in decision making due to the unavailability of the right information [11], while information islands can prevent the integration of information [12]. Preventing data overload and allowing the integration of the maintenance-related information from various sources can avoid these issues [13]. The efficiency of maintenance depends on the availability of information services, at the right time, with the right quality, for the right stakeholders [11]. Insufficient or inadequate maintenance support information results in the No Fault Found (NFF) phenomenon [14], ultimately a costly error.

The use of Information and Communication Technology (ICT) and other emerging technologies facilitates easy and effective collection of data and information [15]. Providing the right information to the correct information consumer or producer at the right time is essential [15,16]. However, this makes managing designs and modifications and estimating item reliability and criticality throughout the system’s life cycle much more complex (Karim, 2008).Therefore, there is a need to integrate knowledge discovery with maintenance support for effective decision-making.

Some research has considered improving the maintenance of railway signalling systems (e.g. Availability analysis [17,18,19]; Reliability analysis [20,21,22]; RAM performance [23,24]; Life cycle cost [25]; Risk evaluation [26]; Electromagnetic compatibility (EMC) [27,28]; Dependability optimisation [29]; Condition-based maintenance [30]; etc.), but to the best of our knowledge, no previous research has considered improving maintenance of railway signalling systems by enhancing the information logistics.

The purpose of this paper is to explore the use of information logistics for railway signalling systems to improve the efficiency of their corrective maintenance. It describes the information logistics used by the Swedish railway infrastructure manager (Trafikverket) for railway signalling systems and suggests improvements. The paper reviews the current maintenance of railway signalling systems, looking at company interviews and company data, such as work orders (WO), and discussing relevant literature. It describes how and where data are processed and analyses corrective maintenance WOs to determine how much time is spent on corrective action and knowledge management. Finally, it identifies areas of improvement and proposes possible improvements.

2 Research methodology

Our case study is based on the Swedish infrastructure manager (Trafikverket). Based on unstructured interviews and a literature review, we sought to define the status of information logistics and knowledge management in the maintenance of Swedish railway signalling systems, examining how information is currently managed and suggesting possible improvements.

The databases analysed are listed in Table 1. A brief description of the databases is given in the results section, and more information can be found in previous research [17,31].

Table 1: Trafikverket databases related to signalling systems

Database	Description
BIS	System architecture [32]
BVDOC	Generic documentation
IDA	Project documentation [33]
0felia	Corrective maintenance [34]
BESSY	Preventive maintenance inspections [35]
PATCY	ATC design performance
Duvan	Analysis of operation and maintenance performance

Since one of the purposes of this paper is to link information logistics performance to maintenance performance, we performed a data analysis of the corrective maintenance database to find indicators showing the relation between them. Data were gathered from the corrective maintenance actions performed on the infrastructure of a Swedish railway line. This is a fully operative railway line; the signalling system ATC (Automatic Train Control) supervises and controls the network. The line has been operative with no major changes for many years; hence, we can assume that the WOs deal with maintenance and not design changes or failures. The data comprise WOs from January 2003 until November 2012 on a line 203km long in the northern part of Sweden.

Data analysis comprised the following steps: analyse the WOs for the railway infrastructure, looking for the reasons for failure; identify the WOs for signalling systems to find WOs on the same system and location, as well as "no failure found" work orders.

3 Case study

Trafikverket has several linked databases for information management. Figure 2 shows a schema of the most important databases for signalling systems and their relationships.

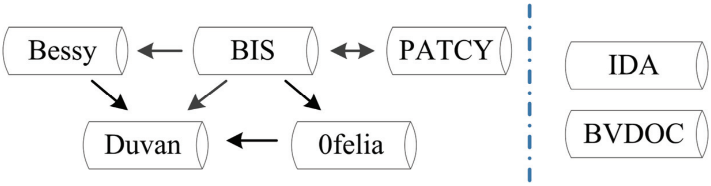

Figure 2: Data fusion architecture schema.

The architecture of the whole railway infrastructure is managed by a software tool (BIS) which allows us to see which items compose a section of the railroad (signalling, power supply, track components, etc.). The specific location of each item is defined, together with the model and serial number. The information in this database is the basis for such activities as infrastructure design, budgeting, operation and maintenance, traffic analysis and planning, reports, etc. The database allows us to look for a specific item and see its historical data, or to look at a specific location and see what has been installed there and what inspections have been performed over time. A copy of the state of the architecture is saved periodically, and by comparing them, it is possible to trace the changes over time.

Documentation is managed in two different databases, depending on the class of the data. The documentation repository BVDOC stores and classifies generic regulations and manuals not assigned to any specific project. IDA is the documentation and file database for the Swedish transport administration. It is an adaptation of ProjectWise from Bentley Systems. This tool supports management while developing new projects and maintaining existing ones. It manages various types of information, from documentation to CAD files. Specific information from projects is stored on this database, including contracts, manuals, drawings, etc. The processes for reviewing and updating information are described in the software tool's manual.

BIS exchanges information with several other railway databases. Two software tools manage corrective (0felia) and preventive maintenance (Bessy). Since the data analysis for this study is based on corrective maintenance work orders, 0felia is described in more detail in the following section.

Maintenance and safety inspections in the infrastructure are registered in Bessy. The results and dates of these inspections are registered for each item inspected. Scheduled inspections are also indicated. The regulations governing the safety inspections required for each system and subsystem of the railway infrastructure are defined by the Swedish infrastructure manager; these can be found in the documentation database BVDOC.

Another database involved in the operation and maintenance of signalling systems is PATCY. The purpose of PATCY is to record and upload ATC projects to the architecture database BIS. It uses Duvan as the platform for analysis of the operation and maintenance of the railway network based on information from the databases Bessy, 0felia and BIS. As the data are not updated immediately, there is a delay.

3.1 0felia: Corrective maintenance

One important part of information and knowledge management in the maintenance phase of the life cycle is maintenance performance. By analysing the records of corrective maintenance actions, it is possible to identify the weak points of the system and determine how they can be improved.

The corrective maintenance database “0felia” is based on the BMC Software Remedy User but is adapted to meet the specific requirements of the management of the corrective maintenance of the railway infrastructure. More information about BMC software can be found on the Internet. 0felia has its own manual for data analysis.

The process of failure reporting is described in a Trafikverket document (see references in Table 2 for more information); the document lists the appropriate steps to take from the time a failure is identified and reported until corrective action is finished and the WO related to the failure is closed. Every record is associated with a WO. A number of partners are involved in the process: the failure can be identified by the train operator, by the railway infrastructure manager who controls activities on the railway network, or by a subcontracted company that performs the corrective maintenance. Various types of communication are used, from computer databases to phone calls.

0felia offers information on the WOs at a specific location or line of the railway infrastructure, at a specific time. Once the location and dates are specified, a list of the WOs for corrective maintenance actions is generated. Each row of the list is a WO, identified with an ID of the failure report, date when the order was opened, location, status of the order, symptom, system, subsystem, component, and name of the maintenance worker. The exact location of the failure, when the corrective action was performed and when the WO was closed can also be determined, as can the real failure, the reason for failure and the action performed to close the WO.

Table 2: 0felia corrective maintenance: description of parameters

Report label	Label description
Failure report ID	Each WO record is assigned a code for identification.
Status	WO status associated to each report: open, in progress, closed.
Identification date	Date when the WO report was opened
Notification date	Date when personnel were notified of the WO
On the way dates	Date when personnel arrived at the failure location
Corrective action start date	Date when corrective action began
Found date	Date when the failure was identified
Corrective action end date	Date when the failure was corrected
Completed date	Date when the WO was closed
Response time	Response time between notification and start of corrective action
Corridor ID	Code of the railway corridor where the failure is located
Location from	Section of the track where the failure is located
Location until	
Symptom	Symptom that identifies a failure
Description	Description of the failure
Technology system failure	Technology related to the failure (power supply, signalling, track, etc.)
Field competence	Technology related to the WO (electrical, mechanical, telecommunications, etc.)
System Asset	System where corrective action is performed, following the architecture description of Trafikverket (Trafikverket, 2012)
Location	Location where the corrective action is performed
Model type	Model identification of the asset (Part number)
Subsystem asset	Subsystem where corrective action is performed, following the architecture description of Trafikverket (Trafikverket, 2012)
Component	Component where corrective action is performed
Device	Device where corrective action is performed
Real failure	Real failure related to the corrective WO
Failure mode (Real failure)	Cause of the failure
Action performed	Corrective action performed

This information can be exported to an excel file for further analysis. Each column displays different data, from the opening of the WO to the performance of corrective action and the closing of the WO. A list of the main features appears in Table 2. With these data, we can study how much time is spent identifying the failure and preparing to perform the corrective action. Quality of failure identification can be analysed by studying repeated work orders for the same component over a short period.

Table 3: 0felia work order

Report label	Example case			
Failure report ID	FRXXX1	FRXXX2	FRXXX3	FRXXX4
Active repair time	1 h. 50 min	15 min	1 h. 30 min	1 h.
Symptom	Failure code ATC	Failure code ATC	Failure code ATC	Failure code ATC
System	Balise group	Balise group	Interlocking / RBC	Interlocking / RBC
Location	SUS 2/2	SUS 2/2	SUS 2/2	SUS
Subsystem asset	-	-	Control and supervision	Control and supervision
Component			ATC	ATC
Real failure	No failure	No failure	Not possible to define	Bad contact
Cause	No reason known	No reason known	No reason known	Material Fatigue / Aging
Action performed	Control	Control	Control	Unit replacement

Table 3 gives a sample failure report. Four WOs relate to a failure reading and ATC code. The failure component is identified as the balise group. The first WO was open for four hours with two hours dedicated to corrective action. In this example, no corrective actions were performed since it was not possible to identify the failure. Looking at the data, we see that the failure appeared three more times during the following days. The third WO related to the same failure, and this time the failure was assigned to the component related to the ATC (part of the subsystem of control and supervision on the interlocking system), but no failure was found. It was not until the fourth failure that corrective action was performed, and the component was replaced.

Human factors can complicate the analysis of the failure data. Table 2 shows different data describing the same failure (e.g., the four WOs in the same location have three descriptions of the track section, depending on the track location description and the track section codes). Therefore, manual filtering is required to ensure the quality of the information.

3.2 Data analysis

The WOs are classified according to technologies, identifying the following systems in the railway infrastructure: power system, track system (e.g. switches and crossings), telecom system, electricity system, signalling system (e.g. ATC, signals, boards, etc.).

In what follows, the values found for each WO parameter are described (failure modes, causes of failure and repair actions). More values for each parameter can be considered, but this paper focuses on ones that can tell us if the information logistics need to be improved: the system, the real failure and the symptom (initial identification of the failure)

The studied signalling system is composed by the following subsystems:

- Track circuits: responsible for train location.
- Balise group: input from track to onboard signalling system (e.g. speed limits, driving mode, etc.).
- Level crossings: coordinate road traffic across the railroad.
- Signals: give or restrict permission to the train coming onto a track section.
- Signalling boards: inform train of fixed information (e.g. tunnels, bridges, speed restriction area, etc.).
- Traffic management system (TMS): interface between traffic operator and railway network.
- Interlocking (IXL) / Radio Block Centre (RBC): receive input from different systems (e.g. track circuits, level crossings, signals, TMS), calculate and return as an output the train operation restrictions to ensure safe traffic operation.

The WO failure modes include: Not defined (failure mode not specified in WO; Non operative (system /subsystem does not work properly); NFF (no failure found); Electrical; Mechanical and External.

As shown in Figure 3 (left), 31% of the WOs were identified as related to signalling systems. In other words, most of the WOs were generated by some symptom related to signalling systems, even though the real failure and the system to repair could differ.

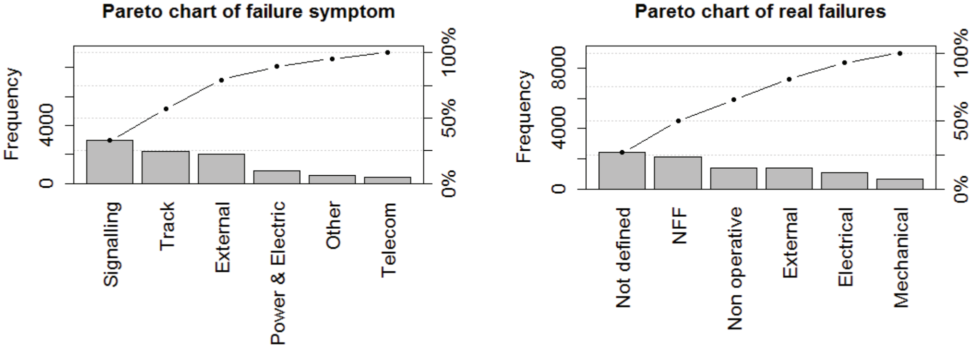

Figure 3: Left: Corrective maintenance work orders depending on the railway system (Symptom); Right: Work orders depending on the failure (Real failure).

Some conclusions can be also reached by analysing the failure identification. Figure 3 (right) shows that on 23% of the WOs opened, no failure was found (NFF), and another 27% could not define the failure. This can be caused by one of two things: either there was no failure, or there was one but it could not be identified (it remains and failure will recur).

Table 4 shows the relationship between the parameters and the failure modes. From these data we can identify how the different system assets fail. Interlocking systems most frequently have a “non operative” failure mode, while balise groups and track circuits have “NFF” as the most recorded failure mode.

Table 4: Failure modes depending on system asset affected.

	System affected						
Failure mode	Balise group	IXL	Level crossing	Sign	Signal	TMS	Track circuits
Electrical	15	71	54	0	207	5	140
External	1	4	9	1	4	0	1
Mechanical	16	31	92	10	26	0	10
NFF	80	86	107	2	66	6	162
Non operative	55	290	84	2	51	4	118
Not defined	53	181	202	19	96	16	78

We can assume that one reason for the high number of WOs with a failure mode of “Non operative”, “NFF” and “Not defined” is the complexity of the system where the failure occurred. Other reasons can be related to environmental conditions or electromagnetic disturbances (EMC). For balise groups, a failure on a balise can have the same effect as a failure on the connection or the interlocking of the signalling systems.

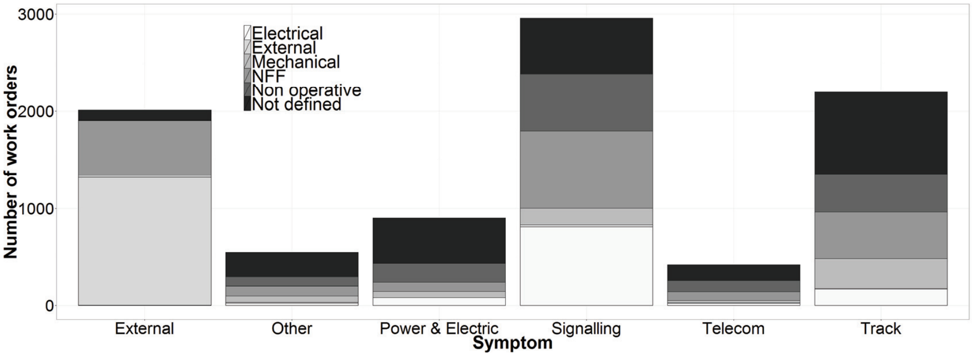

Figure 4: Real failure depending on the symptom.

Figure 4 shows the relationship between symptoms and real failures. Approximately 24% of the WOs where no failure was found and 27% of the WOs where it was not possible to define the failure were related to signalling systems. In particular for signalling systems, 66% of the WOs were related to “NFF”, “Non operative” or “Not defined” failure modes.

4 Discussion

In addition to our analysis of the databases used in information logistics, we carried out unstructured interviews with personnel involved in the processes to understand the actual state of affairs and to find areas of improvement. As a result of these interviews and our analysis of the data, we conclude that the Swedish infrastructure manager could make improvements in the following areas:

- In BIS, the relationships between the different systems are not visible; each item is described as independent. Seeing the interrelations between the installed systems would avoid interoperability problems when performing maintenance or changing the design.
- Integrating the management of the hardware and software would give a more integrated view of the system's configuration.
- Tools, software applications and procedures are used to diagnose and maintain the different railway systems. Since they are linked to the system architecture, linking information on the maintenance tools to information on the architecture would give a holistic perspective of the system's needs.
- Unifying the documentation repository would bring together the various requirements of the system, managing the access of information according to levels of access rights.
- Accessing reports on architecture modifications would clarify the reasons for modifications to the railway network. This knowledge could be transferred and applied elsewhere.

We suggest the following changes to ensure more efficient and effective information logistics:

- Improve the change control management process to allow analysis of changes chronologically on a specific component or on a railway corridor and the reasons for those changes.
- Enhance visibility of information related to different systems / subsystems / items to improve failure identification (and improve overall maintenance).
- Facilitate access to maintenance and diagnostics tools (e.g. hardware and software tools, manuals, procedures) to reduce downtime.
- Reduce dependency on the expertise of the personnel
- Transfer inter-organizational knowledge between stakeholders

Enhancing these areas would improve the configuration management process. At the same time, the time required to identify the failures from the data analysis should be reduced, for example, by creating a common database to unify information. The learning process and knowledge transfer are facilitated if information is easy to find.

The results of the data analysis show that signalling systems play an important role in corrective maintenance. Given the number of WOs related to these systems, it seems clear that improving their maintenance would lead to an overall improvement in railway maintenance.

Not having the proper data can lead to incorrect failure identification causing more time to spent on corrective maintenance actions; this, in turn, reduces system availability. The comparison of the number of WOs for each system and the real failures recorded indicates that more complex systems more frequently have no clear failure mode identified. Identifying failures in electronic based systems presents difficulties since aging is not directly visible (unlike mechanical fatigue). This can be seen in the high number of WOs with failure modes recorded as NFF, not defined or not operative failures, or failures where the failure mode is not identified; in such cases, either no action is taken or the component is replaced. These WOs require extra time on corrective maintenance because more time is spent trying to identify a failure (sometimes unsuccessfully); with better knowledge of the system, maintenance performance would improve. Hence, improving the knowledge of the system through enhanced information logistics is a must to diagnose failure and reduce the time spent on corrective maintenance.

A common database benefits management companies; with such a database, all stakeholders can share common information while certain data remain restricted to specific companies or to individuals within that company. A proper security system could manage accessibility to the system. For example, on a need to know basis, the operator manager could see the resources relevant for his/her specific needs

It is possible to develop solutions that control information while making it more easily accessed by those involved in signalling system maintenance and operation, such as the configuration management (CM) process. In addition, a configuration needs to be adapted to various stakeholders' processes (e.g. design, manufacturing, operation, and maintenance processes).

Even within the same management company, different users require different system information. In a well-structured and easily accessed configuration management process, the following can occur: maintenance managers can analyse corrective and predictive maintenance, identifying tendencies and suggesting management improvements; maintenance crews can easily obtain information and material needed to perform repairs, as the WOs are linked to the configuration of the infrastructure; logistics and supply managers can determine which devices are installed, which are being repaired and which are in stock; operation managers can receive information on problems in the railway operation and determine their cause and also perform simulations of how a change in the configuration of the signalling system can affect the availability of the line and improve the capacity of the railway network; quality and safety managers have easy access to the certificates of the devices and how to perform any action on the infrastructure, thereby reducing the time needed for a review or audit or to keep track of safety issues; project and process managers have complete visibility of the management numbers obtained from the Key Performance Indicators (KPIs) and, thus, know the real situation of the infrastructure and processes.

A good configuration management process provides better control of information and ensures better visibility. Information and knowledge management are improved by increased accessibility to information related to the system and any changes to it. In turn, better access to information allows faster and better diagnosis of failures, thus improving maintenance performance. The downtime of the railway network is reduced and maintainability is increased.

For optimal maintenance of a signalling system, it is necessary to keep track of the configuration of the various systems and where they are located. These configurations include not only the software and hardware of each subsystem, but also the interfaces between systems and where each device is located.

5 Conclusions

The purpose of this paper was to explore the use of information logistics for railway signalling systems to improve the efficiency of their corrective maintenance. It discusses the information logistics used by the current Swedish infrastructure manager for railway signalling systems, identifies weaknesses and suggests improvements.

A great deal of information is gathered by the various databases, but data suffer from a lack of visibility and the links between the different repositories are not well established. This leads to a dependency on the expertise of the personnel, an approach which is not beneficial in the long term.

The lack of proper data can lead to incorrect failure identification, which, in turn, means more time spent on corrective maintenance and lower system availability. Even when a failure is correctly identified, if the item is not repaired to assure interoperability with the rest of the systems, operation will not be possible.

It can be concluded that increased visibility of the information and reduced time to gather the required data needed for maintenance activities will improve the efficiency of corrective maintenance of railway signalling systems. This can be done by unifying the databases and improving the CM model. Some approaches to achieve this goal are the unification of databases and the improvement of the CM model. This paper presents how information logistics can improve the performance of the corrective maintenance, and states the basis of further research.

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Paper III

Dependability improvement through configuration management – A study of railway signalling systems

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Dependability improvement through configuration management – A study of railway signalling systems

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ABSTRACT

The reliability, maintainability and related maintenance support of signalling systems affect the railway network´s availability. Constituting a system-of-systems spread over a wide geographical area, signalling systems consist of a large number of items with different lifecycles making it a challenge to define and describe the structure and relationship between the system's inherent items at any specific time. System configuration describes a system's structure to which other data sources can be related. Some current research discusses asset maintenance management in the railway infrastructure, but not many holistic approach deals with signalling systems. The purpose of this paper is to investigate how the process of configuration management, can improve the dependability of the railway system. The paper presents a model for the configuration management of railway signalling systems. The model is based on the results of company surveys and interviews, data analysis and literature review. This model provides better control and visibility of the information related to the system and any changes made to it. Faster and better failure diagnostics can be performed, thus improving maintenance performance. This, in turn, provides better availability of the system by reducing the downtime of the railway network; hence, an improvement in maintainability is also achieved.

Keywords: Railway, Maintenance, Dependability, Maintenance support performance, Information logistics, Configuration management, Signalling systems, Capability Maturity Model Integrated, CMMI.

1. Introduction

A railway network is a complex system with several technologies working together to solve problems created by the increasing demands on capacity, speed and mobility for the transportation of goods and passengers. The Swedish rail network is approximately 12 000 km in length. About 4 000 km consist of double tracks, and 10 000 km are electrified [1]. The total amount of freight transport in the Swedish rail network for 2009 was 19,4 billion tonne-kilometres, and the passengers transport was 11,1 billion person-kilometres [2]. Clearly, the maintenance of the railway infrastructure is key to maximise its operation.

Systematic maintenance management of the railway assets must consider the short-term cost and performance demands and guarantee the Reliability, Availability, Maintainability and Safety (RAMS) in the long run [3]. The dependability of a system describes the availability performance of the system and the various factors influencing it, including reliability performance, maintainability performance and maintenance support performance [4]. Maintenance and maintenance support provision is one of the main prerequisites to ensure dependability of systems throughout their life cycle [5]. Railway infrastructure managers need maintenance analysis and planning tools that will enable them to systematically analyse and optimise budget needs, minimise the total costs for the required RAMS level, and guarantee the ongoing quality of the railway assets [6]. The first step in maintenance management is to establish a complete asset register that links infrastructure quality measurements, maintenance work history and transport data (tonnage) with a specific asset and its location [6].

During the operation and maintenance of the railway infrastructure, many data are collected and managed. Data sources include the system architecture, maintenance reports, work orders performed, etc. The managers responsible for determining maintenance actions usually face an abundance of data and have a complicated task transforming these data into information to support maintenance actions [7]. Poorly processed data lead to incomplete information and misinterpretations. To get a holistic picture of where failures are located and the dominant factors causing those [8], infrastructure managers should know the parameters which must be measured; often this is not the case. In addition, different information and systems should be linked with each other so that more detailed information is available in less time [8]. This data fusion is important when dealing with railway signalling systems. Maintenance should ensure both the operation of the different items and their interoperability.

A railway signalling system can be defined as a System-of-Systems (SoS). A SoS is composed of a number of different systems; each has its own purpose, but the main function is interoperability of the different systems [9,10,11]. Signalling systems are challenging to model, given the amount of information derived from both software (SW) and hardware (HW) in the various locations of the systems' many devices. Since signalling systems ensure the safe operation of the railway network, their reliability and maintainability directly affect the capacity and availability of the railway network, in terms of both infrastructure and trains. For efficient maintenance, it is necessary to keep track of the configuration of the different systems and where they are allocated. These configurations must consider not only the software and hardware of each subsystem, but also the interfaces between systems and where each device is located.

Since a SoS can be understood as a set of system capabilities which together deliver a combined capability, performing maintenance on an SoS creates challenges not usually found in a system. As the correct operation of each separate system does not ensure the operability of the whole SoS, interoperability is key, and the configurations of the different items must be compatible. It is necessary to know which items constitute the signalling system and how they are affected by any changes. Managing configuration information in such a heterogeneous context is complex and requires specifying a process [9].

Many research woks have been undertaken to improve the maintenance of railway signalling systems (e.g. Availability analysis [12,13,14]; Reliability analysis [15,16,17]; RAM performance [16,17]; Life cycle cost [12,20]; Risk evaluation [21]; Electromagnetic compatibility (EMC) [22,23]; Dependability optimisation [24]; Condition-based maintenance [25]; etc.), but no research has been found on the improvement of the maintenance of the railway by enhancing CM of signalling systems.

The purpose of this paper is to investigate how the process of configuration management (CM), related to the railway signalling system, can improve the dependability of the railway system. It proposes a model for the CM process based on company surveys and interviews, data analysis and a literature review. This model can provide better control and visibility of the information related to the system and any changes made to it. This, in turn, can provide a better availability of the system by reducing the downtime; and thus an improvement in maintainability can also be achieved.

2. Maintenance support performance

Conducting effective and efficient maintenance requires accurate information and appropriate information provisioning. Excessive data can cause problems in decision making due to the inability to find the right information [26]. In addition, information islands hamper the integration of the information related to a system [27]. Prevention of data overload and integration of the maintenance-related information from the various sources can avoid these problems [28]. Efficient maintenance depends on the availability of necessary information services, at the right time, with the right quality and for the right stakeholders [26,27]. Insufficient or inadequate maintenance support information leads to the No Fault Found (NFF) phenomenon [30].

Extensive application of Information and Communication Technology (ICT) and other emerging technologies facilitates easy and effective collection of data and information [31]. eMaintenance connects all the stakeholders (e.g. manufacturers, infrastructure managers, operators, etc.), integrates their requirements and facilitates effective decision making in maintenance performance. For eMaintenance to be implemented on complex systems, a number of their characteristics must be considered, such as their complex configurations, due to a large number of heterogeneous items, multiple simultaneous life cycle processes, large numbers of functions, and large numbers of versions and editions of the system, among others. These characteristics create complexity in managing designs and modifications and estimating item reliability and criticality throughout the system's life cycle [26]. CM based on eMaintenance can solve this complexity.

3. Configuration management on maintenance of railway signalling systems

CM is defined as the process of identifying and documenting the characteristics of a facility's structures, systems and components (including computer systems and software), and of ensuring that changes to these characteristics are properly developed, assessed, approved, issued, implemented, verified, recorded and incorporated into the facility documentation [25]. CM is included in railway standards as well. The standard EN 50126 [32] defines the process of CM as the discipline that, applying technical and administrative direction and surveillance, identifies and documents the functional and physical characteristics of a configuration item, as well as the control of and change to those characteristics, records and reports change, processing and implementation status, and verifies compliance with specified requirements.

The railway standard EN 50126 [32] also defines and establishes the relationship between RAMS and CM. It defines RAMS in terms of reliability, availability, maintainability and safety and their interaction, and it defines a process, based on the system lifecycle and tasks within it to manage RAMS. It also establishes certain mandatory requirements. One is to establish and implement adequate and effective configuration management, addressing RAMS tasks within all lifecycle phases [32].

The scope of the configuration management depends on the system under consideration, but it normally includes all system documentation and all other system deliverables. In the design phases, the main focus is on design changes and improvements to validate the final solution; during the operation and maintenance phase, CM seeks to make the entire system transparent and maintain the interoperability between the different parts. Tracing changes in the installed equipment is also important, as it allows managers to oversee the state of the items (e. g. how many devices are undergoing repair).

The CM process can be set up or improved with various approaches such as Software Process Improvement (SPICE), Capability Maturity Model Integrated (CMMI), Six Sigma, Total Quality Management (TQM), etc. Some are general methods to improve processes (Six Sigma), others focus on software management (SPICE), and still others establish a model but not the specific process (CMMI). The CM of signalling systems must take into account the configuration management of both software and hardware in the same model.

The configuration needs to be managed and adapted to the various stakeholders' processes (e.g. design, manufacturing, operation, and maintenance processes). The infrastructure manager must ensure that the entire network fulfils all their requirements (e.g. safety, functionality, and non-functionality). This requires good control of the information and any changes to the configuration of the network [33]. When used for signalling systems, a CM process should make information more accessible to and easily controlled by those involved in maintenance and operation.

4. Research methodology

The proposed CM process is based on the results of company surveys together with a data analysis of the corrective maintenance performed by the Infrastructure Manager. A schema of the methodology is shown in Figure 1. In addition, a literature review examined the current status of research and the different possible approaches. Based on the results of the literature review, the data analysis, and company surveys, a model is proposed to improve the weak points in information logistics and configuration management of railway signalling systems.

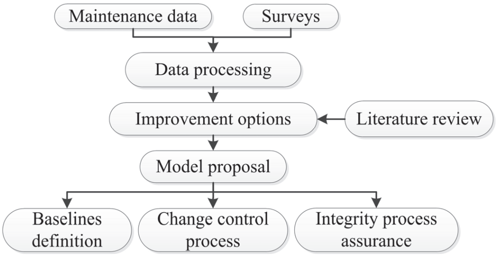

Figure 1. Research methodology

The various stakeholders in the CM process were interviewed to establish their needs. Stakeholders included system engineers, maintenance managers, maintenance personnel, quality and RAMS managers, project managers. The approach depended on the availability of those interviewed; most were interviewed personally, but some were interviewed by email and phone. Once the information was gathered, collective meetings were held to discuss how to combine the various needs and opinions. During the generation of the model, periodic meetings were scheduled to ensure that all requirements were taken into account.

5. Case study

This research focuses on tangible items related to maintenance of railway signalling systems. Maintenance support performance can be improved by applying CM to the item's structure or to the organisation providing maintenance [24]. The former comprises the items that are part of the system; the latter defines the structure of the human resources required to perform the maintenance. Human resources depend on the needs of the system and on the company's budget and policy. Thus, external factors will give a certain independency to the results, apart from the system itself.

This study draws on company surveys by the Swedish Infrastructure Manager (Trafikverket) and data analysis of the corrective maintenance work orders on the Swedish iron ore line for the last 10 years. Other studies have pointed out the relevance of signalling systems and failure identification on railway maintenance on the Swedish railway network [34,35,36]. The focus of this research is to study how to improve the current CM model of Trafikverket for the railway infrastructure.

The implementation of the model is based on the architecture of the railway infrastructure implemented in Sweden [2]. Two main systems of control and supervision can be found: Automatic Train Control (ATC) and European Railway Train Management System (ERTMS), thus the requirements and particular solution will vary depending on the solution installed on each railway corridor. The signalling system is composed by the following subsystems:

- Interlocking (IXL) / Radio Block Centre (RBC): receive the input from the different systems (e.g. track circuits, level crossings, signals, TMS), calculate and returns as an output the train operation restrictions to ensure a safe traffic operation.
- Track circuits: responsible of the train location.
- Balise group: input from the track to the onboard signalling system (e.g. speed limits, driving mode, etc.).
- Level crossings: coordinate the road traffic when crossing the railroad.
- Traffic management system (TMS): interface between the traffic operator and the railway network.
- Signals: give or restrict permission to the train on coming into a track section.
- Signalling boards: Inform the train on fixed information (e.g. tunnels, bridges, speed restriction area, etc.).

The architecture of the whole railway infrastructure is managed by a software tool (BIS) which allows us to see which items compose a section of the railroad (signalling, power supply, track components, etc.) [37]. The specific location of each item is defined, together with the model and serial number.

By analysing the work orders related to corrective maintenance actions, it is possible to identify the weak points of the system and determine how they can be improved. An analysis of the corrective maintenance data shows that signalling systems play an important role in corrective maintenance. Thus, improving their maintenance would improve overall maintenance. An important part of the failure causes on record were NFF or could not identify the failure. Both require extra time in corrective maintenance and can be avoided with better knowledge of the system. An enhancement of the CM would assist the signaling systems to increase the efficacy of the maintenance actions. This occurs by improving the accessibility of the necessary information for the understanding of further possible failures, hence increased knowledge and the time needed to identify failures is reduced, resulting in a higher efficiency for the maintenance action. Hence, our research will focus on the improvement of the following areas:

- Change control management: to be possible to analyse the changes chronologically on a specific component or on a railway corridor and the reasons for that changes.
- Visibility of the information related to different systems / subsystems / items, in order to improve failure identification (which will improve the overall maintenance).
- Facilitate the access of the maintenance and diagnostics tools (e.g. hardware and software tools, manuals, procedures) to reduce the downtime.
- Reduce the dependency on the expertise of the personnel

On the next section, a literature review is performed to identify the different possible solutions to improve the CM process on signalling systems.

6. Methodologies for CM

Even though most of the signalling systems existing research studies do not focus on CM, some results may be applicable to the present study. Kitahara et al. [38] proposed a method to perform CM on the maintenance of the railway software, but did not consider the hardware. Kelly and McDermid [39] designed a change control management process for safety during maintenance; their case study from the aviation sector can be applied to the railway sector. Di Tommaso et al. [40] proposed a methodology to perform hazard analysis of complex distributed railway systems. Drawing on survey findings, De Souza et al. [41] discussed the documentation required for the maintenance of software based.

Turner and Jain [42] studied differences between process management approaches, such as the differences between the Agile approach and the CMMI model for software management. Dayan and Evans [43] noted the similarities between the CMMI model approach and Knowledge Management (KM). Sutherland [44] discussed how to combine software management's Agile and CMMI approaches. SEI has published some studies comparing the CMMI model with other approaches to process improvement, such as how to combine CMMI with Six Sigma [45] and why CMMI should not be combined with Agile [46].

Some results of using the CM process on an SoS have been published. Gorod et al. [9] described the challenges of managing a SoS compared to a normal system, including CM. Bellomo and Smith II [7] listed the challenges of performing a CM process on a SoS.

Fonseca and De Ameida Jr. [47] proposed a process following the CMMI model based on the CENELEC standards. Jansson [48] studied the implementation of the CMMI model to maintain software. CMMI documents have described a CM process divided into goals and tasks [49]. A survey to determine which tools were used by companies to apply the CM process found that tools are chosen based on the requirements of the system. Ren [50] evaluated CM tools for software, including CVS, Firefly, ClearCase and others. The appropriate tool for our model will be determined by the infrastructure manager depending on needs and priorities.

After studying the different possibilities, we concluded CMMI is a good approach to solving the challenges of signalling systems. CMMI is a framework that helps organizations to improve their processes [51]. It was generated from previous models, including software management models (such as the CMM model); it includes processes of software and hardware management, making it a good choice to perform CM in signalling systems. CMMI is a model, not a rigid method; hence, it allows the model to be adapted to the requirements of the system. Other methods like KM or Six Sigma are more focused on process improvement, but they can be combined with CMMI to improve processes. The Agile method specialises in software management; it cannot manage both hardware and software.

7. The CMMI model for configuration management

The CM process should be able to perform the following tasks [49]:

- identify the configuration of the items selected in the system to control at either periodic or punctual points in time, depending on the system configuration;
- distribute periodic reports of the state of the processes and changes performed to provide information on the real status of the system to the different managers and end users;
- track the changes and modifications of both configuration and processes;
- ensure the integrity of the configuration baselines and determine whether they reflect the real installation configuration status.

The CMMI defines specific practices and sub practices for the model's process. The sub practices include identifying the configuration items, establishing a CM system and creating or releasing baselines [49] (CMMI product team, 2010). Successful implementation of the CM process is the result of combining efforts and resources: people must be correctly trained and motivated, they must have the tools and equipment to gain access to the information and they must know the procedures to use. These are called the three critical dimensions [49](CMMI product team, 2010).

8. The model

This research produced a model for the CM process for railway signalling systems. The required information was identified; this included procedures and manuals, mechanical drawings and electrical schemas, software files, hardware serial numbers, etc. Which information was not needed, e.g. fasteners, cables and internal documentation, was also determined. The links between the information were defined.

A description of the tasks and how they are applied in the configuration management process of a signalling system maintenance is given below, based on the requirements of the signalling system maintenance management and applying the CMMI model to improve the CM process. The configuration items that conform to the baselines are identified and described. Different baselines are created for different data. The interactions between baselines are also defined. The process to perform a change in the configuration is proposed, together with the review process to ensure the integrity of the configuration. Applying these practices will ensure the implementation of the CM process.

8.1. Establish baselines

A baseline is the configuration of the system at a fixed point in time; the configuration will be the reference for controlling any changes performed on the system. A baseline describes what items are part of the system and their status; it provides documentation for and information on the real state of the system at that point of time. The concept of baseline could be explained as a picture of the system taken at a particular time. Baselines describe the status of a determined system at a fixed point in time; they serve as a reference for tracking changes (such replacement of items due to failure) on that system. They can also be determined for a particular item and show the changes performed on it during a specific time.

Baselines are needed to identify the configuration items that are part of the system. The configuration items are the required information that defines the system (e.g. HW, SW, location where the devices are installed, manuals, electrical schemas, mechanical drawings, etc.). Each item (i.e., piece of information) is placed on the related baseline and is assigned the properties that will allow us to determine the relations between it and the rest of the items (information in the database)

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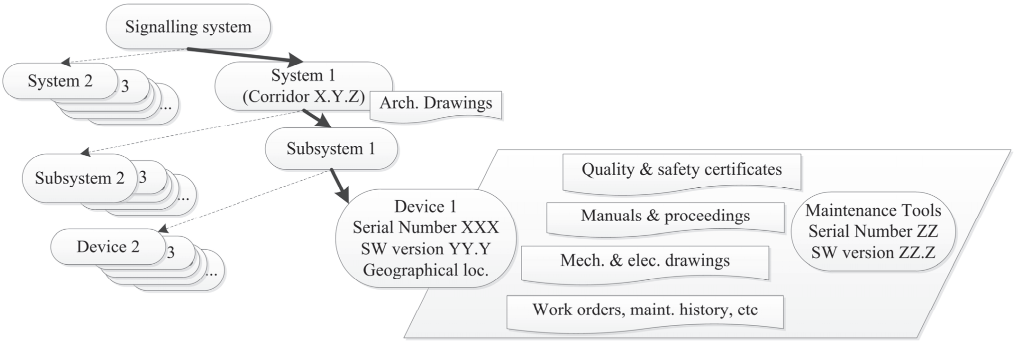

Figure 2. System baseline architecture.

To provide a unified database that is useful to the stakeholders, the needs of the stakeholders have to be taken into account to determine which system characteristics should be controlled and uploaded into the various baselines of configuration, (e.g. models of the devices, tools, software documentation, etc.). Note that some documentation may not require uploading onto the database, including internal notes or certain proceedings that are not relevant.

The information of each item (e.g. SW and HW version, certificates, manuals, corrective maintenance performed on it, etc.) is linked to the systems, subsystems and components related to it, in a parent-child relationship. This enables to control of the individual items and also their interoperability. An overview of the structure of the system baseline is shown in Figure 2.

In the case of the different items that are part of signalling systems, there are varying levels of detail. Therefore, it is important to decide the minimum level of detail that the installed configuration baseline must achieve and which items will not be covered. Items like generic cables or fasteners do not have serial numbers, making it difficult to control where they are placed. They are also easy to replace (not reparable). Modern signalling systems are based on modularity and line-replaceable units (LRU) to make maintenance operations easier and increase availability. The modules can be replaced quickly in case of failure to restore the system to service while the failed module is brought to the maintenance facility to be repaired. This procedure increases availability by reducing downtime. The model proposed here takes the LRUs as the minimum level to control in the configuration baselines.

A CM process needs to control the information involved in the system´s maintenance. Different baselines can be described depending on the configuration items considered. The documentation baseline gathers all data compiled on documentation, such as procedures, mechanical drawings, certificates, etc. The system design baseline makes the structure of a system visible and indicates the models of the different subsystems and devices, together with the software that configures a specific signalling system. From the design structure, the installation baseline specifies what is found in the real installation, indicating not only the model and software of each device but also its serial number and where is it located in the installation. It can also specify if a device is not installed but is in stock or in the maintenance workshop. This baseline helps managers keep track of all installed items and make estimations of availability and maintainability.

Depending on the desired level of detail, more baselines can be added. For maintenance purposes, the baselines of corrective and preventive maintenance are required to control the actions performed on the different components of the railway network. A requirements baseline identifies the needs of the railway network for good operation and links them with the actions that are needed to meet these requirements. Other baselines can be generated depending on the needs of the system.

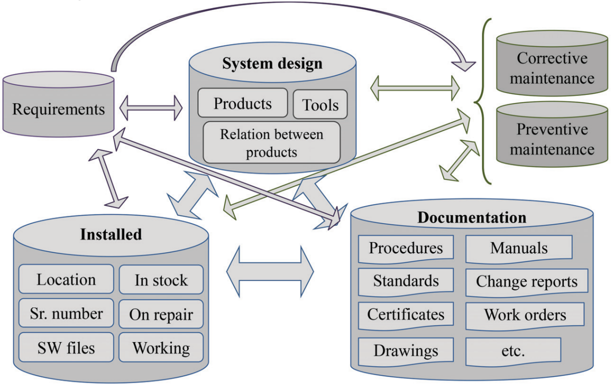

Figure 3. System configuration baselines.

Each configuration item has related information in the different baselines. The whole makes visible all the information related to the item (e.g. location, software and hardware, documentation, maintenance performed, etc.). The proposed baselines and their relationship are shown in Figure 3.

8.2. Change control management

A change can be the consequence of a deviation between the function required and the one delivered. A modification can be caused by a maintenance action (e. g. an item is replaced due to failure) or by an update of the design of the system (e. g. an upgrade of the software). Depending on the cause of the change, the needed change actions may be managed and processed in different ways. In the case where the failure of an item is identified, the item may need to be replaced or repaired. In this case, the change is managed as a work order and the change made is the repair or replacement of the failed device. A change can also be the result of a modification in the design, such as an update in software or new equipment. The procedure defined here allows us to consider both repair and a design modification, since the consequence of both is a change in the system. Depending on the reason, the change will be classified as maintenance or design change in the datasheet.

The change control management process includes the steps from the identification of the reason for the work order to the closure of the request. The action performed is described in the change request report. Figure 4 shows a diagram of the process. Any failure identification should generate a change request. When a failure is identified by any person involved in the operation or maintenance of the railway line where the signalling system is located, the maintenance manager is notified of the failure.

Once a change request is generated, the failure is analysed along with the possible solutions; this is checked by the maintenance manager who consolidates a definitive version of the report; the change request is distributed to the personnel affected by the change, always including the person responsible for the quality and RAMS departments. The safety manager is responsible for pointing out if the change affects safety; in this case, the change must be approved by the safety department

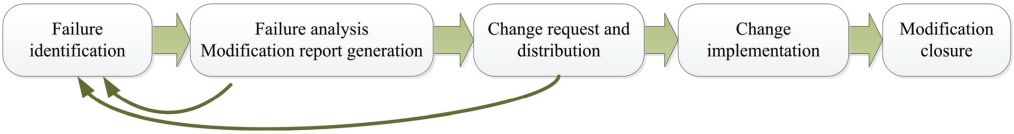

Figure 4. Change control management process.

The change request is reviewed by all personnel affected by the change, safety effects are studied, and the change request is registered on the change control datasheet. Corrective maintenance actions and design changes are identified differently. The change request should annex any evidence required to prove that the requested change was made and should check for non-regression (i.e., the change does not affect functionality and fulfils all requirements for operation).

The configuration manager should be informed of the implementation status of the change in order to perform follow up. The maintenance manager is responsible for closing the change request when all tasks have been performed and all evidence has been collected. Any change in the system should be reflected in the configuration database and linked to the change request, work orders, and evidence of the change performed.

8.3. Establish integrity

One of the goals of a configuration review is to check that the configuration database reflects the reality of the installation and is consistent with the changes performed during the operation of the signalling system.

The configuration should be reviewed before a new version of a baseline is created. The elements controlled in the configuration database should be verified, and all modifications and changes registered in the change datasheet should be implemented in the baselines.

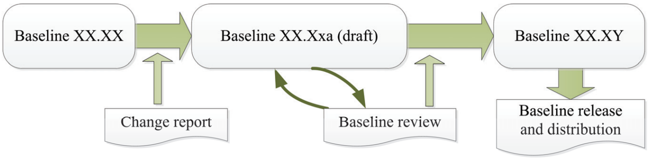

Figure 5. Integrity process assurance.

An overview of the review process is given in Figure 5. A change report identifies the need for a modification of the active baseline. The baseline is then modified to implement the change, creating a draft. This draft is reviewed by the personnel affected by the change to assure the update of the baseline is consistent with the real modification. If a gap is identified, a new draft version will be generated and sent to review, until the baseline reflects the real state of the railway network. Once the integrity of the baseline is assured, the definitive version of the baseline will be released and distributed.

A design baseline configuration review ensures that the design of the system is the same as that implemented in the railway network, checking, e.g., the hardware and software of the different devices. An installed baseline configuration review determines whether the devices (serial numbers) included in the configuration are installed in the location where the configuration database indicates. A documentation baseline review checks that all documents regarding the configuration are linked to each item of the configuration and that they are updated to include the most recent version.

A review of the configuration has the goal of verifying that an element or group of elements of a configuration which constitutes a baseline fulfils the system requirements and is consistent with the real configuration of the signalling system installed in the railway network. These reviews concern all personnel affected by the change requests involved in changes to the baseline, as well the maintenance, configuration, quality and safety managers.

After each review, the configuration manager publishes a report on the state of the configuration database and the changes performed. This is important as it renders visible the real status of the system and any changes that have been made.

Table 1. System design baseline

Subsystem	Component
IXL / RBC	Control & supervision
	Power supply
	Transmission
	Manoeuvre equipment
	IXL / RBC SW
	SW update tool for IXL / RBC
	Testing tool for IXL / RBC
Track circuit	Resistance
	Chocke coil
	Joint isolations
	Cable
	Battery
	Safety relay
	Cable connectors
	Rail
Balise group	Balise
	Cable
	Connectors
	Fasteners
	Generic SW for balise
	SW update tool for balise
	Testing tool for balise
Level crossing	Manoeuvre equipment
	Control and supervision
	Transmission
	Power supply
	Understructure & Overstructure
	Gateway
	Bean
	Signal & Sign
	Level crossing SW
	SW update tool for level crossing
	Testing tool for level crossing
TMS	Central system
	Power supply
	Transmission
	Understation
	Working station
	TMS SW
	SW update tool for TMS
	Testing tool for TMS
Signal	Lamp
	Cable
	Connectors
	Pole & Base
Sign	Sign
	Pole & Base
	Fasteners & Grounding

9. Results

Table 1 shows the system design baseline. Every design solution will be described as part of different systems (e.g. different design baselines depending on if the control system is ATC or ERTMS, or the SW version that is implemented). The different subsystems and their components are identified and listed. The SW for the different subsystems and the tools for testing and uploading SW are included in the baseline since they are linked to the system. This integrates all the information of a specific design, thus facilitating change control management.

The installation baseline describes how the design baseline is implemented in the different corridors, e.g. the number of systems and subsystems and where are they located, the specific SW to answer the requirements that depend on external parameters (e.g. speed limitations to the train on the balise groups), and finally the status of the components associated to a particular system (if the component is in operation, on repair or in stock) (see Table 2). This information will be needed to manage the components that can affect the interoperability. On the contrary, the components of the systems which are replaceable and standardized: (e.g. fasteners, connectors, cables, etc.) are not necessary to control on the baseline.

Table 2. Installation baseline

Parameters	Values
Location	(Corridor, section, etc.)
Serial Number	(Part number of the SW and HW)
SW files	Generic files
	Specific files
Operative status	Working / On repair / In stock

The documentation baseline gathers all the information that corresponds to the different systems; subsystems and components (see Table 3). Standards and specifications gather the requirements to accomplish, procedures and drawings give information of the installation and maintenance, the reports show the historical data of every component and help to analyse possible improvements. To include the certificates in the same baseline simplifies the number of databases to maintain, since it is information related to the system that some stakeholders may need (e.g. quality, RAMS, etc.).

Table 3. Documentation baseline

List of documents
Installation procedure
Corrective maintenance procedures
Inspection procedure (preventive maintenance)
SW update manual
Testing manual
Mechanical drawings
Electrical schemas
Quality
ISA (independent safety assurance) certificate
EMC (electromagnetic compatibility)
RAMS (CENELEC 50126, 50128, 50129)
EMC (electromagnetic compatibility)
ERTMS specification (UNISIG SUBSETS)
GSM-R specification EIRENE / MORANE
Functional Interface Specification (FIS)
Form Fit and Functional Interface Specification (FFFIS)
Operational requirements (Trafikverket)
Change report
Inspection report
Corrective maintenance work orders

The CM proposed simplifies the number of databases to manage. It integrates the different type of information for each system / subsystem / component; hence it simplifies the access to the correct information and improves change control management process.

10. Discussion

Implementing the process of CM following the premises of the CMMI model which has both benefits and drawbacks. Open interviews were performed with different personnel involved in signalling systems development, maintenance and operation performance to identify them. The personnel interviewed worked on different departments such as engineering, RAMS, quality, processes and maintenance performance. Table 4 summarizes these benefits and drawbacks.

10.1. Benefits

The proposed CM model provides a common vision of the different products and processes, making it easier to identify common factors that affect the availability or maintainability of the system and decreasing the time needed to gather all the information. A unified information database for the different stakeholders provides better visibility of the system for all stakeholders, along with easier traceability of any change performed. Failure identification is faster, since there is better knowledge of the system as a whole and there is a direct access to the material and information needed to perform any maintenance action (e.g. manuals, tools needed, software, etc.). For these reasons, the time consumed in corrective maintenance is reduced.

In addition, the cost of staffing the infrastructure is reduced due to the unification of the information in one database. Because the cloud is used to manage information, equipment and a location to store information are no longer required, and maintenance resources are included in the costs of the cloud.

From a management point of view, changes are more visible, and it is easy to trace where, when and why a change has been made. This allows the simulation of possible modifications to improve the availability and maintainability of the railway line and reduce costs before any real change is implemented.

Finally, there is a better return on investment due to the reduction of costs dedicated to managing the different information databases, gathering data for each task and controlling the supplies. Better control of the system and processes gives better quality and decreases failure rate (better identification, diagnosis and prognosis of failures). The result is increased capacity and better customer satisfaction.

Table 4. Pros and Cons of the new CM process

PROS	
Unified information database	The new CM process provides a common vision of the different products and processes. The CM process based on the CMMI model can manage the database in a structured way The process stores data from different sources and locations in a unified database The database can be placed on a server and be accessed remotely. Processes are standardized and do not depend on the experience of the workers.
Ensure traceability of changes	Traceability is ensured: changes are more visible, and it is easy to trace where, when and why a change has been made. CM provides better control of supplies and change control management. Better control of the system and processes gives better quality and decreases failure rate (better identification, diagnosis and prognosis of failures).
Cost reduction	Less time is needed to gather all the information. Return on investment is increased due to the reduction of costs dedicated to managing the different information databases.
Increase productivity	Productivity is increased (less time dedicated to identifying, finding and gathering the equipment needed), Downtime due to repair is decreased (those performing the work order will have all necessary information). The result is improved maintenance performance, increased capacity and better customer satisfaction.
Easier failure identification	All information of the systems and the maintenance equipment is linked to the different failure identifications and work orders.
CONS	
Personnel has to be involved	The personnel need to be involved in the development and implementation of the CM process. Implementing the model will require extra effort until the process is fully implemented. The improvements will not be visible until the process is fully implemented.
Interpretative model	CMMI model establishes guidelines to be followed; it does not specify an exact procedure. The model will be interpreted differently depending on the person developing it. The final users should be involved in the interpretation process so that all needs and requirements are covered
Compromise solution	The process can become extremely complicated, and the effort required can be disproportionate to the benefits expected. The main goal is not to create something new, but to improve the processes of the company in order to improve performance.

10.2. Drawbacks

There are some drawbacks to implementing the CMMI model for CM process. It is challenging to create a useful CM process; the personnel involved in the different areas related to signalling systems (RAMS, quality, management, engineering, etc.) must be involved in the development of the process. The model can have different possible interpretations, so surveys are required to ensure that the best CM process is performed and to determine what modifications are needed to adapt to the real requirements of signalling systems.

While the CMMI model establishes guidelines, it does not specify an exact procedure. This implies that the model will be interpreted differently depending on the person developing it.

Finally, depending on the accuracy of the interpretation of the CMMI requirements, the process can become extremely complicated, and the effort required can be disproportionate to the benefits expected. To avoid this and achieve maximum benefits, it may be useful to adapt the requirements of the CMMI model to the needs of the company where the process is applied (in the case of the signalling systems, this involves the infrastructure manager). It is essential to remember that the goal is not to create something new, but to improve the processes of the company in order to improve performance.

11. Conclusions

The purpose of this paper was to investigate how the process of CM, can improve the dependability of the railway system. The lack of proper data can lead to an increase in failure identification time in corrective maintenance actions which, in turn, leads to lower availability of the system. Even when a failure is well identified, if its interoperability with the rest of the system is not assured during the repair, the system will not be operable. Hence, a CM process is essential for the railway signalling system.

This paper proposes a solution based on adapting the CMMI model to meet the requirements of signalling systems. The goal is to create a tool that makes the accessibility of information and its control easier for all those involved with signalling system maintenance and operation. This model can be applied to the whole railway system, for both trains and infrastructure, since the challenges of the model are the similar.

Finally, the proposed CM model provides better control and visibility of information. Information and knowledge management can be improved by better accessibility to the information related to the system and any change performed on it. With better access to information, a faster and better diagnosis of failures can be performed, thus improving maintenance performance. This provides better availability of the system due to reduced downtime of the railway network. Hence, an improvement in maintainability is also achieved.

Further work could be oriented towards the quantification of the effects of the improvements of CM on the dependability of railway signalling systems. Surveys and data analysis of the corrective maintenance performance could validate and quantify the results obtained in this paper.

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Paper IV

Knowledge management in a railway network: The case of signalling systems

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Knowledge management in a railway network: The case of signalling systems

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Abstract

The railway network is a complex system with several technologies and a multitude of stakeholders working together to solve problems created by the increasing demands on capacity, speed and mobility for the transportation of goods and passengers. However, the presence of many different stakeholders complicates knowledge management and transfer. The purpose of this paper is to analyse the potential for improving inter-organisational knowledge management in the maintenance of railway signalling systems and make concrete suggestions for improvements. Even if information logistics processes can disseminate explicit knowledge on the maintenance of railway signalling systems, they cannot handle the tacit knowledge transfer that often is crucial. The study finds considerable potential for improving the knowledge management process. It suggests possible measures and makes suggestions for future studies.

Keywords: Railway, signalling systems, maintenance, knowledge management, inter-organisational learning, knowledge transfer, know-how.

1 Introduction

The Swedish Transport Administration's total budget is SEK 51.9 billion; on which the major investments have primarily been made in the railway system [1]. The traffic volume for passengers on the public railways amounted to 97 million train kilometres in 2012; the traffic volume for railway goods transport flows on state-owned tracks amounted to 42.9 million train kilometres and volumes for rail transport were 21.0 billion tonne kilometres in 2012 [1].

Sweden has a deregulated railway network system, and approximately 20 companies use the Swedish state's rail infrastructure [2]. The maintenance of the railway network (rolling stock and infrastructure) is also managed by many different companies. The Swedish Transport Administration (Trafikverket) is responsible for making investments in the railway infrastructure and maintaining it, as well as forming the long-term national transport policy [2]. Therefore, in this paper, Trafikverket is referred to as both infrastructure manager and transport administrator.

During the operation and maintenance of the railway infrastructure, lots of data are collected and managed in an attempt to control and analyse the current state of the system. Data include the system architecture, maintenance reports, work orders performed, etc. The railway can be divided into different systems depending on functionality, such as the rolling stock, the track, the power supply, the signalling system, etc. [3]. Signalling systems play an important role in the control, supervision and protection of rail traffic and their availability affects the performance of the whole system. A signalling system is a complex combination of software and hardware; the maintenance manager must understand how changes will affect the system, how the system is built, what role the different parts play and how they are interconnected. If up-to-date documentation is lacking, maintainers have serious problems [4]. The complexity of signalling systems makes knowledge management a necessity to ensure proper performance in all phases of the life cycle.

Signalling systems supervise and control the railway operation with different technologies installed both in the infrastructure along the track and in the rolling stock. To be able to operate on a specific railway corridor, a train requires the same signalling system that is in the infrastructure. Therefore, state companies such as Transitio or Rikstrafiken (via ASJ) provide operators with the necessary rolling stock [2]. In the maintenance area, the train records can help identify failures, since they record information received from the infrastructure. Clearly, sharing knowledge between all railway stakeholders in both the operation and maintenance of signalling systems is crucial.

Railway managers must have a holistic view of the railway systems (particularly signalling systems due to their need to be interoperable) to optimise maintenance. The managers responsible for determining maintenance actions face an abundance of data and have a complicated task transforming this data into information that will support maintenance actions [5]. In addition, confusing data/remarks in the databases often lead to misinterpretations. Structured databases containing the complete information are required to identify where failures are located and the dominant factors causing them [6]. Without well-functioning maintenance, the railway infrastructure would quickly lose its efficiency.

Maintenance support performance can be improved by considering the item structure and/or the organisation providing maintenance [7]. However, an information logistics system does not ensure that the proper personnel will acquire the knowledge, or that the know-how will be stored and transferred. To address this issue, this study focuses on the organisational structure of railway maintenance and operation.

The presence of many different stakeholders running the maintenance and operation of the railway network calls for a functioning knowledge transfer between them if the desired results are to be achieved. Each stakeholder has different knowledge access and needs. However, all stakeholders work on the railway systems, and knowledge transfer between departments and the dissemination of best practices can benefit everyone. Iacono et al.[8] explored the relationship between the design of inter-organisational connections, processes of knowledge creation and transfer, and innovation in a medium-large Italian company in the rail industry sector and compared these to a research consortium. The found that better efficiency of maintenance activities can be achieved by taking advantage of the available maintenance knowledge, thus contributing to time and costs savings [9].

When outsourcing maintenance activities, there is a risk of losing the knowledge of how to perform these activities [10,11]. This can be a problem if an out-sourced company lacks the required knowledge. It can also pose difficulties when changes or improvements in a system's design lead to changes in the maintenance. Knowledge transfer among people doing the outsourcing is not as direct as among people belonging to the same company. And while explicit knowledge transfer can be ensured by codifying knowledge, tacit knowledge is more difficult to transfer. Hence, the need to provide new procedures for knowledge transfer between companies.

The purpose of this paper is to analyse the potential for improving inter-organisational knowledge management in the maintenance of railway signalling systems and make concrete suggestions for improvements. It identifies areas of improvement in the railway signalling systems' maintenance performance, and discusses how different theories of inter-organisational knowledge management can be applied to improve the maintenance and operation of the railway network, by looking at particular signalling systems.

2 Railway signalling systems

The research is based on the architecture of the railway infrastructure implemented in Sweden [15]. The two main systems of control and supervision are: ATC (Automatic Train Control) and ERTMS (European Railway Train Management System). Previous studies have pointed out the relevance of signalling systems and failure identification in maintenance performed on the Swedish railway network [12,13,14]. The signalling system is composed of the following sub-systems:

- Interlocking (IXL) / Radio Block Centre (RBC): receives input from the different systems (e.g. track circuits, level crossings, signals, TMS), calculates and returns as an output the train operation restrictions to ensure safe traffic operation.
- Track circuits: responsible for the train location.

- Balise group: input from the track to the onboard signalling system (e.g. speed limits, driving mode, etc.).
- Level crossings: coordinate the road traffic crossing the railroad.
- Traffic management system (TMS): interface between the traffic operator and the railway network.
- Signals: give or restrict permission to the train to enter a track section.
- Signalling boards: inform the train of fixed information (e.g. tunnels, bridges, speed restriction area, etc.).

3 Railway stakeholders

Different stakeholders can be present during the operation and maintenance of the railway infrastructure, depending on the policies of the country. An example of these stakeholders is given in this section, using the Swedish railway system. Different information needs can be identified, depending on the work performed (e. g. operation management, corrective or preventive maintenance, RAMS (reliability, availability, maintainability and safety) studies, safety management, etc.); in addition, different companies are involved in the process, and each will have its own needs:

- Infrastructure manager: owns the public transport infrastructure and is responsible for its maintenance; also responsible for the transport planning infrastructure.
- Operators: responsible for train operation (passengers and freight).
- Maintenance companies: subcontracted to perform the maintenance on the train or the infrastructure
- Railway manufacturers: design and produce railway systems (rolling stock, infrastructure, signalling systems, etc.) depending on the requirements of the customer; customers include Swedish infrastructure manager, operators, maintenance companies or other manufacturers.
- Consultancy companies: perform regular studies to analyse maintenance or operation performance and suggest improvements.

Other stakeholders can be identified, not depending on the organisation but on the work performed. These include:

- Project manager: in charge of the development and implementation of a particular solution for the railway system.
- RAMS manager: responsible for ensuring that the system fulfils the safety requirements to operate; also analyses the RAMS parameters to measure the system performance and propose improvements.
- Maintenance manager: implements programs and procedures to ensure the optimal operation of the various railway systems.
- Maintenance personnel: performs corrective and preventive maintenance.
- Logistics manager: organises the inventory and distribution of railway assets.
- etc.

Clearly, a wide variety of stakeholders take part in the operation and maintenance performance of the railway signalling systems, and it is logical to assume that some information and knowledge must be transferred among them. It can also be assumed that sharing knowledge will benefit all stakeholders, as general know-how will increase and the ability to cooperate will be strengthened.

As noted above, each stakeholder has different knowledge access and needs, but they are alike in that all work on the railway systems. The signalling system is more complex than some other systems, however, compounding the problem of knowledge sharing. An aspect setting signalling systems apart is their distributed location: part of the signalling system is located along the infrastructure and part on the rolling stock. Added to this, all systems must be interoperable to function (different signalling systems are not compatible), and if one of the subsystems is modified or updated, this will affect the rest of the components in the system. Hence, a framework to share knowledge is not only beneficial but actually needed for the smooth operation and maintenance of the signalling system. The knowledge transfer and dissemination of best practices between different stakeholders can thus benefit everyone.

4 Dependability improvement through knowledge management

Because it is impossible to get accurate results in the measurement of maintenance performance without having accurate information, knowledge management is crucial [9]. Luxhøj et al. [16] reviewed the relationship between maintenance improvement and organisational learning. They found that the maintenance knowledge base in a company is typically not well organised, structured, or current. Organisational learning can be defined as changes in organisational practices (including routines and procedures, structures, technologies, systems, and so on) that are mediated through individual learning or problem-solving processes [17].

Conducting effective and efficient maintenance requires accurate information and appropriate knowledge provisioning. Insufficient or inadequate maintenance support information leads to the “No Fault Found” (NFF) phenomenon [18]. Hockley and Phillips [19] explained the relationship between NFF and lack of training, sharing information and communication among others as organisational causes of NFF. Zhou et al. [20] proposed a fault knowledge management method to improve maintenance support performance. Horiguchi et al. [21] presented a new concept of the knowledge management framework for sharing technical know-how in an engineering community, using latent connections among technical keywords to search work reports for relevant references. Mansor et al. [9] proposed a knowledge repository or warehouse for maintenance activities consisting of four elements: best practice, databases, discussion forums and assessment tools.

Information logistics processes can handle the dissemination of explicit knowledge but they cannot transfer tacit knowledge, as this depends partly on the expertise of the personnel.

4.1 Outsourcing maintenance

Campbell [10] described a framework to outsource maintenance, addressing such key aspects as objectives, readiness, alternatives, proposals and negotiations. Benefits of outsourcing include the following: the organisation is not limited to its own capabilities; suppliers can have more specialised personnel and better knowledge of a specific area; contractors can have more specialised equipment to perform a service, providing better quality and service at a lower price; outside sources do not require extended time to come up to speed on a new concept, as they are hired because they already possess knowledge and experience; permanent staff are exposed to outside specialists, giving them an opportunity to upgrade their skills [10].

Outsourcing activities have some risks: increased dependency on vendors; difficulty of building new relationships and managing relationships that go wrong; risk of communication and organisation problems; risk of leakage of confidential information; loss of critical skills or developing the wrong skills or losing control over critical functions; lowered morale of permanent employed employees; loss of cross-functional communication; loss of control over a supplier; less incentive to be innovative with short term contracts, based on the lowest winning bid [10,11].

4.2 Knowledge management

Knowledge is personalised information related to facts, judgments, ideas, observations, etc. [22,23]. Knowledge can be classified according to how it is transmitted and articulated. Explicit or codified knowledge is transmittable in formal, systematic language, while tacit knowledge is linked to the individual and is very difficult to articulate [23,24,25].

Thus, tacit and explicit knowledge have different methods of dissemination [24,25], and these must be addressed by knowledge management theories. Blumenberg et al. [24] showed that combined knowledge-transfer processes for tacit and explicit knowledge are more effective than are processes focused on one kind of knowledge (tacit or explicit). Their results also indicated that high levels of shared knowledge positively influence outsourcing performance [24]. On the model used by Toyota, explicit knowledge is disseminated by the supplier association, while tacit knowledge is transferred by the consulting / problem-solving division, the voluntary learning teams and the employee transfers [25].

4.3 Inter-organisational knowledge management

Due to the deregulated environment of the Swedish railway network, it is necessary not only to study the knowledge management processes of the different stakeholders but to optimise performance and maximise benefits by sharing best practices.

Lane and Lubatkin [26] determined that the ability of an organisation to learn from other organisations depends on the similarity of their respective knowledge bases, organisational structures, compensation policies, and dominant logics. Tsai (2001) used the concepts of network position and absorptive capacity to determine the effectiveness on inter-organisational learning and knowledge transfer. Findings indicated that organisational units can be more innovative and perform better if they occupy a central position in the inter-organisational network, but the result will depend on the company´s capacity to replicate new knowledge [27].

The learning processes and outcomes of different people placed in the same task or job with the same learning potential will depend on their personal learning capabilities [17]. Ellström [17] defined four factors that affect learning integration:

- Learning potential in terms of task complexity, variety and control
- Feedback, evaluation and reflection opportunities
- Type and degree of formalisation of work processes
- Employee participation in handling problems and developing work processes
- Learning resources (e.g. time for analysis, interaction and reflection)

Lee and Van den Steen [28] proposed a model to explore the managerial decisions of a company that seeks to maximise the knowledge-based performance of its employees, describing the factors deciding which information is worth to record and manage, and who should have access to that information. In particular, they stressed the importance of recording best practices in the long term even when the performance varies over time, because the additional information serves as backup for when the best practice becomes obsolete [28].

Dyer and Nobeoka [25] showed that if the network can create a strong identity and coordinating rules, it will become an organisational form for creating and recombining knowledge, given the diversity of knowledge that resides within a network. They described Toyota´s inter-organisational knowledge network and explained how Toyota has solved the three dilemmas of sharing knowledge: motivating members to participate and openly share valuable knowledge (while preventing undesirable spill-over to competitors), preventing free riders and reducing the costs associated with finding and accessing different types of valuable knowledge. Toyota´s inter-organisational knowledge management network is based on three processes: a supplier association to facilitate sharing information; a Toyota´s operations management division which gives support to all members of the network; a small group learning for knowledge sharing; and inter-firm employee transfers [25]. Toyota has also established some “rules” within the network that prevent members from protecting or hiding valuable knowledge and from free riding

[25]: intellectual property rights are at the network level, not the firm level; the recipient of knowledge may appropriate 100% of the savings in the short run, but over time will be expected to share a proportion of those savings with the network (e.g., through price cuts to Toyota).

5. Research methodology

Our research is based on different companies related to the railway sector. A schema of the research methodology is shown in Figure 1. The corrective maintenance data processed for this study were obtained from Trafikverket. The data comprise work orders (WO) from January 2003 to November 2012 for a railway corridor 203km long in the northern part of Sweden.

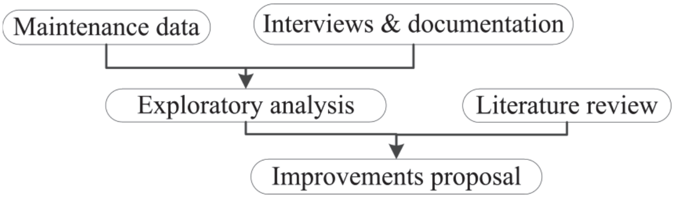

Figure 1: Research methodology.

We used a variety of empirical data to determine whether there is a need to improve the knowledge management of signalling systems. We performed an exploratory analysis on corrective maintenance data obtained from the infrastructure manager. The exploratory analysis identified whether the maintenance performance could be improved using knowledge management theories. By analysing the WOs related to corrective maintenance actions, it was possible to identify areas of improvement. The following information was collected from the WOs:

- Number of “No found failure” or “Not possible to define failure” WO.
- Number of work orders that were opened due to the same failure in a short range of time
- Time since the work order is opened (the failure is detected) until the WO is closed (the failure is repaired).
- Time to repair for each WO,
- Relation between the total time for the corrective maintenance (total time that the work order is opened) and the actual time to repair the failure.

We also used reports, unstructured interviews and scientific articles to determine how knowledge is managed and transferred between Trafikverket and the rest of the stakeholders involved on the maintenance of the signalling systems.

In addition to collecting data, we performed a literature review of current theories of knowledge management, organisational learning, know-how transfer, and knowledge dissemination. We focused on theories of knowledge management and dissemination in inter-organisational networks and outsourcing performance because of the number of different stakeholders in the railway. The literature review suggested several possibilities for improving the maintenance and operation of the railway network, particularly signalling systems. We detail these in following sections.

Admittedly, the research has some limitations. First, we did not analyse the data to determine quantitative measures of the effects of the knowledge management on the maintenance performance. This calls for further research and analysis. Second, present work is based on previous studies, and future research should seek to clarify the knowledge transfer between stakeholders (e.g. interviews with maintenance companies, manufacturers, etc.).

6. Case study

An analysis of the corrective maintenance data shows that signalling systems play an important role in corrective maintenance; 27% of the work orders were related to failures in signalling systems (see Figure 2, left). Yet this is one of the most critical systems in the railway network, because it ensures safe operation. Thus, improving maintenance would improve overall railway maintenance, and improvements in knowledge management for signalling systems would be applicable to other systems in the railway network.

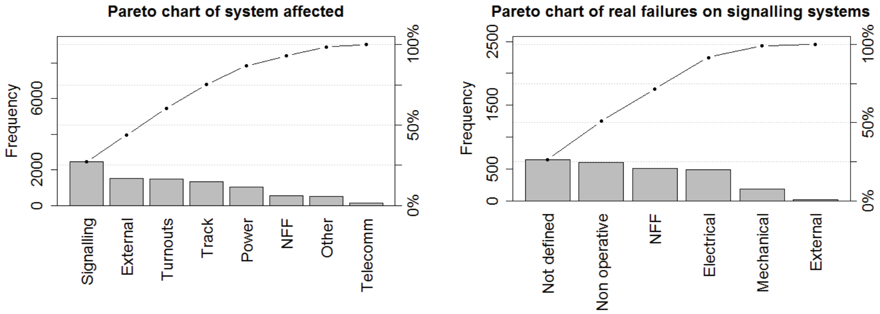

Figure 2: Left: Failure asset classification; Right: Real failure on signalling systems.

6.1 No fault found phenomena

Among the real failure modes recorded on the different WOs, a significant number noted “no failure found” or “could not identify the failure”. For signalling systems, the percentage of WOs where the failure was not possible to define or no failure was found reached 47% (see Figure 2 right). Research in the area of the “no fault found” (NFF) shows the importance of this problem technically but also indicates organisational and behavioural aspects and proposes addressing it as an integrated problem [18,19,29,30].

A practical example is given in Table 1. Four work orders are related to a failure reading an ATC code. The failed component was identified as belonging to the balise group. The first work order was open for four hours, with two hours dedicated to corrective action. In this example, no corrective actions were performed since it was not possible to identify the failure. Looking at the data, we see that the failure appeared three more times in the following days. The third work order related to the same failure, and this time the failure was assigned to the component related to the ATC (part of the subsystem of control and supervision of the interlocking system), but no failure was found. It was not until the fourth failure that corrective action was performed, and the component was replaced.

Report label	**Example case**			
Failure report ID	FRXXX1	FRXXX2	FRXXX3	FRXXX4
Active repair time	1 h. 50 min	15 min	1 h. 30 min	1 h.
Symptom	Failure code ATC	Failure code ATC	Failure code ATC	Failure code ATC
System	Balise group	Balise group	Interlocking / RBC	Interlocking / RBC
Subsystem asset	-	-	Control and supervision	Control and supervision
Component			ATC	ATC
Real failure	No failure	No failure	Not possible to define	Bad contact
Cause	No reason known	No reason known	No reason known	Material Fatigue / Aging
Action performed	Control	Control	Control	Unit replacement

Table 1: Different work orders can be related to the same failure

The corrective data show that NFFs require extra time in corrective maintenance. Hence, improving knowledge management and promoting knowledge transfer can have an impact on the number of NFFs, reducing the work orders and the time spent performing corrective actions.

6.2 Repair time

The times spent on the work orders are particularly instructive. From the database, we can extract the following information on times and dates of corrective maintenance work orders: failure identification; WO opened; start of the corrective action; end of the corrective action and closure of the WO.

To analyse the data, we calculated the total time spent on the corrective action (TTM) given by Equation (1), the time on the repair action (TTR) given by Equation (2), and the relative repair time (RRT) against the total time for each WO given by Equation (3), analysing the general characteristics of each and the relationship between them.

$$\mathrm{TTM} = \mathrm{t(finish\ of\ corrective\ action)} - \mathrm{t(failure\ identification)} \qquad (1)$$

$$\mathrm{TTR} = \mathrm{t(finish\ of\ corrective\ action)} - \mathrm{t(start\ of\ corrective\ action)} \qquad (2)$$

$$\mathrm{RRT\ (\%)} = \frac{\mathrm{TTR(sec)}}{\mathrm{TTM(sec)}} \qquad (3)$$

Table 2 shows the main parameters for the repair time and the time for maintenance, together with the relation between them, calculated as the relative repair time vs. total time. Approximately half the total time is repair time (43%), but the relation is quite distributed; in some work orders TTM is equal to TTR, while in others, they are not comparable. Reasons for this vary: failure mode identification and specification of the needs required for repairing, distance to the failure location, human and /or material resources, etc.

Table 7. TTM, TTR and relative repair time (sec)

	Min	**1st Qu.**	**Median**	**Mean**	**3rd Qu**	**Max.**
TTM (sec.)	180	4560	8700	16580	17400	86340
TTR (sec.)	60	1260	3060	6094	6960	83880
RRT (%)	0.29	19.31	42.96	45.28	70,14	100.00

Table 2: TTM, TTR and RRT

Figure 3 visually summarises the relative repair time depending on the system asset affected by the failure. This figure shows the maximum and minimum times spent, the median and the first and third quartiles. The density distribution is at the perimeter of the boxplots, and its width is given by the number of work orders associated with a failure of the system asset. We cannot make any generalisations about the relationship between TTM and TTR; the relationship varies differently, depending on the asset examined.

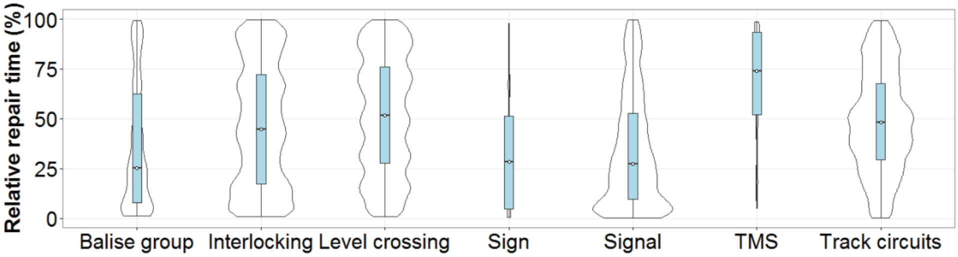

Figure 3: Relative repair time depending on system asset.

For system assets mostly affected by mechanical failures (e.g. signals, signal boards), the relative repair time is proportionally smaller, and the distribution of the relative repair time decreases when the values or TTR and TTM are more similar. Arguably, mechanical failures are easier to identify and these assets have a simpler architecture, thus facilitating repair or replacement and reducing TTR. The balise groups also have a smaller relative repair time, even though most failures are electronically based, due to the simplicity of its architecture.

For electronically based system assets with more complex architecture (e.g. interlocking, TMS), the relative repair time is proportionally higher than for mechanically based assets, and the distribution of the relative repair time does not show a trend. Possibly, more time is spent on identifying the occurred failure and finding the proper corrective action.

NFFs are more common to electronically based systems, and the architecture of these systems is more complex. In such cases, having better knowledge of the systems to maintain can reduce the time required to identify the required corrective maintenance action.

6.3 Knowledge management

Trafikverket uses different types of contracts for the maintenance of the infrastructure; some are performance-based. The condition of the track is assessed before a contract is set up, and changes on the condition of the assets are linked to bonuses and fees [11,31]. All new contracts are performance-based with fixed payments for five years and an option of two more years [31].

A bonus is used as an incentive and ensures gains for the contractor if he succeeds in reaching the objectives or fulfilling the demands. Penalties are often connected with other demands in the contract, and are enforced if the contractor fails to comply. Such expectations include the following [11]:

- Failure reports should be reported back to the system.
- Inspection remarks should be reported back to the system.
- Time to repair must be recorded, i.e. the time from when the contactor has been notified about a failure until the contractor is in place to start the repair.
- Mean time to repair failures should not exceed prescribed time limits.
- Inspections should adhere to prescribed time limits.
- Planned maintenance activities on the track should not be exceeded.
- Maintenance activities on the track should not cause train delays.
- All personnel working on the track must be informed about traffic and electrical safety demands.

Trafikverket has a wide network of combined databases which gather information from the railway network, and to which stakeholders have access depending on their needs to perform the outsourced activity (e.g. maintenance, performance studies, design improvements, etc.). The information related to signalling system found on these databases includes:

- System architecture (BIS database) [15,32]
- Generic documentation (BVDOC database)
- Project documentation (IDA database) [33]
- Corrective maintenance (0felia database) [34]
- Preventive maintenance inspections (BESSY database) [35]
- ATC design performance (PATCY database)
- Analysis of operation and maintenance performance (Duvan database)

Knowledge dissemination and distribution from Trafikverket to stakeholders is done by sharing access to the databases. Other methods are used as well, such as emails, documents, meetings and informal conversations. Knowledge transfer from stakeholders to Trafikverket takes the form of reports (in the case of delivered results) or person-to-person communication (email, phone, conversations, etc.). Knowledge transfer between personnel working on the same project comprises emails, shared databases, documents, meetings, informal conversations etc.

Two common concerns emerged in our interviews of stakeholder experts involved in the maintenance of railway signalling systems (maintenance contractors, Trafikverket and a consultancy). They all pointed out the risk of loss of knowledge and expertise as more tasks are outsourced, and they all thought Trafikverket should have a sufficient depth of knowledge to be able to manage the railway network efficiently.

Espling [11] studied the maintenance strategy for a railway infrastructure in a regulated environment by implementing benchmarking techniques to compare different case studies from the Swedish railway network. Four risk areas were identified when outsourcing maintenance activities: the risk of losing control over maintenance costs, asset condition (asset measuring data to analyse the asset degradation), safety demands (concerning the contractor's employees' knowledge of track safety and asset knowledge) and core competence and asset knowledge [11]. Data on maintenance costs and asset condition are required to perform life cycle cost (LCC) analyses; a lack of information will be problematic in studies of the effect of changes on the infrastructure during the maintenance phase of the life cycle.

Best practices on maintenance contracting include: goal-oriented maintenance contracts combined with incentives; scorecard perspectives, quality meetings and feedback on objectives; frequent meetings where top managers from the local areas participate; cooperation and open and clear dialogue; and the use of Root Cause analysis [11].

7. Discussion and implications

Data analysis shows that signalling systems play an important role in corrective maintenance. Given the number of work orders related to these systems, it seems clear that improving maintenance in this area would lead to an overall improvement of railway maintenance. A significant number of work orders recorded failure causes as "no failure found" or "not possible to identify the failure". Both require extra time spent on corrective maintenance; with better knowledge of the system, maintenance performance would improve.

Better knowledge of the system helps improve preventive maintenance and reduces the time to identify the failure. Better knowledge management would help identify best maintenance practices for signalling systems and would facilitate the transfer of this knowledge to all stakeholders who can benefit. This, in turn, would reduce the time spent on failure identification and reduce the number of NFFs in WOs.

When outsourcing maintenance, there is a risk of losing the knowledge required to identify best practices related to maintenance activities. Since many stakeholders are involved in the maintenance of railway signalling systems, the knowledge is spread between them. To facilitate knowledge transfer between these stakeholders it is necessary to create new inter-organisational knowledge management processes. Some proposals have been developed, such a framework for benchmarking [11], or in the Toyota case, creating an identity through network-level knowledge-sharing routines [25]. Some of the measures implemented by Toyota could be applied to improve knowledge sharing among the stakeholders involved with railway signalling systems.

Integrating ideas from the relatively new Product-Service-System (PSS) theory area is another interesting possibility [36], as it could change how signalling systems and their maintenance are understood.

Suggested measures to improve inter-organisational knowledge management include the following:

- Creating an association of stakeholders would facilitate the creation of opportunities to share knowledge. It would foster the sense of belonging to the same community, and the belief that all members pursue the same objectives (optimise performance with minimum cost).
- Setting up a consulting division inside Trafikverket to support the stakeholders would incur an extra cost for Trafikverket, but it would help to keep knowledge inside Trafikverket and facilitate benchmarking best practices.
- Periodic intra- and inter-organisational meetings could improve tacit and explicit knowledge management. These meetings would provide a framework within which to exchange procedures and best practices and over time would become an inter-organisational structure for problem-solving and best practices identification.
- Other knowledge management strategies such as formal training in short courses, workshops or seminars for all stakeholders would provide additional ways to generate networking opportunities and knowledge transfer.
- Stakeholders could report their maintenance performance; this could be analysed by the railway's infrastructure manager to determine best practices.
- These best practices could be redistributed to all stakeholders and gathered in a common repository to safeguard knowledge and facilitate knowledge transfer among projects, stakeholders or locations.
- Finally, it would be interesting to consider expanding the knowledge network, not only to the maintenance companies but also to other stakeholders involved in signalling systems, including manufacturers and rolling stock owners. For instance, manufacturers could provide in-depth knowledge of the signalling systems and, in exchange, receive feedback on improving the design. As rolling stock owners have access to the signalling subsystems installed on board, they could give information on the performance of the whole signalling system.

The goal is for the infrastructure manager and the stakeholders to understand that sharing knowledge will benefit everyone. Sharing consulting and problem-solving teams can increase both productivity and supplier performance, making knowledge sharing crucial for all stakeholders, from manufacturers to maintenance companies.

8. Conclusions

The purpose of this paper is to analyse the potential for improving inter-organisational knowledge management in the maintenance of railway signalling systems and make concrete suggestions for improvements. It concludes the following:

- Signalling systems play an important role in corrective maintenance; thus, improving their maintenance would lead to an overall improvement of the railway maintenance. Furthermore, improving knowledge management processes would improve maintenance performance.
- Many stakeholders are involved in the maintenance and operation of railway signalling systems; sharing knowledge among these stakeholders is likely to benefit all of them.
- Proposals to improve inter-organisational knowledge management include the techniques used in the Toyota case and Espling's suggestions.
- Sharing knowledge would give stakeholders a holistic perspective of the maintenance and operation of the railway network and improve the effectiveness of the different organisations.
- To reduce the limitations of this study, future research should make use of in-depth data analysis and other qualitative methodologies. Surveys could validate and quantify the results of interviews and quantify the feasibility of each improvement proposed here. Surveys should be given to all stakeholders.

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